Cosmology with Supernovae

Bruno Leibundgut

European Southern Observatory
Karl-Schwarzschild-Straße 2, D-85748 Garching, Germany
Bruno.Leibundgut@eso.org;
http://www.eso.org/∼bleibund

Abstract

Modern cosmology is using many different methods to determine the structure of the universe. Supernovae are among the most important ones due to their extreme luminosity, the time-variability that allows to separate the different supernova explosions and relative ease with which they can be observed.

Since the recognition of supernovae as a separate class of astrophysical objects they have been proposed and used to measure the distance scale and the geometry of the universe.

There are several independent applications with supernovae to measure the current expansion rate, Hubble's constant, and the expansion history of the universe. The latter has led to the surprising discovery that the expansion is actually accelerating and a new component for the universe is needed. Supernovae are also poised to be a major player in the characterisation of the nature of the dark energy.

1 Introduction

In a small, but very influential, book Otto Heckmann (1942) summarised the status of cosmology after the major theoretical developments were done in the first decades of the $20^{\rm th}$ century. In that monograph, he developed the tools required for observers to measure the parameters, which govern the history of the universe. The cosmology he described is the same we use for the interpretation of modern data. It is based on the assumption that the universe is governed essentially by gravity, described through the theory of general relativity, acting in a globally homogeneous and isotropic background.

About a decade before Heckmann published his book, two European astronomers in California described supernovae as a distinct class of exlosive events in the universe. Walter Baade and Fritz Zwicky (1934) realised that supernovae are explosions on a stellar scale with cosmological consequences. The first to suggest that there might be a class distinct from ordinary novae was Lundmark (1925). He based his proposal mostly on the observation of 'S Andromeda' observed in 1885

Reviews in Modern Astronomy 17. Edited by R. E. Schielicke
 ISBN 3-527-40476-7

(designated SN 1885A in modern nomenclature), which appeared about 10 magnitudes brighter than a sample of about two dozen regular novae in the Andromeda galaxy. Lundmark later seemingly was also the first to suggest the name 'super-nova' (Lundmark 1932).

Here I review the current status of supernova cosmology. I will concentrate on the discovery of the accelerated expansion of the universe, often encapsulated in the designation 'Dark Energy', through the use of Type Ia supernovae. The problems connected with the determination of the Hubble constant will be touched upon first, however.

There are some recent monographs and review articles available on supernovae. Last year two books on supernovae appeared (Hillebrandt & Leibundgut 2003 and Weiler 2003). Specific reviews on Type Ia supernovae are Leibundgut (2000) and Meikle (2000). Reviews dealing with supernova cosmology can be found in Perlmutter & Schmidt (2003), Leibundgut (2001) and Riess (2000).

The recent paradigm changes in the cosmological model are based on several new insights. The flatness of space-time as measured by the cosmic microwave background (CMB) fluctuations and the recognition, that the global matter density is near 30 % of the critical density, require an additional component in the energy content of the universe. At the same time the observation that the luminosity distances derived from Type Ia supernovae are larger than the expectation in any non-accelerated universe model have conspired to change our view of the history of the cosmic expansion. The three measurements are complementary to each other and the combination of any two of them provides independent evidence for an additional component in the Friedman equation. However, only the supernova measurement gives a direct indication that we need a repulsive component in the universe. It will also be the supernovae that will provide a first indication to the nature of the dark energy.

2 Supernova Cosmology

Cosmology with supernovae has developed over the second half of the last century. Their extreme luminosities always made them attractive candidates to measure large distances. Various methods were devised to use supernovae to measure cosmological parameters ranging from simple standard candle paradigms to physical explanations of the supernova explosions and subsequent derivation of distances. Essentially, supernovae have been used to determine luminosity distances, i. e. the comparison of the observed flux to the total emitted radiation. The luminosity distance D_L is defined by

$$D_L = \sqrt{\frac{L}{4\pi F}} \tag{1}$$

with the absolute luminosity of the object L and the observed flux F. Of course, this is nothing but the inverse square law. The trick is to find a reliable way to measure the absolute luminosity of the objects.

There are several fundamental tests that will need to be performed until we can be sure that the current paradigm will persist. It is very appealing to think we know all constituents of the universe by now, but further surprises may still be in store for us. The testing has to concentrate on the reliability of the individual measurements. The Type Ia supernovae have been criticised for the fact that they are based on a rather simple assumption, namely that the distances derived from them are accurate. Many publications oversimplify this picture by calling Type Ia supernovae standard candles. This is not only incorrect, also it is misleading and belittles the result. The tests done on supernovae are solid and the theoretical work is progressing steadily.

There are two major cosmological parameters that can be determined through supernova observations. They are the classical parameters, which govern the expansion of the universe in Friedmann-Robertson-Walker models: the Hubble constant, $H_0 = \dot{R}/R$, i. e. the first time derivative of the cosmic scale parameter R, and the deceleration parameter, $q_0 = -\ddot{R}R/\dot{R}^2$ (see section 4 for the detailed equations for these entities and some historical remarks about their use). The former sets the scale of the universe and the magnitude of the current expansion of space and the latter describes the change of the expansion with time (e. g. Sandage 1961, Sandage 1988, Weinberg 1972, Peebles 1993, Peacock 1999). There is a rich literature on the Hubble constant and Type Ia supernovae (SNe Ia) (see Branch & Tammann 1992, Branch 1998, Leibundgut 2001 for reviews). The deceleration parameter has been replaced by more modern formulations specifically including the cosmological constant or some variants thereof (Carroll et al. 1992).

3 The Hubble Constant

3.1 Type Ia Supernovae

The best way to show that objects provide good luminosity distances is to plot them in a Hubble diagram. Originally, this diagram was using recession velocity *vs.* apparent magnitude (Hubble 1936, Sandage 1961). The underlying assumptions are that the Hubble law of linear cosmic expansion holds and that the objects are all of the same luminosity, i. e. standard candles, so that the apparent brightness directly reflects distance.

Since no astronomical standard candle is known – all proposed objects have been shown to be essentially non-uniform in one way or another – we nowadays have to calculate and plot the distance modulus for the objects. The scatter around the linear expansion line is less than 0.2 magnitudes or 20 % (Tonry et al. 2003). Independent of our ignorance of the exact explosion mechanism or the radiation transport in the explosions (see discussions in Hillebrandt & Niemeyer 2000 and Leibundgut 2000 on outstanding problems with SN Ia physics) this proves that SNe Ia can reliably be used as a distance indicator in the local universe. This situation is very much comparable to the Cepheid stars, where the period-luminosity relation is based on empirical data of objects in the Magellanic Clouds.

3.1.1 Type Ia Supernovae as Standard Candles

How well do SNe Ia fare as standard candles? The raw, uncorrected scatter of well-observed supernovae is around 0.2 to 0.4 magnitudes (Tammann & Leibundgut 1990, Sandage & Tammann 1995, Parodi et al. 2000). These translate into uncertainties of about 10 % to 20 % in distances.

However, some SNe Ia have been observed that clearly were much fainter (about 2.5 magnitudes, i. e. corresponding to a full factor of 5 in distance!). From direct distance measurements to SNe Ia the luminosity appears to be rather uniform, but only a limited sample is available for this test (Saha et al. 1999). At first sight the case for SNe Ia is unclear.

The standard candle character does not only imply that the objects always reach the same luminosity at maximum, but that they also have a uniform appearance. Since supernovae are variable phenomena their light curves and spectral evolution can be checked for uniformity. The observables of supernovae are the light curves (at different wavelengths), the colour evolution, the details in their spectrum (line strengths, abundances and velocities), the luminosity (again at different wavelengths) and the supernova environment. In addition, there are several correlations between observables that have been used.

The most intriguing feature of SNe Ia – and critical for the distance determination – is the relation between the light curve shape and the peak luminosity. This immediately shows that SNe Ia are *not* standard candles, but they can be normalised to give exceedingly accurate relative cosmological distances. First found by Phillips (1993), the correlation has been elaborated in different forms in Hamuy et al. (1995, 1996), Riess et al. (1996, 1998), Perlmutter et al. (1997), Tripp (1998), Tripp & Branch (1999), Phillips et al. (1999) and Goldhaber et al. (2001). Essentially, there are three methods describing this relation: the original template method (often referred to as Δm_{15}), the multi-colour light curve shape (MLCS) relation and the stretch relation. The easiest test is provided by SNe Ia in the cosmic expansion flow. Phillips et al. (1999) found that the scatter around the expansion line, after correction for extinction and light curve shape is 0.15 magnitudes in B and 0.18 in V, i. e. better than 10 % in relative distances.

Direct distance measurements through Cepheids have found a scatter in the average absolute magnitude of SNe Ia at maximum of 0.15 magnitudes (0.05 as error of the mean, Saha et al. 1999). Figure 1 shows the tight relation SNe Ia define around the expansion line in the Hubble diagram. The slope of this line is fixed for all cosmological models with a linear expansion in the local universe. The SNe Ia trace this line exceedingly well with a fitted slope of 5.069 ± 0.053 (see also Tammann & Leibundgut 1990, Riess et al. 1996). The 108 objects (taken from Tonry et al. 2003) in the redshift range from 0.01 to 0.1 show a scatter of 0.20 magnitudes around the canonical line. Parodi et al. (2000) find a scatter of less than 0.13 magnitudes for a comparable sample. The intercept for zero redshift together with the absolute luminosity of SNe Ia provides the Hubble constant (e. g. Leibundgut & Pinto 1992). It is the exact value of the absolute peak magnitude of the SNe Ia, which contributes the major uncertainty in this measurement and the ongoing debate.

While there is general agreement that the light curve shape corrections provide a great improvement over the use of SNe Ia as pure standard candles, it has to be noted that the individual methods do not produce identical corrections for a given supernova data set (Drell et al. 2000, Leibundgut 2000). The MLCS (Riess et al. 1996, 1998) and Δm_{15} (Hamuy et al. 1996, Phillips et al. 1999) method yield similar

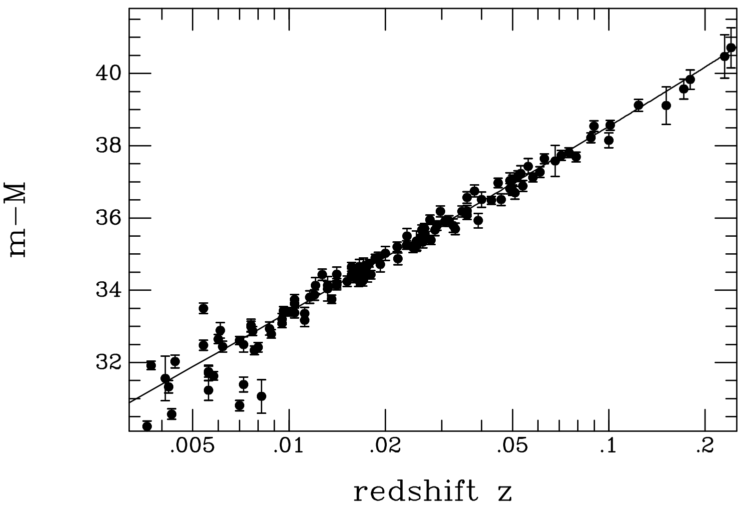

Figure 1: Hubble diagram of nearby Type Ia supernovae. The distances are derived from light curve shape corrected luminosities (data from Tonry et al. 2003).

corrections with an offset for different normalisations, but with a scatter much larger than the typical errors. The stretch method (Perlmutter et al. 1997, Goldhaber et al. 2001) deviates significantly in its mean corrections. The reasons for these discrepancies have yet to be resolved.

It should be noted that the correlations have been mostly determined for the B and V bands, but strong deviations are apparent in all other filter light curves. Most striking is the time evolution in the near infrared where the light curves display strong secondary maxima between 20 and 40 days after maximum depending on filter and supernova (Meikle 2000, Krisciunas et al. 2003). It is this characteristic together with the peculiar objects that are the most obvious indicator that SNe Ia can not be considered as standard candles.

Attempts to include several filter light curves for a multi-dimensional normalisation include MLCS (Riess et al. 1996, 1998), the Δm_{15} method (Phillips et al. 1999) and a multi-colour stretch method (Wang et al. 2003). It has to be seen whether the physics can be evaluated sufficiently to put these empirical methods onto a firm theoretical basis.

For the best-studied objects subtle differences in all light curves are becoming more and more apparent (Stritzinger et al. 2002). Clearly, the differences are not very large, but they are real and hamper our ability to employ the normalisation. We should start to consider that no two SNe Ia are identical.

Other parameters that are showing differences among SNe Ia are the colours and the epochs of maximum light. The colours are difficult to disentangle from the absorption, but a significant difference between a sample of nearby SNe Ia and distant ones has been pointed out (Leibundgut 2001). The majority of the distant objects is bluer than the bluest SNe Ia in the nearby universe. This can not be due to dust as we expect to observe at least some of the nearby objects with their intrinsic colours and not affected by dust in the host galaxies. Although there could be a selection effect at work, this distinction is worrisome. Note, however, that this effect is not present in Knop et al. (2004) and Riess et al. (2004). Both of these analyses are using different methods and improved K-corrections. Unfortunately, the details of how the reddening and the intrinsic colours were derived are not provided in either publication.

Most surprisingly a new study of infrared light curve finds that SNe Ia might be rather accurate standard candles in the near-infrared (Krisciunas et al. 2004). The first significant IR sample shows very small scatter without prior correction for light curves shape.

3.1.2 The Nearby SN Ia Hubble Diagram

One has to adopt that the luminosity normalisation of the distant objects follows what has been found in the nearby sample. Although the High-z Supernova Search Team (HZT; Schmidt et al. 1998, Riess et al. 1998, Tonry et al. 2003, Barris et al. 2004) and the Supernova Cosmology Project (SCP; Perlmutter et al. 1999, Knop et al. 2004) make this assumption in different forms, it is essentially identical. The SCP derives the corrections from all supernovae in their sample, i. e. nearby and distant ones, while the HZT derives the correlations from the (large) nearby sample and applies it to the distant objects (cf. Leibundgut & Suntzeff 2003). It is also interesting to note that the SCP claims that both light curve shape correction and correction for host galaxy reddening affect their result rather little (Perlmutter et al. 1999, Knop et al. 2004). On the other hand, the normalisation and absorption correction done by the HZT (in three different implementations) are important for the cosmological result. This discrepancy between the two teams will need to be resolved at some point.

The first to plot a Hubble diagram of Type Ia Supernovae was Kowal (1968). There are essentially three quantities that can be derived from such a Hubble diagram in the nearby universe: the slope of the expansion line, the scatter around the expansion line and the value of the local Hubble constant from the intercept at zero redshift (e. g. Tammann & Leibundgut 1990, Leibundgut & Pinto 1992). The slope gives an indication of the local expansion and for a linear expansion in an isotropic universe it has a fixed value. The scatter around the expansion line provides a measure of the accuracy of the standard candle and the measurement errors. The intercept of the line, finally, together with an estimate of the absolute luminosity gives the Hubble constant.

More accurate light curve data are becoming available (e. g. Krisciunas et al. 2001, 2003, Li et al. 2001, 2003, Candia et al. 2003, Benetti et al. 2004) and it should be possible to further investigate the correlations between light curve shape, colour and luminosity of SNe Ia. For these reasons modern Hubble diagrams show the distance modulus $(m - M)$ rather than the directly observed apparent magnitude m. The latest version with over 200 SNe Ia has been assembled by Tonry et al. (2003; see also Barris et al. 2004 and Riess et al. 2004) and is shown in Figure 1. For the derivation of the Hubble constant the (normalised) luminosity of the SNe Ia has to be known. The most direct way to achieve this is through the distance ladder and in particular the calibration of nearby SNe Ia by Cepheids (for the most recent results see Saha et al. 1999, Freedman et al. 2001). The main discrepancy for the published values of the Hubble constant from SNe Ia is coming from the different interpretations of the Cepheids, the assumed distance to the Large Magellanic Cloud and application of the light curve shape correction.

The problem with this measurement is apparent from Fig. 1. At very low redshifts ($z < 0.01$) the universal expansion field is disturbed by the Virgo cluster and the recession velocity of the galaxies is not directly proportional to the distance. The most distant galaxies with accurate Cepheid distances, however, have a recession velocity of less than 1500 km s^{-1}, i. e. $z < 0.05$. Even at double the redshift the scatter around the expansion line is still considerable. Hence connecting the supernovae in the Hubble flow with the local counterparts with Cepheid distances leaves some ambiguity on the correct value of the Hubble constant.

3.2 Core-collapse Supernovae

The brilliance of core-collapse supernovae has enticed people to investigate their capabilities as distance indicators as well. Following early work by Baade (1926), originally done for Cepheid stars, the expanding photosphere method (EPM; Eastman et al. 1996) has been applied to several supernovae. The most comprehensive data sample has been assembled by Hamuy (2001). A critical test has become the distance to SN 1999em, which was determined through EPM (Leonard et al. 2001, Hamuy et al. 2002, Elmhamdi et al. 2003) and which also has a Cepheid distance available (Leonard et al. 2003). The discrepancy is most likely attributable to the fact that the correction factor for the dilution of the black body flux in EPM are strongly model dependent and need to be calculated for each supernova individually.

Recently, Mario Hamuy has realised that the expansion velocity and the luminosity during the plateau phase correlate and that Type II SNe may be quite good distance indicators (Hamuy 2003). The distance accuracy achieved this way can be better than 20 %. These determinations are based on the physical understanding of the plateau phase of SNe II and are linked to physics of the supernova atmosphere. This means that they are independent of the *distance ladder*, which is needed, e. g., for the SNe Ia. Typical values for the Hubble constant from SNe II are in the range of 65 to 75 km s^{-1} Mpc^{-1} (Hamuy 2003).

4 Cosmology with Standard Candles

The principle of standard candles is probably the simplest and most often used method to measure cosmological parameters. The combination of the distance modulus and the Hubble law at small redshifts provides a direct way to measure the Hubble constant, H_0. The dimming of a standard candle as a function of redshift z ($z \leq 0.1$) is described by

$$m = 5 \log z + 5 \log \frac{c}{H_0} + M + 25. \qquad (2)$$

Given the fixed absolute magnitude M of a known standard candle any measurement of the apparent magnitude m of an object at redshift z provides the value of

Hubble's constant (in units of km s^{-1} Mpc^{-1}). The speed of light c enters as a form factor. This is typically shown in a Hubble diagram, m vs. $\log(cz)$ (cf. Fig. 1.)

For cosmologically significant distances, where the effects of the matter and energy content of the universe become substantial, the luminosity distance is defined by the integration over the line element along the line of sight.

All early papers on this subject used the series expansion

$$m = 5\log z + 1.086(1-q_0)z + 5\log\frac{c}{H_0} + M + 25 \tag{3}$$

(Heckmann 1942, Robertson 1955, Hoyle & Sandage 1956, Humason et al. 1956). Here, q_0 describes the deceleration of the expansion. The integral of the line element can be solved analytically only in some specific situations (e. g. a negligible cosmological constant: Mattig 1958; special cases including a cosmological constant: Mattig 1968). The earliest publications (McVittie 1938, Heckmann 1942) already warned of the dangers involved in the expansion, which assumed a smooth form for the derivatives of the scale factor. Mattig (1958) showed that for models without a cosmological constant a second order term makes significant contributions. Modern versions of the expansions have now been developed (Visser 2003, Caldwell & Kamionkowski 2004) and are used to explore the characteristics of dark energy (e. g. Riess et al. 2004).

A modern derivation of the relations for an expanding universe with a cosmological constant is given in Carroll et al. (1992). Using the Robertson-Walker metric the luminosity distance, D_L, in an expanding universe, allowing for a cosmological constant Λ, is

$$D_L = \frac{(1+z)c}{H_0|\kappa|^{1/2}}\; S\left\{|\kappa|^{1/2}\int_0^z[\kappa(1+z')^2+\Omega_M(1+z')^3+\Omega_\Lambda]^{-1/2}dz'\right\}. \tag{4}$$

Here $\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M$ stands for the matter content, which depends only on the mean matter density of the universe ρ_M, and $\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$ describes the contribution of a cosmological constant to the expansion factor. κ is the curvature term and obeys

$$\kappa = 1 - \Omega_M - \Omega_\Lambda. \tag{5}$$

$S(\chi)$ takes the form

$$S(\chi) = \begin{cases} \sin(\chi) & \\ \chi & \text{for} \quad \kappa = 0 \\ \sinh(\chi) & \end{cases} \begin{matrix} \kappa > 0 \\ \\ \kappa < 0. \end{matrix} \tag{6}$$

The cosmic deceleration in these models is defined as

$$q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda. \tag{7}$$

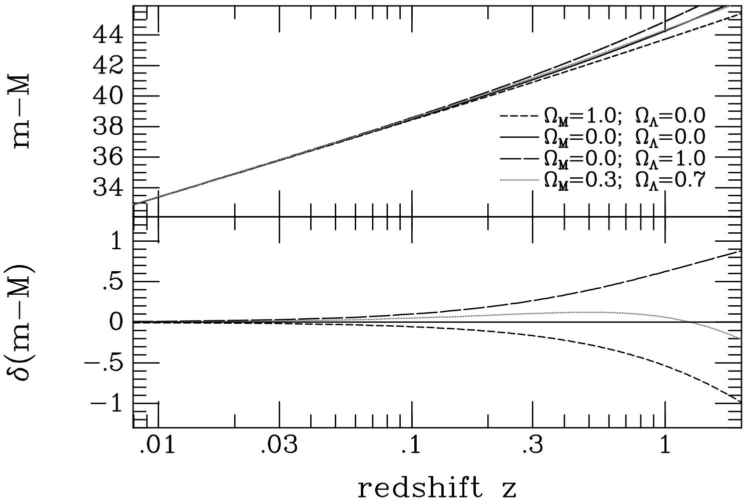

Figure 2: Systematic Hubble diagram of a standard candle. The upper panel shows the classical Hubble diagram with distance modulus vs. redshift. Lines of four cosmological models are drawn. The lower panels are normalized to an empty universe.

The dimming of standard candles in different cosmological models is normally displayed as a set of lines in the Hubble diagram (Sandage 1961, 1988, Perlmutter et al. 1997, Schmidt et al. 1998, Riess et al. 1998). It is, however, more instructive to plot a diagram of the magnitude differences between the various world models. This is the form used in all modern publications of distant supernovae (e. g. Riess et al. 1998, Perlmutter et al. 1999, Tonry et al. 2003, Knop et al. 2003, Barris et al. 2004, Riess et al. 2004, for reviews see Riess 2000, Leibundgut 2001, Perlmutter & Schmidt 2003). Fig. 2 shows how this works. The magnitude difference of the luminosity distances of a standard candle are displayed against the one expected in an empty universe. The magnitude differences between the various cosmological models are more apparent in this diagram. While the presentation in the regular Hubble diagram obscures the fine details, which are relevant for the measurement of the accelerated expansion. A standard candle in an empty universe ($\Omega_M = 0$, $\Omega_\Lambda = 0$) would appear 0.17 magnitudes fainter at a redshift of 0.3 than in an Einstein-de Sitter universe ($\Omega_M = 1.0$, $\Omega_\Lambda = 0$). This difference increases to 0.28 mag at $z = 0.5$ and 0.54 mag for $z = 1.0$. These are small values considering how difficult the observations are and the corrections that are needed to obtain a significant measurement.

Figure 2 also shows that for any models with only attracting gravity, i. e. only matter, no objects should lie in the region with $\delta(m - M) > 0$. In the old paradigm this was an excluded region. The only way to populate this area in Fig. 2 with standard candles is by moving them further away than in the freeling coasting, empty universe, model.

The present-day cosmic deceleration, q_0, combines all energy sources contributing to the change of the expansion rate of the universe. It thus represents a fundamental parameter for the description of the universe we live in. For models without the cosmological constant the fate of the universe is encapsulated in q_0. With a cosmological constant the value of q_0 does no longer provide a unique combination of Ω_M and Ω_Λ (cf. equation 7).

For the Hubble constant the absolute distances are required, while for the measurement of the cosmic expansion history relative distances are sufficient.

We emphasize that the value of the Hubble constant is not required for the determination of the combination of the cosmological parameters Ω_M and Ω_Λ, as can be seen from the equation for the luminosity distance. The apparent magnitude difference of a standard candle measured at two different redshifts is sufficient under the assumption that the absolute luminosity has not changed. Distant supernovae must be compared to a set of nearby supernovae where the curvature κ is negligible.

With the above, the road map to the determination of the parameters Ω_M and Ω_Λ through SNe Ia is clear. The comparison of a set of nearby supernovae with their counterparts at significant redshifts will yield the ratio in luminosity distances, which then can be used to solve for the cosmological parameters.

5 Universal Acceleration Measured by Type Ia Supernovae

We will describe here the current status of the supernova research and outline ongoing projects to distinguish between a cosmological constant or a vacuum density contribution to the energy-momentum tensor in the Einstein equation.

Type Ia supernovae measure luminosity distances to objects out to about a redshift of 1.8 (Riess et al. 2004). These distances are the most accurate currently available to astronomers for cosmological purposes, i. e. beyond the Coma cluster distance. Since the luminosity distances depend on the evolution of the Hubble parameter and this in turn depends on the energy content of the universe through the Einstein equation (e. g. Carroll et al. 1992) one can derive the energy sources dominating over the lookback time covered by the observations. Once the luminosity distances are derived from the supernova data a likelihood calculation provides the most statistically suitable values for the complete supernova data under certain assumptions, like the neglect of dust and evolution. It is pointless to divide the supernova data into subsamples that do not cover the complete redshift range as the effect is not detectable on smaller scales. Figure 3 shows that the current data by far do not warrant such a treatment (as proposed by Padmanabhan et al. 2003, Choudhury et al. 2004, Wang et al. 2004).

The largest available ground-based data set is provided by Barris et al. (2004), which includes a significant set of supernovae at redshifts near 1. This data set confirms the earlier results of the HZT (Tonry et al. 2003) and is consistent with the most recent result of the SCP (Knop et al. 2004). Recently Riess et al. (2004) published a data sample including the most distant objects observed with HST. All astrophysical effects, like dust or evolution of the supernovae, have been ignored in this derivation. The HZT applies a correction for dust in the Milky Way and the host galaxy of the supernova directly. Only if dust at high redshift is systematically

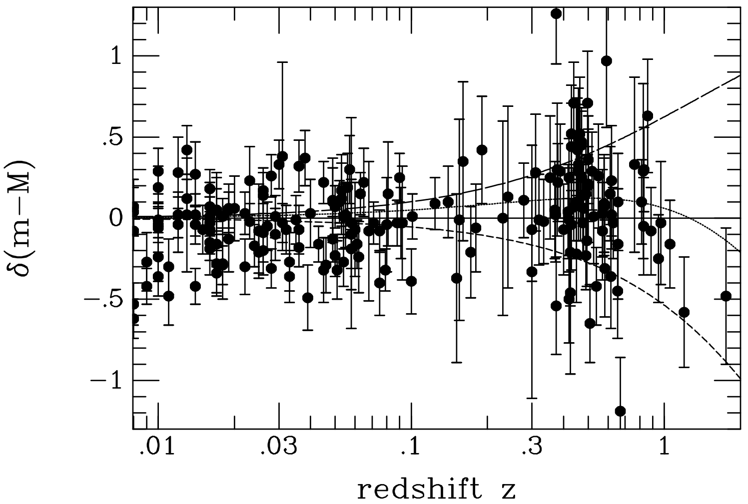

Figure 3: Current status of the SN Ia Hubble diagram (after Tonry et al. 2003). Due to the large scatter in the nearby universe caused by the peculiar motions of the galaxies all objects with $z < 0.01$ were excluded from the analysis. The faintness of the distant objects near $z \approx 0.5$ is the reason for the claimed acceleration of the cosmic expansion.

different from the one in our galaxy is this correction biased. Recent detection of 850 μm emission from host galaxies at $z \approx 0.5$ shows that dust is present in some of these galaxies (Farrah et al. 2004), although the amount may be negligible for the supernova cosmology. These results are in contrast with the claim by Sullivan et al. (2003) that the reddening of distant supernovae in spiral galaxies is very small, when these objects are compared to the SN data from dust-free elliptical galaxies. The reddening derived by Tonry et al. (2003) for distant SNe Ia is typically smaller than the one found for nearby objects. This is not surprising considering that the distant searches are mostly flux limited and will not find many heavily absorbed objects, while the nearby supernovae are drawn from a large heterogeneous sample, which in several cases includes highly reddened objects. There might be secondary selection effects at work as well, like the fact that the distant supernovae often have larger projected distances from their hosts than nearby ones. A last indication that dust is not a severe problem is the fact that among the first distant SNe Ia of the HZT were very blue (Leibundgut 2001) objects. In fact, six out of nine objects were bluer than their nearby counterparts. Although this has now been claimed to possibly be a selection effect (Knop et al. 2004), it is not clear whether this indeed is the case, as the effect should be redshift dependent, which it seems not to be, judging from the small sample in Leibundgut (2001). The recent publication by the SCP (Knop et al. 2004) does not find the same effect for the objects which have multi-wavelength light curves. Further analysis of the K-corrections and the dust properties is clearly required.

Evolution is another potential effect, which could mimic a cosmological signal. This is much harder to control. For reasonable predictions of how progenitor metalicity or age could affect the brightness of SNe Ia one needs a detailed model of the explosion and the radiation escape (Hillebrandt & Niemeyer 2000). Both are unsolved problems. A study of the properties of the SN host galaxies has not shown any correlation with supernovae distances or properties (Sullivan et al. 2003, Williams et al. 2003). Progress can only be made through detailed observations of bright, nearby SNe Ia at all phases. Recent data sets are very encouraging (Krisciunas et al. 2001, 2003, Benetti et al. 2004; for a review see Leibundgut & Suntzeff 2003). In addition to the detailed spectral, light and colour curve data one can use bolometric light curves to derive the total emitted radiation from the explosion (Contardo et al. 2000, Contardo 2001). The latter provides important information on the physical parameters that govern the explosion, like mass of synthesised nickel and the $\gamma-$ray escape fraction at late times.

With no clear indication of evolution, the simplest assumption is to disregard any evolutionary effects; a very dangerous approach, if it goes unchecked. This is the reason that the HZT has spectroscopically confirmed its distant SNe Ia. The spectra have been published together with the light curve data (Riess et al. 1998, Tonry et al. 2003, Barris et al. 2004) and separately for a few objects (Coil et al. 2000, Leibundgut & Sollerman 2001). While the signal for some of the distant supernovae is not very good, and in a few early cases the SN classification may even be doubtful, there are no obvious strong deviations from the spectral appearance of the nearby supernovae. In some cases, the supernova spectra can be used to determine the phase of the distant SNe Ia and to check it with the light curves directly. This provides an independent consistency argument that the distant supernovae behave rather similar to their nearby counterparts. This means that the distant supernovae cannot be very different from the nearby ones. Yet, the colour of the distant objects appears to be systematically bluer. This could be the signature of evolution and will need to be worked out in more detail.

Luminosity distances over a limited redshift range result in degenerate likelihood distributions in the $\Omega_\Lambda vs. \Omega_M$ plane along a line corresponding roughly to $\Omega_\Lambda - 1.4\Omega_M = 0.35 \pm 0.14$ (Perlmutter et al. 1999, Tonry et al. 2003; cf. Fig. 4). These leads to an increased uncertainty along this direction. It should be noted that the most recent determinations of the cosmological parameters by the HZT favour values that are rather different from a flat universe solution (Tonry et al. 2003, Barris et al. 2004). If the universe indeed has a flat geometry, as suggested by the CMB data (e. g. Spergel et al. 2003) then this would be an indication of some unresolved systematic effect. In essence, the HZT SN analysis favours higher values for Ω_M and Ω_Λ than required for a flat universe. This can be seen in Figure 3 where the excess around a redshift of 0.5 is larger than the concordance model predicts. This would argue for a higher value of the acceleration and hence Ω_Λ. At redshifts higher than 1 the supernovae would prefer a stronger deceleration and hence a higher value for Ω_M. At the moment these are most likely due to hidden selection effects and possible (small) systematics in the data. Newer data sets and analyses (Riess et al. 2004, Knop et al. 2004) do not show this effect as strongly. The SCP has not observed a similar trend (Knop et al. 2004), but the redshift range of their published data does not extend beyond $z \approx 0.8$ so far.

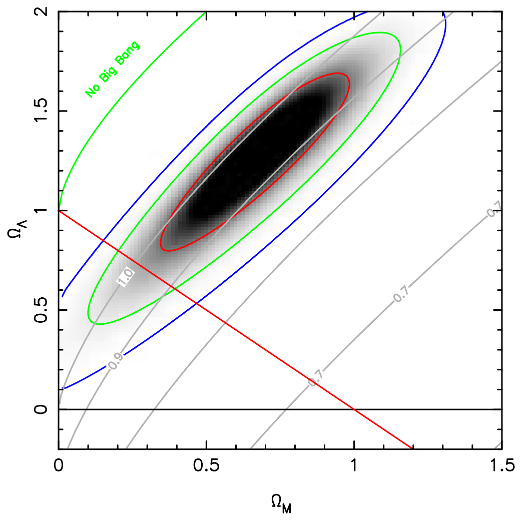

Figure 4: Likelihood distribution for Ω_Λ $vs.$ Ω_M. The input data are from (Tonry et al. 2003). This diagram should be compared to similar ones in Riess et al. (1998), Perlmutter et al. (1999), Riess et al. (2000), Leibundgut (2001), Perlmutter & Schmidt (2003), Barris et al. (2004), Knop et al. (2004) and Riess et al. (2004). The degeneracy along $0.8\Omega_\Lambda - 0.6\Omega_M$ is obvious. The overlap with the flat universe model is not within the 68 % likelihood area here. The grey contour lines show the dynamical age of the universe $H_0 \cdot t_0$. Clearly the SN data favour an age near 1.

6 Characterising Dark Energy

It has been generally accepted that a large fraction of the energy content of the universe is in a form very similar to the vacuum energy or a cosmological constant. Competing theories have been developed to explain the low, but non-zero, value of this energy form. An often used description is the equation of state parameter ($w = \frac{p}{\rho c^2}$), which in the case of dark energy has to be negative, i. e. contain negative pressure p, as the energy density ρ has to be positive (c stands for the speed of light). With $w < -\frac{1}{3}$ the universe is actually accelerating. For field theories w is most likely variable with time and different from the value for a cosmological constant ($w = -1$). The transition from a matter dominated universe ($\Omega_M > \Omega_\Lambda$) happened sometime during the second half the history of the universe between $0.4 < z < 0.8$. It should hence be possible to determine this transition and then map the change as a function of redshift in the interval $0.2 < z < 0.8$. With a well-calibrated and controlled data set of SNe Ia in this redshift interval it should be possible to accurately map the transition and determine the strength of the dark energy and the (integrated) value of w. Several projects have embarked on such a programme. The HZT has started the ESSENCE project with the search and photometry carried out with the CTIO Blanco 4 m-telescope with the supporting spectroscopy from VLT, Gemini, Keck, Magellan and MMT. The goal is to have 200 spectroscopically confirmed

SNe Ia with densely sampled light curves in at least two filters evenly distributed in redshift with $z < 0.8$ (Smith et al. 2002). The CFHT Legacy Survey is aiming for about 900 SNe Ia out to a slightly larger redshift with spectroscopy from VLT, Keck, Gemini and Magellan. In the future the SNAP satellite, in the meantime renamed to Joint Dark Energy Mission (JDEM), should observe about 2000 SNe Ia out to $z < 1.7$.

The supernovae cannot do this alone. They will require an accurate independent determination of the matter density Ω_M from a different source. The required accuracy of this parameter should be a few percent (cf. Tonry et al. 2003).

In the meantime a survey for supernovae has been done within the GOODS collaboration. The goal was to find and follow supernovae at a redshift larger than 1.2, which was achieved for about one third of the sample (Riess et al. 2004). Spectroscopic confirmation of 18 supernovae (nine with $z > 1$) is available (Strolger et al. 2004, Riess et al. 2004). Some of the distant objects could not be classified with a spectrum and rely on a spectroscopic redshift from the host galaxies only. These data constrain Ω_M more accurately than was possible so far, as the supernovae are in the deceleration portion of the Hubble diagram. They also show that evolutionary effects are not likely to explain the faintness of SNe Ia near $z = 0.5$ and the change to more luminous objects at redshifts beyond $z = 1$.

But there never is enough of a good thing. The particle theories predict that w actually would not be constant in time and hence should show a dependence on redshift. Lacking a theory to predict the changes the current discussions use parametrisations of the time dependence. It will be very difficult to measure this time dependence with supernova data in the foreseeable future. A taster is given in Riess et al. (2004), which is the most complete SN Ia set covering the largest redshift range. Even with the exquisite data in that publication are the uncertainties in w' large. Several untested assumptions already had to be used to reach this level. Claims that this has already accomplished are based on the believe that it would be possible to separate the SN data in redshift. The effect is so subtle that it will need a truly accurate and homogeneous data set to achieve this. Only a dedicated space-based mission appears to be able to provide this.

7 Conclusions

The supernova cosmology has developed tremendously over the past half century. From an exotic subfield of variable star research the supernovae have become the most extensively used distance indicator for cosmology. Together with the measurements of the fluctuations in the cosmic microwave background and the determination of cluster masses they provide clear evidence for an accelerating component in the Friedmann equation. In its most simple form this component corresponds to the Einstein's cosmological constant equivalent to a vacuum energy. Modern physics prefers to think of an extra component in the energy-stress tensor and hence a new, decaying, particle field. The current standard model of particle physics does not have room for either of these explanations.

The next step will be to measure the time-dependence of the strength of dark energy. The cosmological constant would not change over time (or redshift), while most particle theory do predict a slight change of dark energy. In absence of a formal theory the change would be sought in the equation of state parameter w. There are two ways to rule out the cosmological constant. First, if $w \neq -1$, and second, if the time-dependence is shown explicitely. The ESSENCE project is trying to determine the integrated value of w over the second half of the history of the universe since the Big Bang. Attempts to derive the first time derivative of w will require a much larger and more homogeneous data set over a larger redshift range. First attempts with the most distant supernovae have yielded interesting indications (Riess et al. 2004), but also show how difficult this measurement will be. The coming decades will see great efforts to solve this cosmic riddle and supernovae are likely to play an important part in its solution.

References

Baade, W. 1926, AN 228, 359

Baade, W., Zwicky, F. 1934, Publ. Natl. Acad. Sci. 20, 254

Barris, B., et al. 2004, ApJ 602, 571

Benetti, S., et al. 2004, MNRAS 348, 261

Branch, D. 1998, ARA&A 36, 17

Branch, D., Tammann, G.A. 1992, ARA&A 30, 359

Caldwell, R.R., Kamionkowski, M. 2004, astro-ph/0403003

Candia, P., et al. 2003, PASP 115, 277

Carroll, S.M., Press, W.H., Turner, E.L. 1992, ARA&A 30, 499

Choudhury, T. R., Padmanabhan, T. 2004, MNRAS in press (astro-ph/0311622)

Coil, A.L., et al. 2000, ApJ 544, L111

Contardo, G., Leibundgut, B., Vacca, W.D. 2000, A&A 359, 876

Contardo, G., 2001, PhD Thesis, Technical University Munich

Drell, P.S., Loredo, T.J., Wasserman, I. 2000, ApJ 530, 593

Eastman, R. G., Schmidt, B. P., Kirshner, R. P. 1996, ApJ. 466, 911

Elmhamdi, A., et al. 2003, MNRAS 338, 939

Farrah, D, Meikle, W. P. S., Clemens, D., Rowan-Robinson, M., Mattila, S. 2002, MNRAS 336, L17

Freedman, W.L., et al. 2001, ApJ 553, 47

Goldhaber, G., et al. 2001, ApJ 558, 359

Hamuy, M. 2001, PhD Thesis, Tucson: University of Arizona

Hamuy, M. 2003, ApJ 582, 905

Hamuy, M., et al. 1996, AJ 112, 2438

Hamuy, M., et al. 2002, AJ 124, 417

Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., Avilés, R. 1995, AJ 109, 1

Heckmann, O. 1942, *Theorien der Kosmologie*, Berlin: Springer

Hillebrandt, W., Leibundgut, B. 2003, *From Twilight to Highlight: The Physics of Supernovae*, Heidelberg: Springer

Hillebrandt, W., Niemeyer, J.C. 2000, ARA&A 38, 191

Hoyle, F., Sandage, A. 1956, PASP 68, 301

Hubble, E. 1936, *The Realm of the Nebulae*, New Haven: Yale University Press

Humason, M. L., Mayall, N. U., Sandage, A.R. 1956, AJ 61, 97

Knop, R., et al. 2004, ApJ 598, 102

Kowal, C. T. 1968, AJ 73, 1021

Krisciunas, K., et al. 2001, AJ 122, 1616

Krisciunas, K., et al. 2003, AJ 125, 166

Krisciunas, K., Phillips, M.M., Suntzeff, N.B. 2004, ApJ 602, L81

Leibundgut, B. 2000, A&AR 10, 179

Leibundgut, B. 2001, ARA&A 39, 67

Leibundgut, B., Pinto, P.A. 1992, ApJ 401, 49

Leibundgut, B., Sollerman, J. 2001, Europhysics News 32, 4

Leibundgut, B., Suntzeff, N.B. 2003, in *Supernovae and Gamma-Ray Bursts*, ed. K. Weiler, Heidelberg: Springer, 77

Leonard, D. C., et al. 2001, PASP 114, 35

Leonard, D. C., et al. 2003, ApJ 594, 247

Li, W., et al. 2001, PASP 113, 1178

Li, W., et al. 2003, PASP 115, 453

Lundmark, K.E. 1925, MNRAS 85, 865

Lundmark, K.E. 1932, Lund Obs. Circ. 8

Mattig, W. 1958, Astron. Nachr. 184, 109

Mattig, W. 1968, Z. Astrophys. 69, 418

McVittie, G.C. 1938, Observatory 61, 209

Meikle, W.P.S 2000, MNRAS 314, 782

Padmanabhan, T., Choudhury, T. R. 2003, MNRAS 344, 823

Parodi, B.R., Saha, A., Sandage, A., Tammann, G.A. 2000, ApJ 540, 634

Peacock, J.A. 1999, *Cosmological Physics*, Cambridge: Cambridge University Press

Peebles, P.J.E. 1993, *Principles of Physical Cosmology*, Princeton: Princeton University Press

Perlmutter, S., et al. 1997, ApJ 483, 565

Perlmutter, S., et al. 1999, ApJ 517, 565

Perlmutter, S., Schmidt, B. P., in *Supernovae and Gamma-Ray Bursts*, ed. K. Weiler, Heidelberg: Springer, 195

Phillips, M.M. 1993, ApJ 413, L105

Phillips, M.M., Lira, P., Suntzeff, N.B., Schommer, R.A., Hamuy, M., Maza, J. 1999, AJ 118, 1766

Riess, A.G. 2000, PASP 112, 1284

Riess, A.G., et al. 1998, AJ 116, 1009

Riess, A.G., et al. 2004, ApJ in press (astro-ph/0402512)

Riess, A.G., Press, W.H., Kirshner, R.P. 1996, ApJ 473, 88

Robertson, H. P. 1955, PASP 67, 82

Saha, A, Sandage, A., Tammann, G.A., Labhardt, L., Macchetto, F.D., Panagia, N. 1999, ApJ 522, 802

Sandage, A. 1961, ApJ 133, 355

Sandage, A. 1988, ARA&A 26, 561

Schmidt, B.P., et al. 1998, ApJ 507, 46

Smith, R. C., et al. 2002, BAAS 78.08

Spergel, D. N., et al. 2003, ApJS 148, 175

Stritzinger, M., et al. 2002, AJ 124, 2100

Strolger, L., et al., AJ submitted

Sullivan, M., et al. 2003, MNRAS 340, 1057

Tammann, A.G, Leibundgut, B. 1990, A&A 236, 9

Tammann, G.A., Sandage, A. 1995, ApJ 452, 16

Tonry, J.L., et al. 2003, ApJ 594, 1

Tripp, R. 1998, A&A 331, 815

Tripp, R., Branch, D. 1999, ApJ 525, 209

Turatto, M. 2003, in *Supernovae and Gamma-Ray Bursts*, ed. K. Weiler, Heidelberg: Springer, 21

Visser, M. 2003, *Classical and Quantum Gravity*, in press (arXiv:gr-qc/0309109)

Wang, L., Goldhaber, G., Aldering, G., Perlmutter, S. 2003, ApJ in press (astro-ph/0302341)

Wang, Y., Mukherjee, P. 2004, ApJ submitted (astro-ph/0312192)

Weiler, K. 2003, in *Supernovae and Gamma-Ray Bursts*, Heidelberg: Springer

Weinberg, S. 1972, *Gravitation and cosmology, principles and applications of the general theory of relativity*, New York: Wiley

Williams, B. F., et al. 2003, AJ 126, 2608