Scientific Background on the Nobel Prize in Physics 2011

THE ACCELERATING UNIVERSE

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

The accelerating Universe

Introduction

The discovery of the accelerating expansion of the Universe is a milestone for cosmology, as significant as the discovery of the minute temperature variations in the Cosmic Microwave Background (CMB) radiation with the COBE satellite (Nobel Prize in Physics 2006, John Mather and George Smoot). By studying the CMB, we may learn about the early history of the Universe and the origins of structure, whereas the expansion history of the Universe gives us insights into its evolution and possibly its ultimate fate.

The expansion of the Universe was discovered by Vesto Slipher, Carl Wirtz, Knut Lundmark, Georges Lemaître and Edwin Hubble in the 1920's. The expansion rate depends on the energy content – a Universe containing only matter should eventually slow down due to the attractive force of gravity. However, observations of type Ia supernovae (SNe) at distances of about 6 billion light years by two independent research groups, led by Saul Perlmutter and by Brian Schmidt and Adam Riess respectively, reveal that presently the expansion rate instead is accelerating.

Within the framework of the standard cosmological model, the acceleration is generally believed to be caused by the vacuum energy (sometimes called "dark energy") which – based on concordant data from the SNe, the observations of the anisotropies in the CMB and surveys of the clustering of galaxies – accounts for about 73% of the total energy density of the Universe. Of the remainder, about 23% is due to an unknown form of matter (called "dark matter"). Only about 4% of the energy density corresponds to ordinary matter like atoms.

In everyday life, the effects of the vacuum energy are tiny but measurable – observed for instance in the form of shifts of the energy levels of the hydrogen atom, the Lamb shift (Nobel Prize in Physics 1955).

The evolution of the Universe is described by Einstein's theory of general relativity. In relativistic field theories, the vacuum energy contribution is given by an expression mathematically similar to the famous cosmological constant in Einstein's theory. The question of whether the vacuum energy term is truly time independent like the cosmological constant, or varies with time, is currently a very hot research topic.

General Relativity and the Universe

The stars in the night sky must have always fascinated human beings. We can only guess what the people of ancient times speculated about when they saw the stars return every night to the same spots in the sky. We know of Greek philosophers who proposed a heliocentric astronomical model with the Sun in the middle and the planets circulating

around it as early as the 3rd century B.C., but it was Nicolaus Copernicus, who in the 16th century developed the first modern version of a model. It took Galileo Galilei's genius in the beginning of the next century to really observe and understand the underlying facts, building one of the first telescopes for astronomy and hence laying the ground for modern astronomy. For the next three hundred years, astronomers collected evermore impressive tables of observations of the visible stars. In the Copernican system, the stars were assumed to be fixed to a distant sphere and nothing in the observations indicated anything to the contrary. In 1718, Edmund Halley discovered that stars actually could move in the sky, but it was believed that this happened in a static, fixed universe. Throughout the 18th and 19th century, the study of celestial bodies was placed on an ever-firmer footing with the famous laws of Kepler and Newton.

In November 1915, Albert Einstein (Nobel Prize in Physics 1921) presented his theory of gravity, which he nicknamed General Relativity (GR) [1], an extension of his theory of special relativity. This was one of the greatest achievements in the history of science, a modern milestone. It was based on the *Equivalence Principle*, which states that the gravitational mass of a body is the same as its inertial mass. You cannot distinguish gravity from acceleration! Einstein had already checked that this could explain the precession of the perihelion of Mercury, a problem of Newtonian mechanics. The new insight was that gravity is really geometric in nature and that the curving of space and time, spacetime, makes bodies move as if they were affected by a force. The crucial physical parameters are the metric of spacetime, a matrix that allows us to compute infinitesimal distances (actually infinitesimal line elements - or proper times in the language of special relativity.) It became immediately clear that Einstein's theory could be applied to cosmological situations, and Karl Schwarzschild very soon found the general solution for the metric around a massive body such as the Sun or a star [2].

In 1917, Einstein applied the GR equations to the entire Universe [3], making the implicit assumption that the Universe is homogenous; if we consider cosmological scales large enough such that local clusters of matter are evened out. He argued that this assumption fit well with his theory and he was not bothered by the fact that the observations at the time did not really substantiate his conjecture. Remarkably, the solutions of the equations indicated that the Universe could not be stable. This was contrary to all the thinking of the time and bothered Einstein. He soon found a solution, however. His theory of 1915 was not the most general one consistent with the Equivalence Principle. He could also introduce a cosmological constant, a constant energy density component of the Universe. With this Einstein could balance the Universe to make it static.

In the beginning of the 1920s, the Russian mathematician and physicist Alexander Friedmann studied the problem of the dynamics of the Universe using essentially the same assumptions as Einstein, and found in 1922 that Einstein's steady state solution was really unstable [4]. Any small perturbation would make the Universe non-static. At first Einstein did not believe Friedmann's results and submitted his criticism to *Zeitschrift für Physik*, where Friedmann's paper had been published. However, a year later Einstein found that he had made a mistake and submitted a new letter to the journal acknowledging this fact. Even so, Einstein did not like the concept of an expanding

Universe and is said to have found the idea "abominable". In 1924, Friedmann presented his full equations [5], but after he died in 1925 his work remained essentially neglected or unknown, even though it had been published in a prestigious journal. We have to remember that a true revolution was going on in physics during these years with the advent of the new quantum mechanics, and most physicists were busy with this process. In 1927, the Belgian priest and physicist Georges Lemaître working independently from Friedmann performed similar calculations based on GR and arrived at the same results [6]. Unfortunately, Lemaître's paper was published in a local Belgian journal and again the results did not spread far, even though Einstein knew of them and discussed them with Lemaître.

In the beginning of the 20th century it was generally believed that the entire Universe only consisted of our galaxy, the Milky Way. The many nebulae which had been found in the sky were thought to be merely gas clouds in distant parts of the Milky Way. In 1912, Vesto Slipher [7], while working at the Lowell Observatory, pioneered measurements of the shifts towards red of the light from the brightest of these spiral nebulae. The *redshift* of an object depends on its velocity radially away from us, and Slipher found that the nebulae seemed to move faster than the Milky Way escape velocity.

In the following years, the nature of the spiral nebulae was intensely debated. Could there be more than one galaxy? This question was finally settled in the 1920s with Edwin Hubble as a key figure. Using the new 100-inch telescope at Mt Wilson, Hubble was able to resolve individual stars in the Andromeda nebula and some other spiral nebulae, discovering that some of these stars were Cepheids, dimming and brightening with a regular period [8].

The Cepheids are pulsating giants with a characteristic relation between luminosity and the time interval between peaks in brightness, discovered by the American astronomer Henrietta Leavitt in 1912. This luminosity-period relation, calibrated with nearby Cepheids whose distances are known from parallax measurements, allows the determination of a Cepheid's true luminosity from its time variation – and hence its distance (within ~10%) from the inverse square law.

Hubble used Leavitt's relation to estimate the distance to the spiral nebulae, concluding that they were much too distant to be part of the Milky Way and hence must be galaxies of their own. Combining his own measurements and those of other astronomers he was able to plot the distances to 46 galaxies and found a rough proportionality of an object's distance with its redshift. In 1929, he published what is today known as 'Hubble's law': a galaxy's distance is proportional to its radial recession velocity [9].

Even though Hubble's data were quite rough and not as precise as the modern ones, the law became generally accepted, and Einstein had to admit that the Universe is indeed expanding. It is said, that he called the introduction of the cosmological constant his "greatest mistake" (Eselei in German). From this time on, the importance of the cosmological constant faded, although it reappeared from time to time.

It should be noted for the historic records that Lemaître in his 1927 paper correctly derived the equations for an expanding Universe obtaining a relation similar to Hubble's and found essentially the same proportionality constant (the "Hubble constant") as Hubble did two years later. After Hubble's result had spread, Arthur Eddington had Lemaître's paper translated into English in 1931, *without the sections about Hubble's law*. In a reply to Eddington, Lemaître [10] also pointed out a logical consequence of an expanding Universe: The Universe must have existed for a finite time only, and must have emerged from an initial single quantum (in his words). In this sense, he paved the way for the concept of the Big Bang (a name coined much later by Fred Hoyle). It should also be noted that Carl Wirtz in 1924 [11] and Knut Lundmark in 1925 [12] had found that nebulae farther away recede faster than closer ones.

Hubble's and others' results from 1926 to 1934, even though not very precise, were encouraging indications of a homogeneous Universe and most scientists were quick to accept the notion. The concept of a homogeneous and isotropic Universe is called the *Cosmological Principle*. This goes back to Copernicus, who stated that the Earth is in no special, favoured place in the Universe. In modern language it is assumed that the Universe looks the same on cosmological scales to all observers, independent of their location and independent of in which direction they look in. The assumption of the Cosmological Principle was inherent in the work of Friedmann and Lemaître but virtually unknown in large parts of the scientific society. Thanks to the work of Howard Robertson in 1935-1936 [13] and Arthur Walker in 1936 [14] it became well known.

Robertson and Walker constructed the general metric of spacetime consistent with the Cosmological Principle and showed that it was not tied specifically to Einstein's equations, as had been assumed by Friedmann and Lemaître. Since the 1930s, the evidence for the validity of the Cosmological Principle has grown stronger and stronger, and with the 1964 discovery of the CMB radiation by Arno Penzias and Robert Wilson (Nobel Prize in Physics 1978), the question was finally settled [15]. The recent observations of the CMB show that the largest temperature anisotropies (on the order of 10^{-3}) arise due to the motion of the Milky Way through space. Subtracting this dipole component, the residual anisotropies are a hundred times smaller.

Einstein's Equations for a Homogeneous and Isotropic Universe

In Einstein's theory [1], gravity is described by the spacetime metric $g_{\mu\nu}$, where the indices run over the time and the three space coordinates, and where the metric varies in spacetime. The infinitesimal, invariant, line element $d\tau$ is given by

$$d\tau^2 = g_{\mu\nu}(x)dx^\mu dx^\nu. \tag{1}$$

There are ten gravity fields over the four spacetime coordinates. However, the symmetries of the theory stemming from the Equivalence Principle reduce that to two

independent degrees of freedom. Einstein used the mathematical theory of differential geometry to find the relevant tensors quadratic in spacetime derivatives of the metric field, the Ricci tensor $R_{\mu\nu}$ and the curvature scalar R, to derive the dynamical equations for the metric tensor. In the modified form with a cosmological constant Λ, the equations are

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}, \tag{2}$$

where G is Newton's constant, which determines the strength of the gravity force, and $T_{\mu\nu}$ is the energy-momentum tensor. Here, as in the following, we have set the velocity of light to unity ($c = 1$).

Einstein's equations (2) represent ten coupled differential equations. With the Friedmann-Lemaître-Robertson-Walker assumption about the Cosmological Principle the metric simplifies to

$$d\tau^2 = dt^2 - a^2(t)\left\{\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right\}, \tag{3}$$

where $a(t)$ is a scale factor and k is a constant that depends on the curvature of spacetime. The constant k has been normalized to the values *-1,0* or *1* describing an open, flat or closed Universe. The variables r, θ and φ are so called co-moving coordinates, in which a typical galaxy has fixed values. The physical cosmological distance for galaxies separated by r at a given time t (in the case of $k = 0$) is $a(t)r$, which grows with time as the scale factor $a(t)$ in an expanding Universe. In order to solve Einstein's equations for this metric one also must assume a form for the matter density. The Cosmological Principle implies that the energy-momentum tensor has a form similar to that of the energy-momentum tensor in relativistic hydrodynamic, for a homogeneous and isotropic fluid with density ρ and pressure p (which both may depend on time). It is, in the rest frame of the fluid, a diagonal tensor with the diagonal elements *(ρ, p, p, p)*. If we insert the metric above and the energy-momentum tensor into the equations (2) , we get the two independent Friedmann equations

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3} \tag{4}$$

and

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}, \tag{5}$$

where a dot means a time derivative and H is the expansion rate of our Universe called the Hubble parameter, or the Hubble constant, with its present value H_0. It is seen to depend on both the energy density of the Universe as well as its curvature and a

possible cosmological constant. With k and Λ set to zero, one defines the critical density as

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

In 1934, Lemaître [16] had already pointed out that the cosmological constant could be considered as a vacuum energy and hence a contribution to the energy density of the form

$$\rho_\Lambda = \frac{\Lambda}{8\pi G}.$$

We will assume that the Universe is composed of a set of components i, each having a fraction, Ω_i, of the critical density,

$$\Omega_i = \frac{\rho_i}{\rho_c}.$$

The two Friedmann equations are not enough to fully solve for the energy density, the pressure and the scale factor. We also need an equation of state, $\rho = f(p)$, which can usually be written as $w_i = p_i / \rho_i$. For example, w_i takes the value 0 for normal, non-relativistic, matter and $1/3$ for photons. Since we now consider the cosmological constant as a part of the energy-momentum tensor we can compare the expression for the energy-momentum tensor for a perfect fluid in the rest frame, with diagonal elements (ρ, p, p, p), to the cosmological term $\rho_\Lambda\, g_{\mu\nu}$, with diagonal elements $\rho_\Lambda\, (1, -1, -1, -1)$. We conclude that $p_\Lambda = -\rho_\Lambda$, i.e., $w_\Lambda = -1$. The cosmological constant can hence be seen as a fluid with negative pressure.

From Eq. (5), it is clear that a static universe cannot be stable. Eq. (5) determines the deceleration or acceleration of the Universe. Since the expansion of the Universe was (wrongly) assumed to be be slowing down (*i.e.,* a negative sign of the acceleration), a parameter q_0, called the deceleration parameter, was defined by

$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\ddot{a}}{aH_0^2}.$$

From Eq:s (4) and (5) it then follows that

$$q_0 = \frac{1}{2}\sum_i \Omega_i\left(1 + 3w_i\right). \tag{6}$$

When we measure the light coming from a distant object, we can obtain two pieces of information apart from the direction to the object. We can measure the redshift and the apparent luminosity of the object: It is straightforward to measure the wavelength of light (e.g. from a given atomic spectral line) that a distant object emits. From Eq. (3)

one can easily compute the relation between the wavelength an object emits, λ_1 at time t_1 and the wavelength observed here λ_0 at time t_0

$$\frac{\lambda_0}{\lambda_1} = \frac{a(t_0)}{a(t_1)}.$$

This is conventionally expressed in terms of a redshift parameter z as

$$z = \frac{\lambda_0 - \lambda_1}{\lambda_1} = \frac{a(t_0)}{a(t_1)} - 1.$$

For small z, we can then interpret the redshift z as the radial velocity of the object (it would correspond to a Doppler effect), and we find again Hubble's law. For cosmological distances, the interpretation is less simple. Once we find standard candles luminous enough, however, measurements of redshift are relatively straightforward.

Measuring a cosmological distance in the Universe is not straightforward. We must use a light signal that is emitted at a certain time and detected at another. During this time the Universe has expanded. There are different distance measures introduced, but the one used for standard candles, *i.e.,* objects with known intrinsic luminosity is the luminosity distance d_L, defined by

$$d_L = (L/4\pi l)^{1/2} \,,$$

where L is the absolute luminosity of the standard candle and l is the apparent luminosity.

Luminosity distance can be computed in terms of the parameters in which we are interested, and for small z we can expand it as

$$d_{L.} = \frac{1}{H_0}\left(z + \frac{1}{2}(1 - q_0)z^2 + ... \right). \tag{7}$$

Again, to be completely clear, d_L is not an unambiguous measure of the distance to the standard candle, but it is a measure sensitive to the parameters we want to determine. In order to use it we need to know of celestial objects with known absolute luminosity. From Eq. (7), we can see that in the nearby Universe, the luminosity distances scale linearly with redshift, with $1/H_0$ as the constant of proportionality. In the more distant Universe, d_L depends to first order on the rate of deceleration, or equivalently on the amount and types of matter that make up the Universe. The general expression has to be written in terms of an integral over the redshift z' of the propagating photon as it travels from redshift z to us, at $z = 0$. In the case that relates to this year's Nobel Prize in Physics, we may assume a flat Universe, $k = 0$ (as indicated to good accuracy by CMB measurements), and since radiation gives only a tiny contribution today, we may as an

approximation keep only the matter contribution Ω_M and that of dark energy Ω_Λ. The expression for the luminosity distance then becomes

$$d_L(z; H_0, \Omega_M, \Omega_\Lambda) = \frac{1+z}{H_0} \int_0^z \frac{dz´}{\sqrt{\Omega_M(1+z´)^3 + \Omega_\Lambda}}. \tag{8}$$

If we could measure d_L accurately for low z as well as for higher redshifts, we could both measure the Hubble constant and determine the energy components of our Universe, in particular the value of Ω_Λ [17]. It may be noted from the expression under the square root in Eq. (8) that when one measures very high redshift objects, the influence of the cosmological constant is reduced, and the optimal range is roughly for *0.3 < z < 2*.

Standard Candles in Astronomy

A well-known class of standard candles, as mentioned above, is the Cepheid variable stars, which nowadays can be identified out to distances of about 10 Mpc. To obtain a record of the expansion history of the Universe, one needs, however, standard candles that can be identified over distances at least 100 times larger. Already in 1938, Walter Baade [18], working closely with Fritz Zwicky at the Mt Wilson Observatory, suggested that supernovae are promising as distance indicators: they are extremely bright and can, over a few weeks, outshine an entire galaxy. Therefore, they would be visible over a considerable redshift interval. The SNe that have been discussed over the past decades as standard candles [19] are designated type Ia (SNe Ia).

According to William Fowler (Nobel Prize in Physics 1983) and Fred Hoyle [20], type Ia supernovae occur occasionally in binary systems, when a low-mass white dwarf accreting matter from a nearby companion approaches the limit of 1.4 solar masses (Nobel Prize in Physics 1983, Subramanyan Chandrasekhar), and becomes unstable. A thermonuclear explosion ensues and an immense amount of energy is suddenly released. The evolution of the supernova brightness with time – the so-called light curve – can be observed over a few weeks. In a typical galaxy, supernovae occur a few times in thousand years. In our galaxy, supernovae have been observed with the naked eye, e.g., by Chinese astronomers in 1054 and by Tycho Brahe in 1572. The supernova 1987A (not of type Ia) in the nearby galaxy the Large Magellanic Cloud, at a distance of 160 000 light years, was observed both in light and in neutrinos (Nobel Prize in Physics 2002). For a review of supernova Ia properties, and their use as standard candles, see, e.g., the review by David Branch and Gustav Tammann [21].

SNe Ia are identified through their spectral signatures: The absence of hydrogen features and the presence of a silicon absorption line. Their spectra and light curves are amazingly uniform, indicating a common origin and a common intrinsic luminosity. The small deviations from uniformity can be investigated and corrected.

Observations of how the brightness of these SNe varies with redshift, therefore, allow studies of the expansion history of the Universe. And because – according to theory –

the expansion rate is determined by the energy-momentum density of the Universe and the curvature of spacetime, discovery of the ultimate fate of the Universe appears possible.

Detection of Type Ia Supernovae

The homogeneity of SNe Ia spectra makes this class of objects eminent standard candle candidates. Because the peak luminosity occurs after only a short time, a supernova must be observed early on after the explosion in order to determine the peak magnitude with high precision. There is also another catch: SNe Ia are rare, occurring only a couple of times per millennium in any given galaxy. However, to get a statistically significant determination of cosmological parameters, a large observational sample is needed, including SNe at fairly high redshifts ($z > 0.3$).

The first systematic search for SNe Ia at high redshifts was made during the late 1980s by a Danish-British collaboration [22] working at the 1.5 m Danish telescope at La Silla, Chile. Two years of observations resulted in the discovery of two distant SNe – one of them of Type Ia, the SN1988U at $z = 0.31$. However, this supernova was observed after its maximum which hampered the precision of the peak brightness determination. So, it seemed that discovery of distant SNe was possible but difficult. Obviously larger and faster instruments were needed to ensure the required statistics.

The Supernova Cosmology Project (SCP) was initiated in 1988 by Saul Perlmutter of the Lawrence Berkeley National Laboratory (LBNL), USA, with the aim of measuring the presumed deceleration of the Universe - using SNe Ia as standard candles. In an expanding Universe dominated by matter, gravity should eventually cause the expansion to slow down. To address the problem of sufficient statistics, Perlmutter and collaborators developed a strategy that they dubbed *Supernova on Demand*. Using a CCD-based wide-field imager at a 4 m telescope, the group would observe thousands of galaxies over two to three nights just after new Moon. Imaging the same patches of the sky about three weeks later and using improved image-processing techniques, allowed selection of entire batches of about a dozen or so new SNe at a time. The timing ensured that many SNe would be close to peak brightness, making essential calibration possible. And, because the SNe were guaranteed, timely follow-up observations on the world's largest telescopes in Chile, Hawaii and La Palma could be scheduled in advance for a pre-defined date. The first high-z SN was discovered in 1992, and by 1994, the total number found by SCP reached seven. The first results were published in 1995 [23].

In the mean time, light curves of several nearby type Ia SNe were measured by astronomers led by Mario Hamuy at the Cerro Calán Tololo Interamerican Observatory in Chile [24]. Using this and other data, it was shown by Mark Phillips [25] that a relation between peak brightness and fading time could be used to recalibrate the SNe to a standard profile. The brighter ones grew and faded slower – the fainter ones faster, and the relation allowed to deduce the peak brightness from the time scale of the light curve. The few "abnormal" occurrences were filtered out.

Prompted by the success of the *Supernova on Demand* strategy and motivated by the importance of the quest for q_0, Brian Schmidt of the Mount Stromlo Observatory in Australia organized, in 1994, a competing collaboration, consisting of supernova experts, backed by the renowned scientist Robert Kirshner – the High-z Supernova Search Team (HZT). Over the following years the two collaborations independently searched for supernovae, often but not always at the same telescopes. Like SCP, HZT could successfully demonstrate the validity of the chosen strategy, finding batches of SNe at or close to maximum light that then could be followed up by spectroscopic observations (see Fig. 1).
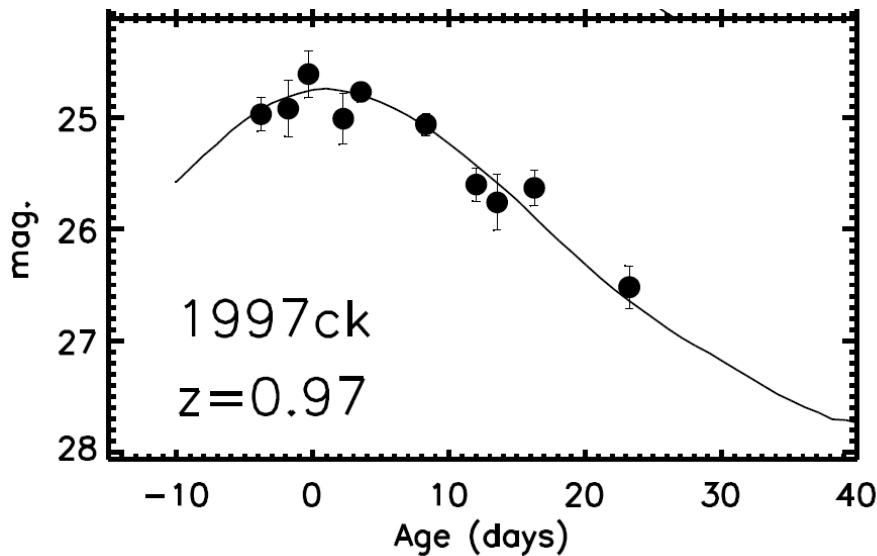

Figure 1. One of the high redshift supernovae of type Ia for which the HZT collaboration [27] could measure the magnitude, i.e., the luminosity, both before and after the peak luminosity.

In the beginning of 1998, both groups published scientific papers and gave talks at conferences, cautiously pointing out that their observations seemed consistent with a low matter density Universe.

The two breakthrough papers [27, 28] implying that the expansion of the Universe does not slow down but actually accelerates, were submitted for publication later that year. The HZT article is based on observations of 16 SNe Ia mainly analyzed by Adam Riess, then a postdoctoral researcher at University of California at Berkeley, whereas the SCP paper, with Perlmutter as the driving force, includes 42 Type Ia SNe.

The fact that both groups independently presented similar - albeit extraordinary - results was a crucial aspect for their acceptance within the physics and astronomy community.

The Observations

Figure 1 shows the supernova data from [28] plotted in terms of brightness (bolometric magnitude) versus redshift.
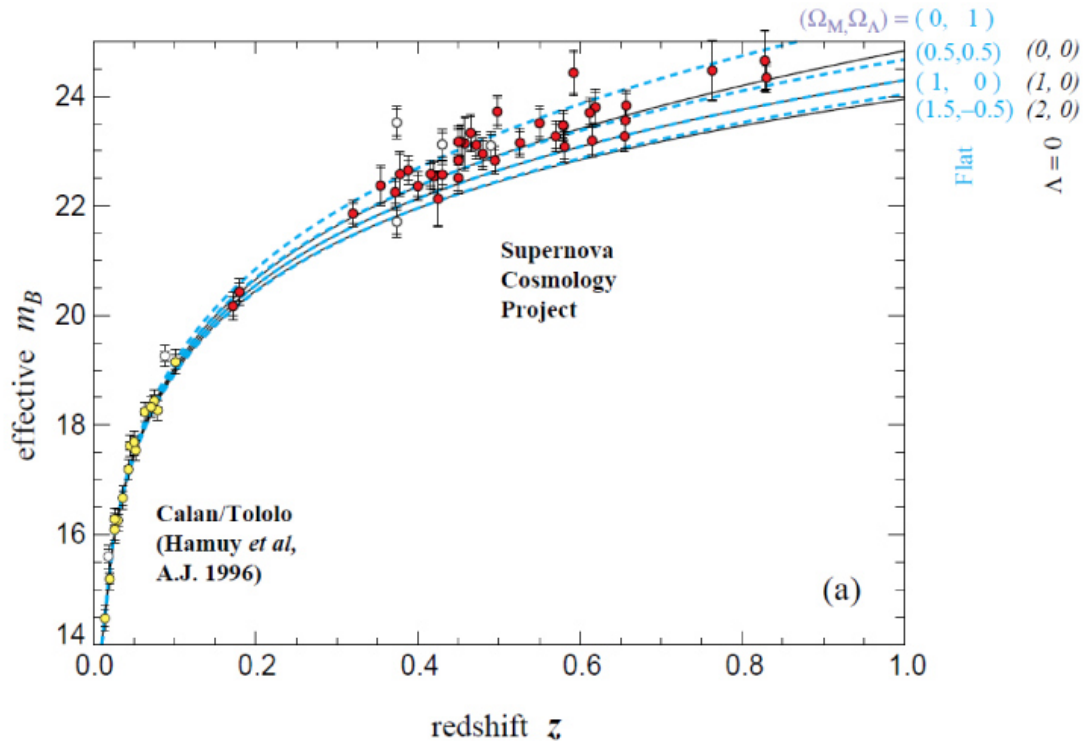

Figure 1: The Hubble diagram for 42 high redshift type Ia supernovae from SCP and 18 low redshift supernovae from the Calan/Tololo Supernova Survey. The solid curves represent a range of cosmological models with $\Lambda = 0$ and $\Omega_M = 0$, 1 and 2. The dashed curves show a range of "flat" models where $\Omega_M + \Omega_\Lambda = 1$. Note the linear redshift scale.

The larger the magnitude, the fainter is the object. On the redshift scale, $z = 1$ corresponds to a light travel time of almost 8 billion light years. The data is compared to a number of cosmological scenarios with and without vacuum energy (or cosmological constant). The data at $z < 0.1$ is from [26]. At redshifts $z > 0.1$ (i.e., distances greater than about a billion light years), the cosmological predictions start to diverge. Compared to an unrealistic empty Universe ($\Omega_M = \Omega_\Lambda = 0$) with a constant expansion rate, the SNe for a given high redshift are observed to be about 10 - 15% fainter. If the Universe were matter dominated ($\Omega_M = 1$), the high-z supernovae should have been about 25% brighter than what is actually observed. The conclusion is that the deceleration parameter q_0 is negative, and that the expansion at the present epoch unexpectedly accelerates (see above). The result of the analyses of the two collaborations, showing that $\Omega_\Lambda = 0$ is excluded with high significance, and that the expansion of the Universe accelerates, is shown in Fig. 2.
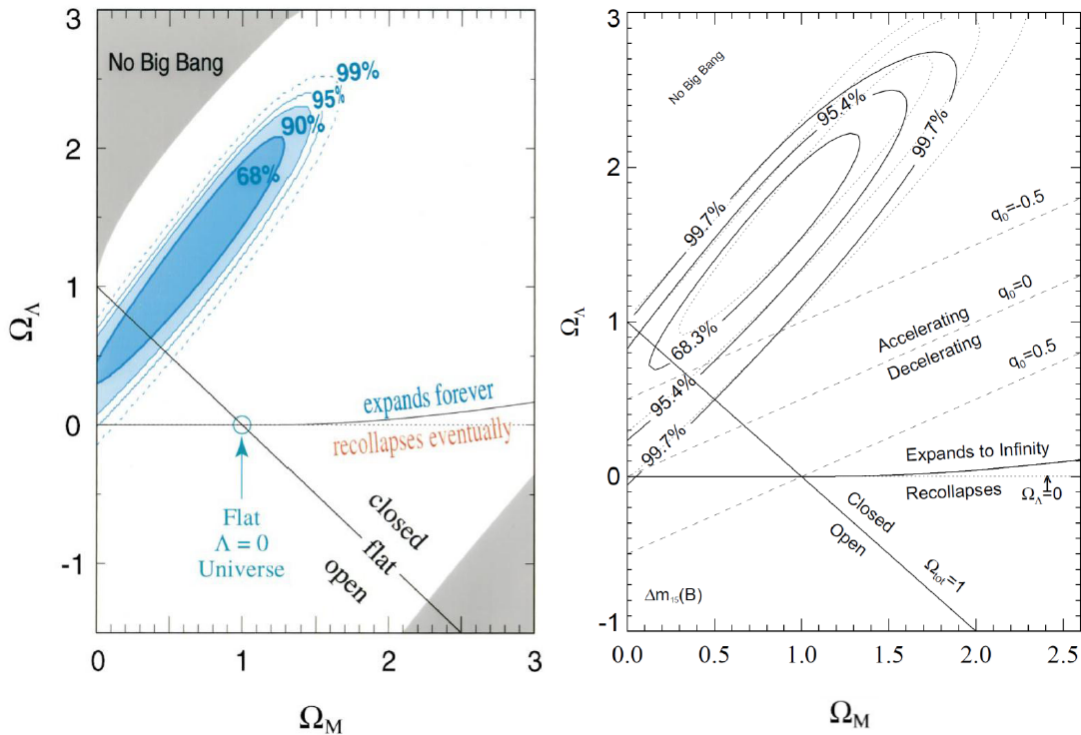
Figure 2. The left-hand panel shows the results of fitting the SCP supernova data to cosmological models, with arbitrary Ω_M and Ω_Λ [28]. The right-hand panel shows the corresponding results from HZT [27].

Could the dimness of the distant supernovae be the effect of intervening dust? Or might the SNe Ia in the early Universe have had different properties from the nearby, recent ones?

Such questions have been extensively addressed by both collaborations, indicating that dust is not a major problem and that the spectral properties of near and distant SNe are very similar. Although not as evident at the time of the discovery, later studies of SNe beyond $z = 1$ [29], from the time when the Universe was much denser and Ω_M dominated, indicate that at that early epoch, gravity did slow down the expansion as predicted by cosmological models. Repulsion only set in when the Universe was about half its present age.
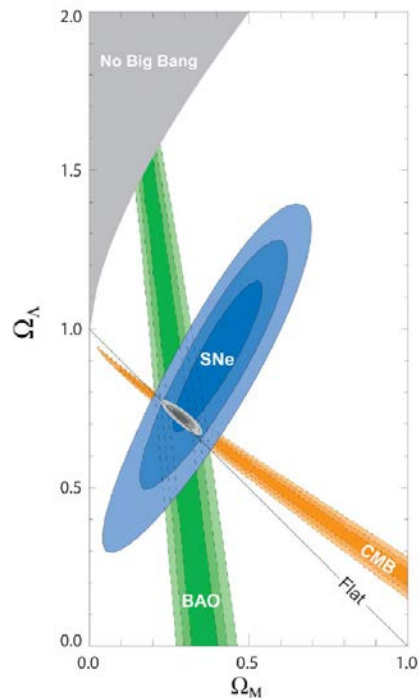
Figure 3. A summary figure from Review of Particle Properties, http://rpp.lbl.gov, showing the combination of supernova observations (SNe), the microwave background (CMB) and the spatial correlation between galaxies ("Baryon Acoustic Oscillations", BAO).

The dramatic conclusion that the expansion of the Universe accelerates has been confirmed during the last decade by precision measurements of the CMB and by studies of galaxy clustering, see Fig. 3.

What is Dark Energy?

The driving force behind the acceleration is unknown, but the current belief is that the cause of the expansion is vacuum energy (in this context called *dark energy*) – as suggested by Lemaître already in 1934 [16]. The SN results emerged at a time when some cosmologists, for many different reasons, argued that the Universe might be vacuum dominated. Others were, however, reluctant to accept such a claim implying a non-zero cosmological constant. The SN observations were the crucial link in support of vacuum dominance, directly testing models with $\Lambda > 0$. The currently accepted cosmological standard model – the Concordance Model or the ΛCDM model – includes both a cosmological constant Λ and Cold (i.e. non-relativistic) Dark Matter. The SNe results combined with the CMB data and interpreted in terms of the Concordance Model allow a precise determination of Ω_M and Ω_Λ (see Fig. 3).

The predictions of the Concordance Model agree, within the experimental uncertainties, with all the presently available data. None of the alternative models proposed to explain the SN observations, based on inhomogeneities of the Universe at large scales, extra

dimensions or modifications of general relativity, seem to convincingly account for all observations.

The very successful Standard Model for Particle Physics, which describes nature at the smallest scales where we can measure, has two inherent sources for vacuum energy, quantum fluctuations and spontaneous symmetry breaking. In relativistic quantum physics the vacuum is not empty but filled with quantum fluctuations, allowed by Heisenberg's uncertainty principle (Nobel Prize in Physics 1932). A naïve estimate of the size of the vacuum energy density, using the gravity constant G, Planck's constant $\hbar$ and the velocity of light, c, would imply a contribution to the energy density ρ_Λ of the order of

$$\rho_\Lambda \sim \frac{M_P c^2}{l_P^3},$$

where M_P is the Planck mass ($\sim 10^{19}$ GeV/c^2) and l_P is the Planck length ($\sim 10^{-33}$ cm), i.e., about 10^{118} GeV/cm^3. This is to be compared to the present-day critical density of $\sim 0.5 \cdot 10^{-5}$ GeV/cm^3. Since the energy density of the Universe according to measurements seems very close to critical, the naïve estimate is wrong by 122 orders of magnitude.

Prior to the discovery of the accelerated expansion of the Universe, particle physicists believed, that there must be a symmetry principle forbidding a cosmological constant. There is, however, another mechanism in the Standard Model that generates vacuum energy. In order to explain how the Universe can be so homogeneous with different parts that seemingly cannot have been in causal contact with each other, the idea of an inflationary phase in the early Universe was put forward [30]. It states that at a very early stage, the Universe went through a phase transition, breaking certain symmetries, spontaneously generating a time-dependent, huge vacuum energy density that during a very short time made the Universe expand enormously. A similar effect may still be at work, leading to the vacuum energy that we see today. This so-called *quintessence* may perhaps be detectable, as such a vacuum energy would have a weak time dependence (see [31], and references therein).

Other important but yet unanswered questions are why Ω_Λ has its measured value – and why Ω_Λ and Ω_M at the present epoch in the history of the Universe are of the same order of magnitude. At present we have no theoretical understanding of the value of Ω_Λ.

Conclusion

The study of distant supernovae constitutes a crucial contribution to cosmology. Together with galaxy clustering and the CMB anisotropy measurements, it allows precise determination of cosmological parameters. The observations present us with a challenge, however: What is the source of the dark energy that drives the accelerating expansion of the Universe? Or is our understanding of gravity as described by general relativity insufficient? Or was Einstein's "mistake" of introducing the cosmological

constant one more stroke of his genius? Many new experimental efforts are underway to help shed light on these questions.

References

[1] A. Einstein, "Die Feldgleichungen der Gravitation", Sitzungsber. Preuss. Akad. Wiss. Berlin, **1915**: 844-847, (1915),

[2] K. Schwarzschild, "Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie", Sitzungsber. Preuss. Akad. Wiss. Berlin, **1916**: 189-196, (1916),

[3] A. Einstein, "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie", Sitzungsber. Preuss. Akad. Wiss. Berlin, **1917**: 142-152, (1917),

[4] A. Friedmann, "Über die Krümmung des Raumes", Zeitschrift für Physik, **10**, 377-386, (1922),

[5] A. Friedmann, "Über die Möglichkeiten einer Welt mit konstanter negativer Krümmung des Raumes", Zeitschrift für Physik, **21**, 326-332, (1924),

[6] G. Lemaître, "Un univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques", Annales de la Société Scientifique de Bruxelles, **A47**, 49-59, (1927),

[7] V. Slipher, "The radial velocity of the Andromeda nebula", Lowell Observatory Bulletin, **58,** vol II:56-57 (1913),

[8] E.P. Hubble, "Extragalactic nebulae", Astrophys. J., **64**, 321-369, (1926),

[9] E.P. Hubble, "A relation between distance and radial velocity among extra-galactic nebulae", Proc. Nat. Acad. Sci., **15**, 168-173, (1929),

[10] G. Lemaître, "The beginning of the world from the point of view of quantum theory", Nature, **127**, 706, (1931),

[11] C. Wirtz, "De Sitters Kosmologie unter der Radialbewegung der Spiralnebel", Astr. Nachr., **222**, 21-26, (1924),

[12] K. Lundmark, "The motions and distances of spiral nebulae", MNRAS, **85**, 865-894, (1925),

[13] H.P. Robertson, "Kinematics and world structure", Astrophys. J., **82**, 284-301, (1935); "Kinematics and world structure II", *ibid.*, **83**, 187-201 , (1936), "Kinematics and world structure III", *ibid.*, **83**, 257-271 , (1936),

[14] A.G. Walker, "On the Milne's theory of world-structure", Proc. Lond. Math. Soc. (2), **42**, 90-127, (1936),

[15] A.A. Penzias and R.W. Wilson, "A measurement of excess antenna temperature at 4080 Mc/s", Astrophys. J., **142**, 419-421, (1965),

[16] G. Lemaître, "Evolution of the expanding universe", Proc. Nat. Acad. Sci., **20(1)**, 12-17, (1934),

[17] A. Goobar and S. Perlmutter, "Feasibility of measuring the cosmological constant Λ and mass density Ω using type Ia supernovae", Astrophys. J., **450**, 14-18, (1995),

[18] W. Baade, "The absolute photographic magnitude of supernovae", Astrophys. J., **88**, 285-304, (1938),

[19] C.T. Kowal, "Absolute magnitudes of supernovae", Astron. J.,**73**, 1021-1023, (1968),

[20] W.A. Fowler and F. Hoyle, "Nucleosynthesis in supernovae", Astrophys. J., **132**, 565-590, (1960),

[21] D. Branch and G.A. Tammann, "Type Ia supernovae as standard candles", Ann. Rev. Astron. Astrophys., **30**, 359-389, (1992),

[22] H.U. Nørgaard-Nielsen, L. Hansen, H.E. Jørgensen, A.A. Salamanca, R.S. Ellis, W.J. Couch, "The discovery of a type Ia supernova at redshift of 0.31", Nature, **339**, 523-525, (1989),

[23] S. Perlmutter et al., "A Supernova at *z=0.458* and implications for measuring the cosmological deceleration", Astrophys. J., **440**, L41-L44, (1995),

[24] M. Hamuy et al., "The 1990 Calán/Tololo Supernova Search", Astron. J., **106**, 2392-2407, (1993),

[25] M.M. Phillips, "The absolute magnitude of Type Ia supernovae", Astrophys. J., **413**, L105-L108, (1993),

[26] M. Hamuy et al., "The Hubble diagram of the Calán/Tololo Type Ia supernovae and the value of H_0", Astron. J., **112**, 2398-2407, (1996),

[27] A.G. Riess et al., "Observational evidence from supernovae for an accelerating universe and a cosmological constant", Astron. J., **116**, 1009-1038, (1998),

[28] S. Perlmutter et al., "Measurement of Ω and Λ from 42 high-redshift supernovae", Astrophys. J., **517**, 565-586, (1999),

[29] A.G. Riess et al., "Type Ia supernova discoveries at $z > 1$ from the Hubble Space Telecope: Evidence for past deceleration and constraints on dark energy evolution", Astrophys. J., **607**, 665-687, (2004),

[30] A. Starobinsky, "A new type of isotropic cosmological models without singularity", Phys. Lett., **B91**, 99-102, (1980);
K. Sato, "First order phase transition of a vacuum and expansion of the Universe", MNRAS, **195**, 467-479, (1981);
A.H. Guth, "The inflationary universe: A possible solution to the horizon and flatness problems", Phys. Rev., **D23**, 347-356, (1980);
A.D. Linde, "A new inflationary scenario: A possible solution to the horizon, flatness, homogeneity, isotropy and primordial monopole problems", Phys. Lett., **B108**, 389-393, (1981);
A. Albrecht and P.J. Steinhardt, "Cosmology for Grand Unified Theories with radiatively induced symmetry breaking", Phys. Rev. Lett., **48**, 1220-1223, (1982),

[31] E.J. Copeland, M. Sami and S. Tsujikawa, "Dynamics of Dark Energy", Int. J. Mod. Phys., **D15**, 1753-1936, (2006).