Supernovae at high redshift*

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Abstract. Distant supernovae provide a convenient tool for cosmology. As bright beacons with supposedly very small variation in their peak luminosity Type Ia Supernovae can be used to determine distances and derive cosmological parameters. Beyond the Hubble constant, which still requires the knowledge of the absolute luminosity, the cosmic deceleration can be measured from relative distances. Two groups have undertaken this experiment with the conclusion that the distances are too large to be accommodated within matter-dominated world models. The distances can be explained by additional acceleration due to a cosmological constant.

Supernovae also provide direct evidence of the stellar death rate at significant look-back times. The evolution of the supernova rate as a function of redshift can give direct evidence of the star formation history throughout the observable universe. These studies are emerging as a main challenge for large telescopes.

1 Introduction

The observations of distant supernovae has become common place with the advent of large-aperture telescopes and large-field imaging cameras. It is now possible to find supernovae, classify them by a suitable spectrum, and follow their light curves in several filters out to redshifts of about 1. The near future will see further advances in redshifts and look-back time to probe even earlier epochs of star formation. Since supernovae are stellar end-products they can trace star formation more directly than any other method.

Future observational programs will employ all known supernova types and use their specific characteristics for cosmological purposes. It is of course the extreme luminosity of Type Ia Supernovae (hereafter SNe Ia) which opened the distant universe to supernovae first.

To employ any astronomical object for the derivation of cosmological parameters requires sufficient physical understanding of its properties in the nearby

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universe. Evolutionary effects must then be considered and, if necessary, corrected. In particular, the use of SNe Ia as standard candles demands a sufficient understanding of the explosions and their physical background to reliably apply them to cosmological problems.

The understanding of the local ($z < 0.1$) supernovae forms the basis for the cosmological results. There are basically four independent indications that SNe Ia form a rather homogeneous group of objects. These are the Hubble diagram ($\log z$ *vs.* m), the absolute luminosity at maximum as determined from direct distance measurements (mostly Cepheid stars), the uniform light curves and spectral evolution, and the fact that the peak luminosity of SNe Ia can be 'corrected' with a distance independent quantity, namely the decline rate after maximum light. We will discuss each of these features in the following.

Several Hubble diagrams of nearby SNe Ia have been published in the past few years. They all demonstrate the linear expansion to a high degree (e.g. Tammann & Leibundgut 1990, Hamuy et al. 1996b, Riess et al. 1996, Saha et al. 1999), although deviations from the linear expansion within a recession velocity of about 7000 to 10000 km/s have been claimed (Zehavi et al. 1998, Tammann 1999). The Hubble diagrams show a remarkably small scatter of the supernovae around the expansion line, which provides ample evidence that they all seem to reach a very similar absolute luminosity.

Another, more direct, route is the measurement of the absolute luminosities of SNe Ia. This direct comparison provides a further test of the uniformity of the standard candle assumption for SNe Ia. Such a program has been undertaken with the determination of Cepheid distances to now eight nearby SNe Ia (Saha et al. 1999). It is remarkable that almost all objects reached the same luminosity to within 20%.

The very uniform appearance of SNe Ia is further evidence for their great similarity. Although a strong explosion with the complete disruption of a star gives rise to the supernovae, the temporal evolution of the light emission follows a rather narrow parameter space. Deviations are observed, but it is amazing that the chaotic explosion mechanism and the complicated energy release yield the uniform events we observe.

Several observable parameters of SNe Ia seem to be correlated. The first, and foremost, such relation was the decline vs. peak luminosity dependence (Phillips 1993, Hamuy et al. 1996a, Riess et al. 1996, Riess et al. 1998, Phillips et al. 1999). In the meantime it has been found that the color (Hamuy et al. 1996b), the expansion velocity of the ejecta (Mazzali et al. 1998), the line strengths (Nugent et al. 1995), and the galaxy type (Hamuy et al. 1996a, Riess et al. 1996) also correlate with the peak luminosity.

After a correction with these distance independent observables, the scatter around the Hubble line becomes very small and is of the order of the photometric uncertainties (Hamuy et al. 1996b, Riess et al. 1996, Phillips et al. 1999, Suntzeff et al. 1999, Jha et al. 1999). This remarkable fact, has boosted the use of SNe Ia as distance indicators and seems by now accepted by most people.

Yet, there are a number of unexplained features of SNe Ia exists and an accepted theory for the explosion and the radiation transport in the ejecta is still missing. The very relation between the peak luminosity and the decline rate is not understood (e.g. Höflich et al. 1996). The secondary peak in the $RIJHK$ light curves (Ford et al. 1993, Suntzeff 1996, Vacca & Leibundgut 1996) is likely due to the complicated release of photons in the expanding fireball. The bolometric light curves show this shoulder as well (Contardo et al. 1999). The spectrum is not formed in a regular photosphere, but is the result of complicated scattering of photons out of the ejecta. The input energy is coming from the radioactive decays of ^{56}Ni and its daughter product ^{56}Co, which is converted into a pseudo-continuum through down scattering in many lines (e.g. Pinto & Eastman 1999).

The bolometric luminosity of SNe Ia can differ among individual objects up to a factor of two (Contardo et al. 1999). Extreme cases, like SN 1991bg (Filippenko et al. 1992, Leibundgut et al. 1993, Turatto et al. 1996) and SN 1997n (Turatto et al. 1998), can be several times fainter.

Several independent determinations of Ni masses of SN Ia explosions exist by now (Spyromilio et al. 1992, Bowers et al. 1997, Cappellaro et al. 1997, Mazzali et al. 1998, Contardo et al. 1999). A fairly large range of Ni masses is inferred for the individual explosions. The theoretical understanding of this range in Ni masses is not very complete, although a number of explosion mechanisms has been proposed and could be responsible for what we observe (e.g. Höflich & Khokhlov 1996).

We have thus a fairly mottled view of SNe Ia as distance indicators. On the one hand a strong empirical basis for the use of SNe Ia as 'modified standard candles' has emerged, while the detailed physics of the events are largely undetermined.

2 Distant Type Ia Supernovae

Supernovae are rare. Although they can outshine their parent galaxies, they maintain this luminosity only for a brief time, which makes their detection at significant redshifts ($z > 0.1$) very difficult. Only dedicated wide-field searches which reach a limiting magnitude of at least $R \approx 23$ can hope to find a sufficient number of SNe Ia out to redshifts of about 0.5 (Perlmutter et al. 1995, 1997, 1999, Schmidt et al. 1998). More distant objects become increasingly difficult to find. Searching several square degrees of sky during a single night and comparing them with observations obtained several weeks before can provide about a dozen candidates which then are classified through spectroscopy (Riess et al. 1998, Perlmutter et al. 1999).

The two teams working in this field are now routinely discovering about 20 objects in a search run (Schmidt et al. 1997, Perlmutter et al. 1998b). A total of 53 supernovae with $z > 0.15$ have by now been published (Nørgaard-Nielsen et al. 1989, Riess et al. 1998, Perlmutter et al. 1999).

The High-z Supernova Search Team (Schmidt et al. 1998) has followed a strategy of trying to characterize the distant supernovae in as many aspects as possible. We have obtained light curves in at least two filters to detect any dust absorption in the host galaxy (Garnavich et al. 1998a, Schmidt et al. 1998, Riess et al. 1998). All objects have been positively identified as SNe Ia from spectra, and doubtful cases could be investigated in detail (Riess et al. 1998). The Supernova Cosmology Project (Perlmutter et al. 1995, 1997, 1998a, 1999) has amassed a sample of 42 distant supernovae. Many of these supernovae have a classification from spectroscopy and also two filter observations, but some are lacking this information.

Both teams developed the search and analysis software independently. The distant supernova samples are completely independent and there exists only a small overlap in the nearby supernova set, which is drawn partially from the Calan-Tololo supernova search (Hamuy et al. 1996a). The High-z team currently enjoys a larger nearby sample (29 supernovae).

It has to be noted that the cosmology depends on the local sample just as much as it does on the distant one. Since the measurement of the deceleration is relative, the nearby sample provides the essential comparison set.

The main result is that the distant supernovae (mean redshift for both groups is around 0.5) are too dim when compared to the local sample (Figure 1). It is important to note that this result is based entirely on the observational data and does not depend on any world model. The brightness difference to a cosmology with $\Omega_M = 0.2, \Omega_\Lambda = 0$ is plotted in the lower panel. It is clear that the local sample is insensitive to the exact cosmology and provides the zero-point for the various world model lines. The distant supernovae are about 0.25 mag fainter (Riess et al. 1998). The exact same result is found by the Supernova Cosmology Project (Perlmutter et al. 1999).

Various corrections have been applied in the analysis to arrive at Figure 1. They include the exact photometry of the supernova on the irregular galaxy background (achieved through subtraction of a galaxy template image), the K-correction to convert the magnitudes from the observer system into rest-frame wavelengths, the $(1+z)$ correction for time dilation (Leibundgut et al. 1996, Goldhaber et al. 1997), the light curve fitting, and the correction to the luminosity for light curve shape. All the details are given in Schmidt et al. (1998), Riess et al. (1998), Woudt et al. (2000) and Perlmutter et al. (1999).

The faintness of the distant supernovae can be explained in several different ways. Proposed explanations include evolution of the supernovae, dust with absorption properties different from Galactic dust, and the effect of a cosmological constant. More exotic explanations have been proposed as well, but will not be discussed here.

Evolution has been the downfall of every proposed standard candle in the past. SNe Ia are not fully understood and it is quite conceivable that they have

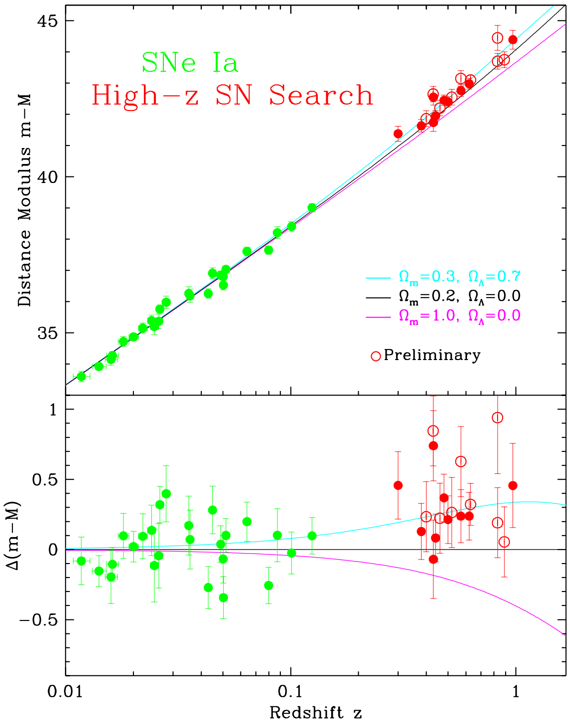

Fig. 1. Hubble diagram of the High-z SN Search Team

evolved over half the current age of the universe. However, the basic energy source of SNe Ia is the thermo-nuclear explosion and explanations have been sought in abundance differences which lead to slightly different explosion energetics (Höflich et al. 1998, Dominguez et al. 1999, Umeda et al. 1999). None of these abundance differences are very compelling at the moment, but can not be excluded. However, the effect is expected to be strongest in the local supernova sample, which presumably contains progenitors of the largest age range. The fact, that the luminosity correction works so well in this sample (Schmidt et al. 1998) gives us confidence, that it also would do so for the distant supernovae. A systematic sampling difference is largely diminished by the correction, but is also not seen in the data (Riess et al. 1998, Perlmutter et al. 1999). No other clear signatures of differences in the light curves or the spectral evolution have been detected so far, although the quality of the spectroscopy is not always sufficient to draw stringent conclusions. The High-z SN Team has now shifted its emphasis to observe higher quality spectra to explore any evolutionary signatures. A rest-frame I light curve of SN 1999Q (Riess et al. 2000) also displays the familiar secondary maximum of SNe Ia.

The first sign of a possible systematic difference between local and distant supernovae has been reported in their rise times (Riess et al. 1999).

Dust has messed up many astrophysical measurements. We still do not have a very good handle on dust outside our own Milky Way although indications have been presented that at least in nearby galaxies the optical properties are not too different from the solar neighborhood. Dust has been invoked to explain the faintness of the distant supernovae (Aguirre 1999a, b). The dust properties have to be such that no or very little reddening can be observed. The precaution taken by the observers to obtain a reddening estimate has payed off. By extending the wavelength baseline (to include the rest-frame I-band) it will be possible to test this hypothesis soon (Riess et al. 2000). It has to be noted that different dust characteristics would have wide-ranging implications for other cosmological results, such as the inferred star formation history (e.g. Madau et al. 1996, Madau, this volume) or quasar luminosities (e.g. Shaver et al. 1997).

A further explanation for the faintness of the distant supernovae is the existence of a cosmological constant (Riess et al. 1998, Garnavich et al. 1998b, Perlmutter et al. 1999). Baring any strong evolutionary effects or grey dust, the distant supernovae do not allow a solution with positive matter density for any model with $\Omega_\Lambda = 0$ (Fig. 1). Hence, a cosmological constant (or another source of energy, e.g. Caldwell et al. 1998) is unavoidable (Caroll et al. 1991, Turner & Tyson 1999). With the currently measured distances the expansion must have accelerated during the last $\sim$5 Gyr.

3 Cosmological implications

The supernova result has some surprising implications for our understanding of the universe. One very interesting consequence of the accelerated expansion concerns the estimate of the dynamic age of the universe. Since the expansion was slower in the past, the inferred age is larger than in an Einstein-de Sitter or massless model. With a Hubble constant of $H_0 = 65$ km s^{-1} Mpc^{-1} an age of about 14 Gyr is inferred. This for the first time comfortably contains the age of the oldest known stellar components of the universe (Chaboyer et al. 1998), thus ending a debate which had started when the expansion of the universe was discovered by Edwin Hubble (1929).

Recent measurements of the cosmic microwave background have provided a first hint of the first Doppler peak in the CMB power spectrum (Hancock et al. 1998, Lineweaver 1998). Since the CMB constraint is nearly orthogonal to the supernova result (White 1998), the two combined give fairly strict constraints of the values of Ω_M and Ω_Λ (Lineweaver 1998, Garnavich et al. 1998b, Perlmutter et al. 1999). Interestingly enough the value found for Ω_M corresponds very well with the matter density inferred from clusters of galaxies (Turner & Tyson 1999). We thus have a consistent picture of cosmology at the moment.

Since the CMB result favors a flat geometry of the universe, inflationary models are en vogue again. On the other hand, severe problems arise from a cosmological constant: the value of the vacuum energy has to be tuned after the inflationary phase and lacks any explanation at the moment.

For a flat universe, the equation of state can be determined (Lineweaver 1998, Garnavich et al. 1998b, Perlmutter et al. 1999). The currently favored values would exclude cosmic strings or textures as dominating energy sources and find that the cosmological constant is the best explanation.

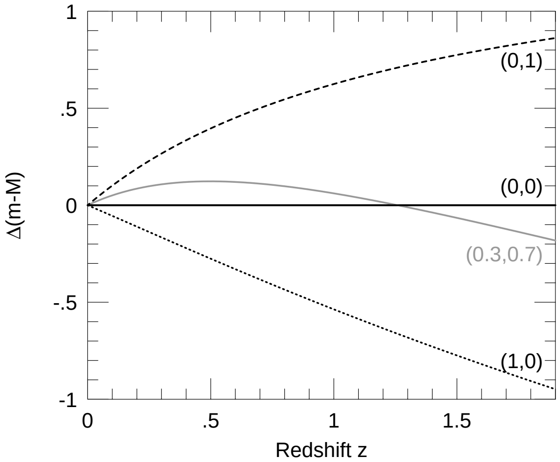

Fig. 2. The relative distance modulus for different cosmological models $(\Omega_M, \Omega_\Lambda)$

The existence of the cosmological constant can be fairly easily checked with further observations of SNe Ia. At early times the universe was dominated by matter and only later has been turned around by the cosmological constant. Hence, at sufficiently large lookback times, i.e. redshifts, we should find a decelerated universe (Fig. 2). With the current best fit parameters we find that supernovae near $z \approx 0.8$ should be the relatively faintest, while at redshifts >1.3 they should appear brighter. This non-monotonic behavior can be observed and is very unlike any of the other possible explanations. It has to be expected that evolutionary effects grow as a function of redshift and also the dust contents of the universe would have to be fine-tuned to mimic the predicted luminosity behavior for a cosmological constant.

4 Distant core-collapse supernovae as cosmological probes

After the successful observations of distant SNe Ia it can be expected that other supernova types may provide important cosmological information as well. Supernova rates will tell us something about the progenitor systems. In particular, the short fuse for core-collapse supernovae provides a simple way to measure the star formation rate at significant redshifts (Madau et al. 1998, Dahlén & Fransson 1999).

There are several ways how to observe distant core-collapse supernovae. An interesting proposal is to observe their X-ray/UV shock breakout (Chugai et al. 1999), which essentially depends on the size of the progenitor star. These are the most luminous moments of a SN II. Time dilation stretches the approximately day-long flash to several days at significant redshifts. The flashes have the advantage that they could be observed in the observer's optical window.

The advent of large telescopes opens up the infrared domain for faint objects. This is necessary to reach the rest-frame optical wavelengths of these supernovae as their UV flux is strongly suppressed (Cappellaro & Turatto, 1995, Kirshner et al. 1993) due to very strong Fe line blanketing. Especially the range from $0.5 < z < 4$ is interesting as the most intensive phase of star formation (Madau et al. 1998, Dahlén & Fransson 1999).

As the brightest signatures of individual stars supernovae are interesting *stellar* cosmological probes. Supernovae have an important role to play for our understanding of the constituents of the universe and their history.

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