The High-Redshift Supernova Search – Evidence for a Positive Cosmological Constant[1]

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Abstract

A new component of the Universe which leads to an accelerated cosmic expansion is found from the measurements of distances to high-redshift type Ia supernovae. We describe the method and the results obtained from the observations of distant supernovae. The dependence on the understanding of the local type Ia supernovae is stressed. The lack of a good understanding of the stellar evolution leading to the explosion of the white dwarf, the exact explosion physics and the current difficulties in calculating the emission from the ejecta limit the theoretical support. Despite the current ignorance of some of the basic physics of the explosions, the cosmological result is robust. The empirical relations seem to hold for the distant supernovae the same way as for the local ones and the spectral appearance is identical. The distances to the high-redshift supernovae are larger than expected in a freely coasting, i.e. empty, Universe. A positive cosmological constant is inferred from these measurements.

1 Introduction

The quest to measure the global dynamics of the Universe has dominated cosmological observations since the discovery of cosmic expansion. Observational tests have been devised ever since, but only recently have the measurements achieved an accuracy which allows us to draw more definite conclusions. Evidence has been accumulated from the observations of the mass concentrations on the largest scales and the time required to build them up from the earliest imprints in the cosmic microwave background (Bahcall & Fan 1998), from the fact that the formation of old stellar systems are incompatible with the Hubble time as derived from the present-day expansion rate, the Hubble constant (e.g. Carroll et al. 1992, Sandage 1988), and finally from the first direct distance measurements at redshifts larger than 0.1.

It is through the use of Type Ia supernovae that we now are able to glimpse at what the global energy density of the Universe may be and what is governing the expansion field. The intriguing new results are quite contrary to the expectations and will need a lot more scrutiny. Ultimately, the result will have to be supported by independent measurements of the changes of the expansion rate of the Universe.

If the distances derived from the supernovae are indeed larger than expected in a freely coasting Universe, i.e. q_0=0, then a new component to the cosmic energy budget has to be added (Schmidt et al. 1998, Garnavich et al. 1998a, Riess et al. 1998, Perlmutter et al. 1998, 1999). This is commonly expressed as a cosmological constant, but could be in a more general form (White 1998, Garnavich et al. 1998b). This new form of energy is a different, independent component to the dark matter, which was the topic of this conference.

We will describe how type Ia supernovae (SNe Ia) can be used to determine cosmological distances and point out the caveats with the current measurements (§2). The High-z Supernova Search Team has presented results of the first two years observing with astonishing conclusions. The Berkeley Supernova

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Cosmology Project independently arrived at the same conclusions through the same technique, but a completely independent data sample. Their results are presented in this volume by Isobel Hook and Pilar Ruiz-Lapuente. We will concentrate on the results found by the High-z Team in section 3. Potential pitfalls of the measurement are presented in section 4. We finish with a brief discussion of the implications of an accelerated expansion and conclusions (§5).

2 Type Ia supernovae in cosmology

2.1 Probing the nature of cosmological redshifts through time dilation

The regular temporal behavior of SNe Ia provides a simple, yet important, test of the basic interpretation of redshift as due to cosmic expansion. The most stringent indication of this has been the uniformity of the cosmic microwave background (Mather et al. 1990, Peebles et al. 1991). A direct proof for the expansion, however, had been missing but is provided by a clock at high redshift. The SN Ia light curves have been proposed as such a clock and can also be used to search for any evolutionary effects in the explosion (Wilson 1939, Colgate 1979, Tammann 1979, Leibundgut 1990). The fundamental nature of the cosmological redshift can be probed with a single distant supernova and the assumption that it does not differ significantly from nearby ones. Such an analysis became possible for the first time with light curves of SN 1995K at a redshift of 0.48 (Leibundgut et al. 1996) and a small sample of five supernovae from the Supernova Cosmology Project (Goldhaber et al. 1997). The same effect has been observed in the spectral evolution of the distant SN 1996bj (Riess et al. 1997). The result strikingly demonstrates the conventional interpretation of redshift being an effect of the cosmic expansion rather than any theories involving connections of redshift with an energy loss of the photon. SN 1995K could not be explained in a non-expanding Universe unless it would have had unprecedented attributes (Leibundgut et al. 1996). In particular, the light curve shape would have made it the slowest declining SN Ia observed ever with a spectrum basically indistinguishable from local SNe Ia (Schmidt et al. 1998). This is contrary to all correlations found in the local sample. Nonetheless, other interpretations of these observations have been advanced as well (Narlikar & Arp 1997, Segal 1997).

2.2 Cosmological distances from standard candles

Distance measurements from SNe Ia are made through a modified standard candle scheme, where luminosity distances are derived. This is a very simple test of the global geometry which has been proposed for several decades (Heckmann 1942, Robertson 1955, Hoyle & Sandage 1956, Sandage 1961) for a number of standard candle candidates. The assumption in this method is that the luminosity evolution of the standard candle is negligible or at least can be measured accurately. For SNe Ia it is generally assumed that their maximum luminosity does not change as a function of cosmic age. We will discuss this assumption below (§ 4.2). For an exact standard candle the cosmological parameters are described in the implicit equation

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

(e.g. Carroll et al. 1992). 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

$$\kappa = 1 - \Omega_M - \Omega_\Lambda .$$

The integration provides the cosmological distance element out to the source redshift z.
$S(\chi)$ takes the form

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

The change of the expansion rate, usually denoted as the deceleration parameter q_0, is defined as $q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda$.

The supernova distances are measured as the distance modulus

$$m - M = 5\log(D_L) + 25$$

with the luminosity distance in units of megaparsecs. The most probable values of the cosmological parameters are then found in a least squares fit, possibly assuming certain boundary conditions (Riess et al. 1998, Perlmutter et al. 1998, Leibundgut 1998). It has to be noted that the present-day value of the Hubble constant, H_0, is not of relevance in the determination of the energy density of the Universe, but rather depends on the zero-point which is derived from the nearby supernovae. The deceleration is entirely measured from the apparent magnitude differences between the nearby sample and the distant supernovae. With a sufficiently large redshift range the degeneracy between Ω_M and Ω_Λ can be broken by standard candles (Goobar & Perlmutter 1995). A much more effective way, however, is to find a measurement which depends on the cosmological parameters in a different way. This can be achieved by the comparison of the supernova result with measurements of the cosmic microwave background (White 1998, Eisenstein et al. 1998, Garnavich et al. 1998b).

2.3 Type Ia Supernovae as standard candles

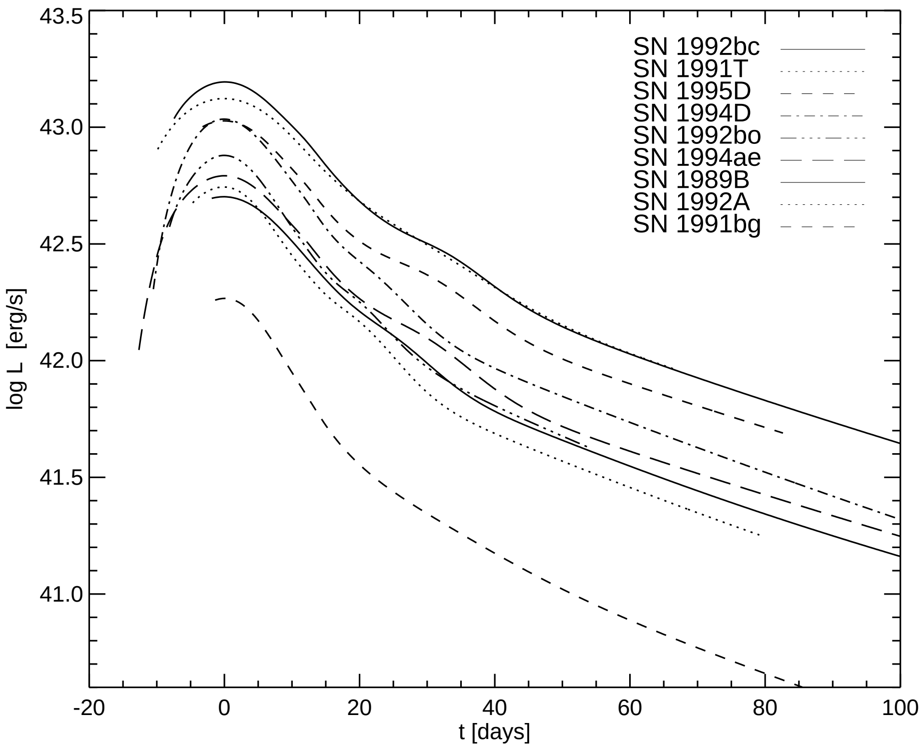

Figure 1: Bolometric light curves of nearby SNe Ia (Contardo et al. 1999).

Recent years have seen a dramatic increase in observational material on SNe Ia. Well-sampled light curves in many filters have been assembled for about 50 nearby supernovae ($z < 0.1$; Hamuy et al. 1996a, Riess et al. 1999). The first secure absolute distances from direct Cepheid measurements of SNe Ia have confirmed that they exhibit a very small scatter in their maximum light luminosity (Saha et al. 1998, Tammann in this volume). These results are used to refine our understanding of the explosive events. The most important result for cosmological applications of SNe Ia is the nearly uniform luminosity and the possibility to correct for variation in the peak luminosity by a distance independent parameter, i.e. the decline from maximum during the first two weeks (Phillips et al. 1993, Hamuy et al. 1996b, Riess et al. 1996, 1998). It seems that SNe Ia can be described fairly well as a one parameter family as many different parameters correlate with the decline rate. The decline rate, usually denoted as Δm_{15} for the B band, correlates with the peak luminosity (Hamuy et al. 1996a, Riess et al. 1996), the expansion velocity of the ejecta (Mazzali et al. 1998), the color at maximum light (Hamuy et al. 1996b, Riess et al. 1996, Branch

1998), the galaxy type (Hamuy et al. 1996b, Riess et al. 1996, 1999), line ratios of certain elements (Nugent et al. 1995), and possibly with the late-decline rate of individual filter light curves (Hamuy et al. 1996c). Most of these correlations have been established for B and V filters. The correction to the luminosity at maximum is at heart of the use of SNe Ia to measure cosmological distances.
Despite these well-established correlations some questions remain as to the exact nature of these explosions. The bolometric light curves constructed from the optical data do not show such a nice correlation with the decline rate. Fig. 1 displays a set of bolometric light curves of well-observed, nearby SNe Ia. It is obvious that the second maximum observed in the I (Suntzeff 1996, Ford et al. 1993) and the near-infrared light curves (Elias et al. 1985) also appears in the bolometric light curves (Contardo et al. 1999). This was originally pointed out by Suntzeff (1996) for the bolometric light curve of SN 1992A. The strength of this inflection varies between individual events. A clear trend of luminosity and strength of the inflection is not detected and there seems to be another parameter governing the energy release from the fireball. Surprisingly the decline of the bolometric light curve of SN 1991bg does not differ from the one of the other SNe Ia. This is in marked contrast to the filter light curves of this supernova. The B and V light curves of SN 1991bg declined much faster than for any other known SN Ia (Leibundgut et al. 1993, Turatto et al. 1996).
It should also be stressed that we currently do not understand the physics for the decline – luminosity relation (see, however, Höflich et al. 1996). The hydrodynamics and the radiation transport of the SN Ia ejecta is fairly uncertain and a number of models have been proposed (Arnett & Livne 1994, Woosley & Weaver 1994, Khokhlov et al. 1993, Höflich & Khokhlov 1996). Supernova atmospheres are far from thermal equilibrium as demonstrated by the lack of emission in spectral regions with none or few emission lines (Spyromilio et al. 1992) or the occurrence of maximum luminosity in different filter bands (Contardo et al. 1999).
The exact stellar evolution which leads to the progenitors of SNe Ia is not understood and a variety of astronomical objects has been proposed (cf. Branch et al. 1995). Also the explosion physics have not been solved yet. A number of explosion models has been proposed, but observational distinctions have eluded us so far. These uncertainties have to be addressed in any serious application of SNe Ia for cosmology.

3 Evidence from distant supernovae for a cosmological constant

The High-z Supernova Team was formed in 1994 to pursue the observations of distant, i.e. $z > 0.3$, supernovae. The team members have access to almost every major telescope and are located on four different continents. The current tally is at 116 candidate supernovae discovered with 45 spectroscopically confirmed SNe Ia (Woudt et al. 1999). We will concentrate on the first ten fully reduced objects as published by Riess et al. (1998).
A number of corrections have to be applied to the data before luminosity distances can be derived. Technical problems include the accurate photometry as most supernovae are very faint. The photometry then has to be converted to the rest frame of the supernova. This K-correction is not only a function of redshift and phase, but also depends on the decline rate and spectral appearance of the supernova. All light curves are then corrected for time dilation by dividing the phases with $(1+z)$. The reddening of the distant supernovae is determined from the intrinsic rest frame color. A reddening correction is applied either implicitly in the multi-color light curve shape method (Riess et al. 1996) or as an extra step when the Δm_{15} procedure is used. Indeed, only one or two objects in our sample show significant reddening (Riess et al. 1998). Finally, a correction for the light curve shape is applied to the distant supernovae. The correlation establishing this correction is based on a large sample of nearby supernovae (Hamuy et al. 1996a, Riess et al. 1999). It is important to realize that the relation has to be derived for the local sample in exactly the same way as it is applied to the distant set. In particular, the same filter set and also the same phase range have to be applied, in order not to introduce additional parameters which are not measured for the distant supernovae (Riess et al. 1998). Interestingly, the significance of the derived result strongly depends on the control of the local sample (Riess et al. 1998, Leibundgut 1998). A detailed discussion of these corrections and their accuracies is given in section 4.1.
For each supernova a luminosity distance is derived in this way. Comparison to theoretical models is then made through a modified Hubble diagram where the luminosity distance, i.e. distance modulus, is plotted vs. the redshift (Fig. 2). The local supernovae determine the locus of all models in the linear expansion regime (out to $z \approx 0.1$). It is the relative distances of the high-z supernovae compared to the

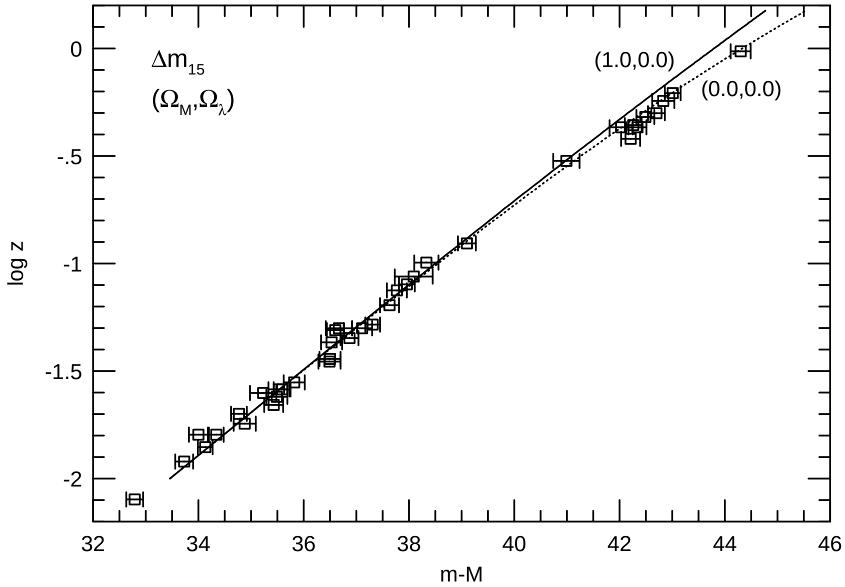

Figure 2: Hubble diagram of local and distant supernovae (data from Riess et al. 1998). The curves indicate the distance vs. redshift evolution in an Einstein-de Sitter (full line) or an empty Universe (dotted line).

Table 1: Summary of the results on the cosmological parameters from SNe Ia

Method	Ω_M	Ω_Λ	age (10^9 years)	P($\Omega_\Lambda > 0$)	P($q_0 < 0$)
MLCS	...	...	14	2.9σ	2.4σ
ΔM_{15}	...	...	15	3.9σ	3.8σ
MLCS+SN 1997ck	$0.00^{+0.60}_{-0.00}$	$0.48^{+0.72}_{-0.24}$	14	2.8σ	2.7σ
ΔM_{15}+SN 1997ck	$0.72^{+0.44}_{-0.56}$	$1.48^{+0.56}_{-0.68}$	15	3.8σ	3.7σ

local sample which provides the information on the change in the expansion.
It is evident in this figure that the data for the distant SNe Ia do not follow either model plotted. They are compared to the Einstein-de Sitter models ($\Omega_M = 1, \Omega_\Lambda = 0$) and an empty Universe without matter and no contribution of a cosmological constant ($\Omega_M = 0, \Omega_\Lambda = 0$). While the Einstein-de Sitter model is clearly ruled out, a model with no mass density and no cosmological constant is also not a good fit. The distant supernovae all lie below, i.e. at larger distances, than the expectations from these models. This becomes even clearer when the Hubble diagram is normalized to the empty Universe model (Fig. 3).
The distant SNe Ia show a systematic trend towards distances which appear to be even larger than in a freely coasting universe. The distant SNe Ia are about 0.2 magnitudes from the dividing line of an empty Universe. If the luminosity of SNe Ia has not changed since $z \approx 0.5$, the mean of the redshift distribution, then we are forced to admit that the distances of these objects have to be larger than in a non-decelerated Universe, and an acceleration has boosted the distances. The most obvious candidate for such an acceleration is a positive cosmological constant.
Of course, the caveat of any luminosity evolution or other subtle systematic effects have to be critically reviewed before this result can be accepted. We will come back to these issues in section 4.2.
The luminosity distances are most sensitive to the combination $\Omega_M - \Omega_\Lambda$ (e.g. White 1998, Eisenstein et al. 1998). Thus, the supernovae determine an uncertainty region nearly perpendicular to the flat geometry solutions. For our data set we find that any solutions for a positive matter density require also a contribution of a cosmological constant. The confidence intervals are given in Table 1. We do not have a large enough redshift range for an accurate determination of Ω_M and Ω_Λ independently. Despite this current limitation we find a very high confidence limit for a cosmological constant and even an acceleration of the universal expansion since the time the SNe Ia exploded.

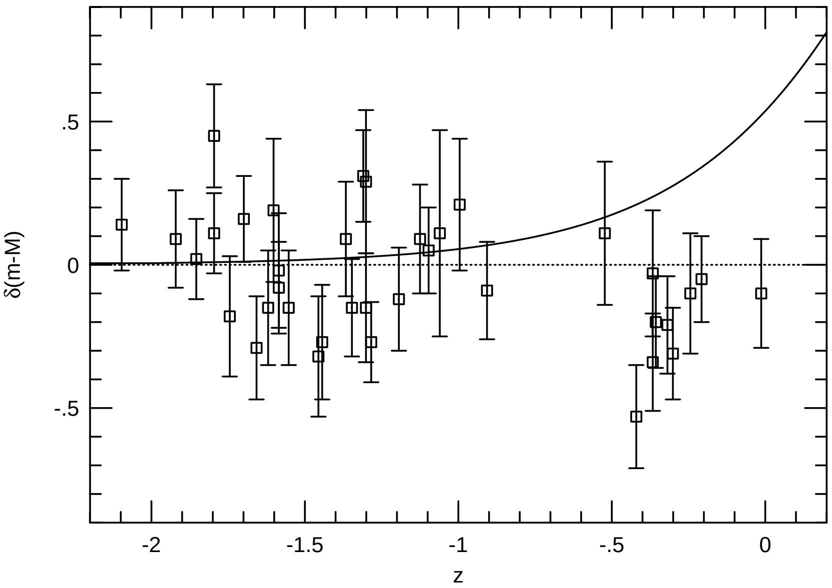

Figure 3: Distance differences from the individual supernovae from the expected line in an empty Universe.

4 Systematic error sources

There are number of effects which possibly could alter the result we found in the previous section. They can be roughly divided into two classes. Technical impediments, like accurate photometry, K-corrections, light curve sampling, sample contamination, and selection effects can be controlled by adequate observing and reductions strategies. Fundamental problems arise from possible gravitational amplification or de-amplification, absorption, and evolution of SNe Ia explosions.

4.1 Corrections to the observed data

Accurate photometry is a pre-requisite for the determination of the peak brightness of the objects. The most important contaminant is the background light from the galaxy on which the supernova is superposed. In many cases, the underlying host galaxy light has to be carefully subtracted. As the supernova fades these problems are exacerbated. This is particularly important as the decline rate is determined by the later phase, i.e. fainter, observations. The individual photometry points are then corrected for the effects of the redshift. The observed flux has to be converted to a rest frame magnitude to be comparable to the local SNe Ia. These K-corrections are time-dependent and have to be determined from nearby supernovae over the whole range of the light curve. A slight dependence of the K-corrections on the decline rate, i.e. the intrinsic color, of the supernova has been noted (Riess et al. 1998) and has to be included. Despite the complications in this process a very good accuracy has been obtained (e.g. Schmidt et al. 1998), as the problem can be controlled very well and only depends on the availability of sufficient data on nearby supernovae.
Since the peak magnitudes are required to determine the decline parameters and the distances, a well-sampled light curve is needed for each supernova. Global observing campaigns are organized to achieve this goal. The critical observations near maximum and about two weeks after maximum, which are the most crucial for the determination of the peak magnitude and the decline-rate corrections, are virtually guaranteed by the search technique for the distant supernovae (Perlmutter et al. 1997, Schmidt et al. 1998). The sample of local supernovae is large enough that we can select suitable subsamples (Hamuy et al. 1996b, Riess et al. 1999). For well-sampled light curves the errors of the light curve parameters are significantly reduced.
A critical evaluation of each object in the sample for its supernova type is unavoidable. Since the classification for supernovae is based on spectroscopy near maximum light (Harkness & Wheeler 1990, Filippenko 1997), it is imperative to obtain a spectrum of each object. Occasionally the spectrum is not decisive enough and even the combination with the light curve can not exclude ambiguities. In the sample discussed here we have one object for which it was not possible to unambiguously determine its

classification (Riess et al. 1998). For another object, SN 1997ck at $z = 0.97$, it was not possible to obtain a spectrum. Exclusion of these objects from the sample does not change our results (Table 1).
Selection effects could change the result. A recent discussion of the Malmquist bias by Teerikorpi (1998) demonstrates that such an effect, if not detected, could yield to an underestimate of the deceleration. In effect, since there is some intrinsic scatter for every standard candle, the volume which is sampled for a standard candle at a given redshift is biased to a larger distance than indicated by the straight mean magnitude and the distances are over-estimated. Basically, the volume sampled at $m + \sigma m$ is larger than the one with $m - \sigma m$, where σm is the scatter of the standard candle. This effect works in all magnitude limited samples. For the distant supernovae one also has to consider that some objects may have been missed by the search. Fortunately, the scatter of the nearby sample of SNe Ia shows such a small range (0.15 mag, Schmidt et al. 1998) that the expected systematic errors are still smaller than the total offset measured for the distant SNe Ia.

4.2 Astrophysical influences

Gravitational lensing of distant objects is unavoidable. Most importantly the apparent brightness can be changed due this effect. Since gravitational amplification is wavelength independent it can not be detected in the objects' light directly. For SNe Ia this is the only effect which can not be inferred from the SN observations alone. Mapping of the gravitational potential along the line of sight is required (e.g. Wambsganss et al. 1998). The redshift out to which SNe Ia have been observed so far is not large enough to suffer from any significant influence from gravitational lensing (Wambsganss et al. 1997, Holz 1998). Even in the most extreme case where all matter is clumped ('empty beam') our result of an accelerated expansion will not change significantly (Holz 1998).
A possible explanation of the apparent faintness of the distant supernovae could be absorption. All observations are corrected for absorption by the Galaxy. Observing in two filter bands should allow us to detect absorption in the host galaxy. This implicitly assumes that the intrinsic color evolution of all SNe Ia can be traced and that the reddening law is the same at $z = 0.5$ as in our Galaxy. Any absorption at other redshifts is not considered. The average column density as measured from QSO absorbers out to $z \approx 0.5$ is small and can be ignored. Most distant SNe Ia have a very small absorption. This is due to two selection effects. First, heavily absorbed supernovae are less likely to be discovered and, second, the spectroscopic follow-up observations concentrate mostly on SN candidates well separated from the galaxies to avoid strong contamination from the galaxy light. Thus, we do expect rather small reddening for most of the distant supernovae. It is unlikely that dust extinction systematically affects the distances to mimic the observations. This is because, significant absorption along certain sight lines would increase the scatter in the observed distances. This is not observed (Riess et al. 1998).
A most critical assumption is the equivalency of the distant supernovae to the local ones. Any evolution of the supernovae as a function of, e.g. progenitor age, could influence the peak luminosity of the light curve. After all, the distant supernovae exploded some 5 Gyr earlier than the ones in the local Universe. The lack of detailed explosion models currently prevents a robust theoretical prediction. An attempt was made to investigate the influences of a number of parameters on the light curves (Höflich et al. 1998). The strongest effect found was the chemical composition of the progenitor star which could change the blue part of the optical spectrum. The influence is rather small, however. An empirical test for the similarity of the distant SNe Ia with the local ones is by comparing the observational properties of the distant sample to the nearby one. The currently available spectroscopy has not detected any significant deviations (Riess et al. 1998, Perlmutter et al. 1998). In most cases, the spectra are not of high enough quality to guarantee this result, but the few objects with excellent spectroscopy show the same evolution as for nearby SNe Ia (Riess et al. 1997, 1998, Perlmutter et al. 1998). The rest-frame colors and the light curve shapes of the distant objects also do not deviate. We are faced with the possibility that all measurable distance independent quantities of SNe Ia appear unchanged, while the luminosity could have changed. This is a rather unlikely proposition, but will need more critical scrutiny.
Possible sample differences, as typically produced by a selection bias, have to investigated as well. The global sample properties of the local and distant sample have been found to be very similar (Riess et al. 1998, Leibundgut et al. 1999). The good standard candle quality of SNe Ia is a very important asset in this respect.

5 Discussion and Conclusions

Distant SNe Ia provide striking evidence for an acceleration of the universal expansion over the last ~ 6 Gyr. Commonly such an acceleration has been identified by the possible contribution of a vacuum density, i.e. cosmological constant. This is the first clear indication for the existence of a significant vacuum density. The cosmological constant acts like a negative pressure term for the expansion. It is possible to examine the equation of state of the Universe in more detail by splitting the contributions to the geometric term in the equation for the luminosity distance into the several components (Garnavich et al. 1998b). By doing so the dominant source of the acceleration can be determined. The best fit to the data is using a component very similar to the cosmological constant where pressure is proportional to the negative density ($P \propto -\rho$). Topological defects could also be responsible. A network of non-commuting cosmic strings would have an average effective relation of $P \propto -\frac{\rho}{3}$, but are excluded for any flat spatial geometry ($\Omega_{\rm total} = 1$).

It is interesting that the best cosmological parameters found in our study provide an age estimate of the Universe which is in agreement with the oldest stellar components. The age we find (Table 1) is about 14 Gyr, which comfortably includes the globular cluster ages (Riess et al. 1998). The fact that the Universe has suffered from an accelerated expansion means that the simple extrapolation based on the present-day value of the Hubble constant underestimates the age of the Universe.

As mentioned in the introduction, the combination of the supernova result with accurate measurements of the cosmic microwave background (CMB) fluctuations provides the possibility to restrict the allowed range in the $\Omega_M - \Omega_\Lambda$ plane considerably (White 1998, Eisenstein et al. 1998). The two measurements are almost orthogonal in this parameter space. A first attempt was made by White (1998) and Garnavich et al. (1998b) combining the supernova data with the constraints found on the CMB (Hancock et al. 1997). The combined constraints give a narrow region around $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ with 3σ confidence limits reaching from about $-0.2 < \Omega_\Lambda < 1.3$ and $\Omega_M < 1.0$ (Garnavich et al. 1998b). The Einstein-De Sitter model is excluded by many σ.

A number of distant SNe Ia have been already observed and are about to be analyzed and published. The Berkeley Supernova Cosmology project is publishing a large set of supernovae (Hook, this volume, Perlmutter et al. 1999). The High-z team expects to have about 20 additional SNe Ia analyzed next year. The supernova sample has increased to a size where statistical uncertainties are not important any more. It is the systematic error sources described in section 4.1 and 4.2 which dominate the uncertainty in the measurements. They will have to be tackled one by one. The most important seems currently the question of evolution. We need a much better understanding of the spectral evolution of SNe Ia at high redshift. This implies that spectroscopy not just for the classification of the object, but for a detailed spectral analysis will have to be obtained. In addition, programs to investigate the environment of the distant supernovae and compare them to the local sample are under way. They include the study of the parent galaxy morphology and metalicities.

The CMB constraints will improve with the future space missions of MAP and PLANCK. There are excellent prospects that the value of Ω_M and Ω_Λ will be pinned down fairly accurately in less than 10 years from now.

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