Type Ia Supernovae and q_0[1]

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Abstract. Type Ia Supernovae hold great promise to measure the cosmic deceleration. The diversity observed among these explosions, however, complicates their ability to measure cosmological parameters considerably. The comparison of near and distant objects depends critically on the global properties of the samples. Systematic errors are introduced in cases where the samples are not compatible. Our discussion of systematic uncertainties emphasizes the dependence on the zero-point defined by the nearby SNe Ia sample and the influence of the application of light curve corrections to the luminosity. Other error sources are in principle controllable. We illustrate the effects in an analysis of four SNe Ia at $z > 0.4$.

1. Introduction

It is more than 70 years since it was realized that the Universe is expanding, yet we still do not know its exact dynamic state. The long debate on the present-day value of the expansion rate, Hubble's constant, appears to be coming to an end and most astronomers agree on similar values. The coming years will see a discussion on the global change of the expansion rate and the final fate of the Universe. Supernovae have been at the forefront of this research for the last decade and will also play an important role in the near future by measuring the deceleration q_0 and separating the contributions of matter Ω_M and a cosmological constant Ω_Λ.

'Supernovae Type Ia [are] the best standard candles known so far' (Branch & Tammann 1992). Even though this statement has been challenged in recent years it holds pretty much true. The magnitude-redshift relation of Type Ia Supernovae (SNe Ia) has always displayed a rather small scatter (Kowal 1968, Tammann & Leibundgut 1990) and almost all SNe Ia exhibit very similar B, V, and I light curves (Leibundgut et al. 1991, Hamuy et al. 1996). A debate on SN Ia uniformity has started with the discovery of a few under– and overluminous events (SN 1991bg: Filippenko et al. 1992a, Leibundgut et al. 1993, Turatto et al. 1996; SN 1992K: Hamuy et al. 1994; SN 1991T: Filippenko et al. 1992b, Phillips et al. 1992; SN 1992bc and SN 1992bo: Maza et al. 1994) which show

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many, but not all, signatures of what normally is called a SN Ia. There are important differences in the appearance of these objects, but it seems that a clear separation into subclasses is not possible, if they are indeed distinct from the majority of SNe Ia. Even highly selected samples (Vaughan et al. 1995, Sandage et al. 1996, Saha et al. 1997) show internal scatter in absolute peak luminosity.

It is the maximum luminosity of SNe Ia which is normally used when they are employed as standard candles. A limited and small range of peak brightness is crucial. The total scatter of nearby SNe Ia in the Hubble flow ranges from about 0.25 magnitudes in B (Hamuy et al. 1996, Saha et al. 1997) to 0.19 magnitudes in I (Hamuy et al. 1996). The scatter can further be reduced by empirical corrections derived from distance-independent parameters which correlate with the peak luminosity. The light curve shape is the most frequently used method (Phillips 1993, Hamuy et al. 1996, Riess et al. 1996). Another option is to apply appropriate selection criteria to limit the range of absolute magnitudes of known SNe Ia in which case the pure standard candle approach may still be valid (Vaughan et al. 1995, Sandage et al. 1996, Saha et al. 1997).

Defining subsets of objects is a valid procedure as long as the selection does not result in a degeneracy. None of the light curve correlations found for SNe Ia have so far been explained by theory. The use of SNe Ia in cosmology is one of the main incentives to better understand SN Ia physics.

The current knowledge of the explosion physics and the radiation transport in the highly non-thermal envelopes is far from being complete (Eastman & Pinto 1993, Pinto & Eastman 1997, Eastman 1997, Pinto 1997, Höflich et al. 1993, 1995, 1996, 1997). Detailed observations obtained for many nearby objects indicate that some of the fundamental assumptions adopted a few years back have been in error. Especially the assumption of a thermal radiation field in SNe Ia is wrong and a more exact treatment is necessary. The emerging radiation resembles a black body in the optical fairly well results, however, from redistribution of the flux due to the many lines of iron and iron-like elements blocking the UV radiation. A very clear sign of the non-thermal nature of the radiation emitted by SNe Ia is the time of maximum light in different filter passbands. For a simple, expanding ball of gas in thermal equilibrium the maximum at longer wavelengths should be reached at later phases as the gas cools adiabatically. This is not true for most SNe Ia where the I light curve peaks before the B maximum is reached (Vacca & Leibundgut 1996, Contardo et al. 1998), a sign of the wavelength dependence of the ejecta opacity. A detailed radiation model explaining this observation is still lacking. The spectral individuality of SNe Ia at maximum light has been recognized as due to small abundance differences in the outer envelope which are of little relevance for the explosion physics itself (e.g. Jeffery et al. 1992, Mazzali et al. 1993). It may be sensitive to some of the precursor history, but not necessarily represent a true signature of fundamental differences among the observed explosions.

The light curve tracks the temporal evolution of the energy release. Most of the energy generated in the explosion by burning matter to nuclear statistical equilibrium goes into unbinding the white dwarf. The rest is stored in radioactive material synthesized in the explosion (Clayton 1964, Colgate & McKee 1969). The conversion of the γ-rays from the radioactive decays to lower energy photons and their escape from the ejecta defines the light curve (Arnett 1982, Leibundgut & Pinto 1992). Since the release is highly time dependent due to the decreasing column density and rapidly changing opacities in the envelope, it has been very difficult to calculate light curves of SNe Ia. A technical complication is the conversion of the total released energy into the filter passbands of observed light curves requiring the calculation of the complete spectrum to obtain enough wavelength points. The observers have had little input into the bolometric light curves of SNe Ia (Leibundgut & Pinto 1992). Attempts have been made by Suntzeff (1996) for SN 1992A with superb and Leibundgut (1996) for SN 1990N with rudimentary data. Only recently have data sets, like the one for SN 1994D, become available for a detailed determination of a bolometric flux evolution (Vacca & Leibundgut 1996). Interestingly, the variations among SNe Ia persist in the bolometric light curves and a variety of shapes is found. Most strikingly, the second maximum observed in the infrared appears as an inflection of variable strength in the bolometric light curves (Contardo et al. 1998). This points to important fundamental differences in the energy release among individual SNe Ia. The light curve correction procedures will have to be tested on the bolometric light curves which are a much more physical quantity than the filter light curves. It should be pointed out that the combination of these effects indicates a more complicated picture than what has been captured in simple scaling relations. They may be adequate to render SNe Ia suitable objects to measure cosmological distances, but do not suffice to describe the physics of the explosion.

Apart from the general difficulty of demonstrating the small luminosity scatter of SNe Ia, their use also requires a careful error analysis. Section 2 will outline how cosmology is done with standard candles and basically summarizes work presented in fundamental papers of several decades ago. In §3 we apply the theory to observed SNe Ia. A discussion of the sources of systematic errors and how they are treated is given. The analysis of the first set of 4 SN Ia serves as an illustrative example. We conclude (§4) with an assessment of how suitable SNe Ia are for cosmology.

2. The use of standard candles in cosmology

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 is described by

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

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}). This is typically shown in a Hubble diagram, $\log(cz)$ *vs.* m.

For cosmologically significant distances, where the effects of the matter and energy contents of the Universe become significant, 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

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

(Heckmann 1942, Robertson 1955, Hoyle & Sandage 1956, Sandage 1961). q_0 here is the deceleration of the expansion. The integral of the line element can be solved analytically only in some specific cases (e.g. 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 of the exact equation, and Mattig (1958) showed that for models without a cosmological constant a second order term makes significant contributions.

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 in an expanding universe, allowing for a cosmological constant Λ, is

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

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 $\Omega_\Lambda = \frac{\Lambda}{3H_0^2}$ describes the contribution of a cosmological constant to the expansion factor. κ is the curvature term and obeys

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

$S(\chi)$ 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 cosmic deceleration in these models is defined as $q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda$.

The dimming of standard candles in different cosmological models is normally displayed as a set of lines in the Hubble diagram (Sandage 1961, Leibundgut & Spyromilio 1997, Perlmutter et al. 1997). It is, however, more instructive to plot a diagram of the magnitude differences between the various world models (Fig. 1, cf. also Schmidt et al. 1998, Garnavich et al. 1997). The differences between the various models become more apparent in this diagram. A standard candle in an open universe ($\Omega_M = 0$, $\Lambda = 0$) would appear 0.17 magnitudes fainter at a redshift of 0.3 than in a flat universe ($\Omega_M = 0.5$, $\Lambda = 0$). This difference increases to 0.33 mag at $z = 0.6$ and 0.54 mag for $z = 1.0$ (Fig. 1). These are small values considering how difficult the observations are and the corrections which are needed to obtain a significant measurement.

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. There is, however, a degeneracy in q_0 when a cosmological constant

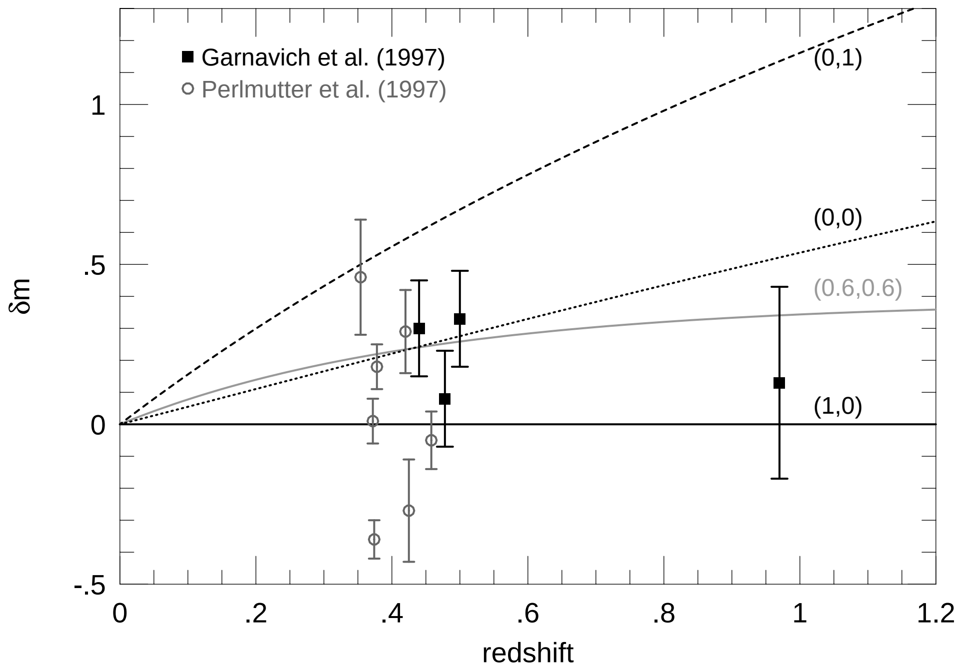

Figure 1. Magnitude differences of a standard candle for various cosmological models. The lines for various combinations of $(\Omega_M, \Omega_\Lambda)$ are shown. They correspond to $q_0 = 0.5$ (solid line), $q_0 = 0$ (dotted), $q_0 = -1$ (dashed), and $q_0 = -0.3$ (grey).

is included (cf. Fig. 1). The separation of Ω_M and Ω_Λ requires the observation of standard candles over a large range of redshifts (Goobar & Perlmutter 1995).

It is important to realize that the value of the Hubble constant is not required for the determination of q_0. What is important is the apparent magnitude difference of a standard candle measured at two different redshifts. Distant supernovae have to be compared to a set of nearby supernovae where q_0, or equivalently the curvature κ, is negligible.

3. The cosmological deceleration as measured by SNe Ia

3.1. Systematics

Even though the scatter in peak luminosity is small, SNe Ia are not perfect standard candles. Various effects can play an important role when they are applied to measure distances. Most importantly, the samples which are compared for the derivation of the cosmological parameters have to be compatible and commensurate.

Even a perfect standard candle suffers from extinction along the line between the object and the observer. The differences in the absorption along different lines of sight, least known in the host galaxy, can modify the observed luminosities. Supernovae must be checked carefully for reddening. SNe Ia display a range of intrinsic colors and can not be corrected for absorption based on color alone. Rest-frame color still is a good indicator of unreddened objects as there is a well-defined blue cutoff in the color distribution, but it can only be measured through light curves in at least two filters. The concentration on SNe in elliptical galaxies could partially remedy this problem (Branch & Tammann 1992), but a suitable sample of nearby SNe Ia in elliptical galaxies would have to be established. There also appears to be a luminosity difference among SNe Ia between star-forming and elliptical galaxies which may be a worry (Hamuy et al. 1996, Schmidt et al. 1998).

Some correction methods treat reddening implicitly (Riess et al. 1996) with the assumption that the color correlates with the peak luminosity. Light curves in at least two filters are mandatory for this application.

Type Ia supernovae have to be recognized as such which is reliably done through spectroscopy (Oke & Searle 1974, Filippenko 1997). Peculiar supernovae have been distinguished by their spectral appearance (Filippenko et al. 1992a, 1992b, Phillips et al. 1992, Leibundgut et al. 1993, Branch et al. 1993). Spectroscopic observations of supernovae are an indispensable requisite for any supernova research. Contamination of the sample by supernovae of other types is unacceptable and dangerous. Peculiar SNe Ia have to be detected as well. The High-z Supernova Search (Schmidt 1997) thus has set out from the beginning to obtain spectroscopy of all supernovae discovered in its search.

Any global differences in the composition and global properties of the comparison samples introduce systematic errors in the result. To illustrate this consider the average luminosity of two samples which are used to derive cosmological parameters. If, due to Malmquist bias, the more distant sample has a systematically higher luminosity than the nearby sample, and we would just apply the standard candle paradigm, the mean distance difference would be underestimated. The implications are the derivation of too large a value for the Hubble constant or an overestimation of q_0.

There are two more uncertainties when using SNe Ia for the determination of q_0. One is evolution and the other distortions due to gravitational lensing effects. Evolution would be a clear violation of the standard candle paradigm. Since we are looking at explosions, which occurred at a time when the universe was only half its current age, we have to make sure that they are the same as the ones we observe nearby. This would be a bold assumption if unchecked. Depending on the progenitor stars of SNe Ia there could be substantial evolutionary effects. If SNe Ia result from sub-Chandrasekhar-mass white dwarfs, the mass dependence could introduce luminosity differences which would skew the luminosity function (Ruiz-Lapuente et al. 1995, Canal et al. 1996). Since more massive white dwarfs are formed first, it is conceivable that these distant SNe Ia are from an intrinsically more massive population and thus also more luminous, which would have an effect comparable to the Malmquist bias described above. Even with Chandrasekhar-mass progenitors the luminosity could be substantially changed due to abundance differences in the parent populations. The smaller metallicities could mean that the line opacities governing the radiation escape in SNe Ia are significantly changed which would result in changed luminosities in the observed filters. The only way to check any of the above conjectures lies in carefully observing the distant objects and asserting their similarity with the nearby sample. If the distant sample looks the same as the nearby one in all aspects we can measure, we have a good chance that they have the same average luminosity as well. It is not sufficient to exclude strange-looking or non-conforming objects as they may be the sign of real differences invalidating the standard candle approach altogether.

Gravitational lensing always affects light traveling over cosmological distances. Amplifications introduced by the lensing have been investigated in combination with SNe Ia (Wambsganss et al. 1997). Gravitational lensing, unlike absorption, is achromatic. It can not be inferred from the observed light alone. Luckily, at the redshifts of the supernova searches ($z < 1$ so far) the systematic amplification (or dimming) of standard candles for current models of the mass distribution is small ($\Delta q_0 < 0.04$ for all $z < 1$; Wambsganss et al. 1997).

3.2. Observing distant supernovae

There are currently two large observational programs which try to determine the deceleration of the universe using SNe Ia. They both make use of SNe Ia as standard candles or modified versions thereof. The High-z Supernova Search Team (Schmidt 1997, Schmidt et al. 1998, Garnavich et al. 1997, Leibundgut et al. 1996, Leibundgut & Spyromilio 1997) and the Berkeley Cosmology Project (Perlmutter et al. 1995, 1997) have discovered a large number of supernovae over the last three years. In fact, these two supernova searches now contribute the majority of all discoveries per year. Figure 2 shows a summary of all SNe Ia found in these two searches up to June 1997. It should be compared to a similar figure from 1996 (Leibundgut & Spyromilio 1997) to appreciate the rapid progress. Both groups have mastered the art of detecting these extremely faint objects very efficiently. The numbers reported are actually lower limits as both groups now only announce bona fide supernovae at high redshifts. Not even all types of SNe are reported any longer as the highest interest is in distant SNe Ia. This should be taken as a word of caution when interpreting the numbers for supernova rates. The discovery of SNe Ia dominates the distribution. Only very few Type II supernovae have been announced at redshifts larger than 0.3 and a single SN Ic has been discovered in the High-z SN Search.

The total number of SNe discovered in the two searches is 107 objects, 70 of which are confirmed SNe Ia at $z > 0.25$ (29 High-z SN Search and 41 Berkeley Cosmology Project).

The emphasis has shifted from actually finding the supernovae to organizing the critical follow up observations. Spectroscopy is the prime classification resource and also serves as a discriminator against unusual objects. Photometry is required to establish the essential light curve parameters, if such a correction should be applied.

These observations are challenging for any telescope. As an example consider a SN Ia at z=0.5: the observed peak magnitude reaches 21.9 in the R band (SN 1995K; Schmidt et al. 1998), but the crucial light curve parts for the decline rate determination are around $R = 23$ and, if some of the light curve tail should be observed, magnitude levels with $R > 25$ have to be considered. It can not be emphasized enough how important it is to achieve accurate photometry at these magnitudes as only small deviations can result in substantial, in terms of the effect to be measured, over-corrections. This is even more so, should systematic effects creep in, which skew the correction unilaterally through, e.g., contami-

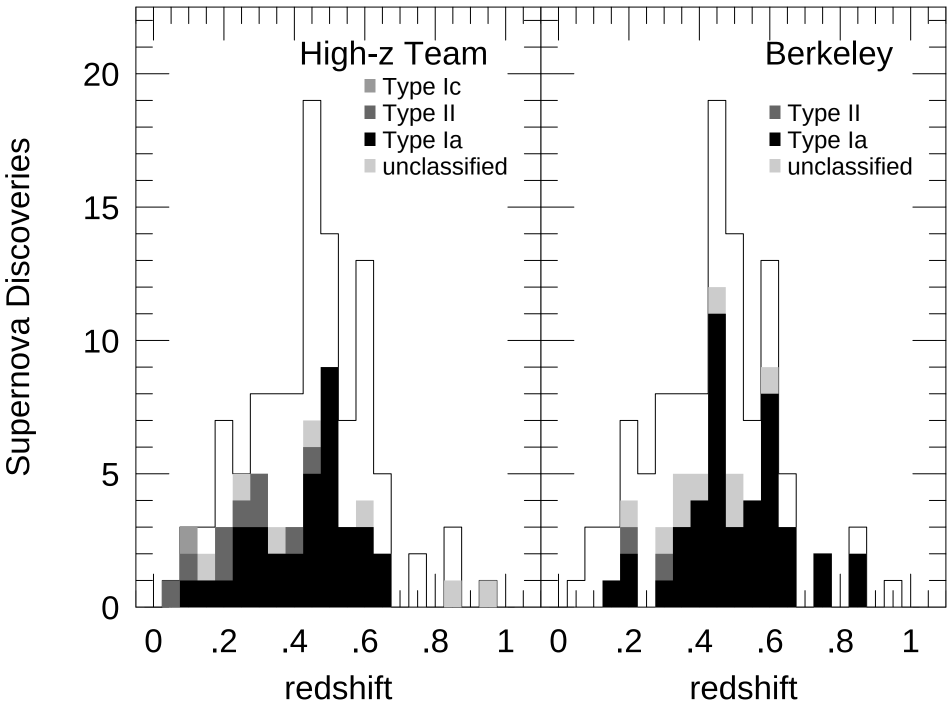

Figure 2. Supernova discoveries reported by the distant SN searches in IAU Circular until July 1997. The top line indicates the total number of SNe from both searches combined.

nation by the galaxy background. It is dangerous to “blindly” apply light curve correction procedures without the assurance that the objects are indeed SNe Ia.

All observations obtained so far indicate that the distant supernovae look very similar to the local ones (Leibundgut et al. 1996, Leibundgut & Spyromilio 1997, Perlmutter et al. 1997, Schmidt et al. 1998, Garnavich et al. 1997). Spectra, light curves, and rest-frame colors of distant supernovae appear identical to the bulk of the local population, and evolutionary effects are not apparent (Schmidt et al. 1998).

Technical issues in the analysis are the accuracy of the photometry, the calculation of K-corrections, any application of luminosity corrections, and uncertainties in the zero-point defined by the nearby sample. While the photometry and the K-corrections appear to be under control, the correction for the light curve shape can become problematic. The maximum magnitude of a SN Ia is measured fairly easily as the techniques employed in these searches by design discover SNe close to maximum (Perlmutter et al. 1997, Schmidt et al. 1998). Typical photometric errors of individual light curve points are about 0.05 to 0.15 magnitudes near the peak, but increase to 0.3 magnitudes a couple of weeks from maximum. The error in the determination of the filter maximum is around 0.1 to 0.2 magnitudes. The uncertainties in the K-corrections are negligible (<0.05 magnitudes; Kim et al. 1996, Schmidt et al. 1998). Light curve corrections introduce two uncertainties. They are defined by photometry points which are less well measured than near maximum and the correction parameters themselves carry uncertainties (Hamuy et al. 1996). It has yet to be shown unambiguously that the light curve corrections also decrease the scatter in the distant sample. Contrary to the simple determination of the maximum magnitude these methods make use of the whole light curve shape. This is a very valuable asset when the photometry errors are not significant, but can become problematic when applied to points with large errors. In addition, the corrections change the zero-point of the sample, a very contentious issue in the Hubble constant discussion (Hamuy et al. 1996, Saha et al. 1997). It will be very important to resolve this ambiguity also for the determination of q_0.

The statistical uncertainty in the zero-point of the nearby SN Ia sample is typically about 0.03 (Hamuy et al. 1996). The contribution to the uncertainty in q_0 scales with $1/z$ and for a sample with a mean redshift of 0.5 contributes about 0.06 to the total uncertainty in q_0.

3.3. The first four High-z supernovae

SN 1995K is the first SN Ia discovered in the High-z SN Search (Leibundgut et al. 1996, Schmidt et al. 1998). Three more supernovae have become available recently (Garnavich et al. 1997). We will use this small sample of four SNe to exemplify the analysis of distant SNe Ia and describe the systematic influence of the basic assumptions.

The spectrum and the light curves of SN 1995K show no signs of any peculiarity for a SN Ia at $z = 0.478$ (Leibundgut et al. 1996, Leibundgut & Spyromilio 1997, Schmidt et al. 1998). Once the time dilation has been removed the light curve is comparable to regular nearby SNe Ia. K-corrections are nearly constant throughout the observed phase due to the near match of the R and I filters to rest-frame B and V, respectively, at $z \approx 0.5$. The rest-frame color derived for this object is $(B - V) \approx -0.1$, consistent with unreddened nearby objects (Vaughan et al. 1995, Tammann & Sandage 1995). The peak magnitude in rest-frame B and V is 22.9 and 23.0, respectively. It can thus be assumed that it is a good candidate for the measurement of deceleration.

SN 1997ce and SN 1997cj are spectroscopically confirmed SNe Ia at redshifts of 0.44 and 0.50, respectively (Garnavich et al. 1997). Spectra of these two supernovae show the characteristic Si II (SN 1997ce) and Ca II (SN 1997cj) absorption. They both have a well sampled light curve from ground-based and *HST* observations in rest-frame B and V without apparent peculiarities. The color at maximum for both objects is also consistent with $(B - V) \approx 0.0$ indicating that absorption is negligible. We find peak magnitudes of 22.9 (B) and 23.0 (V) for SN 1997ce and 23.3 (B and V) for SN 1997cj from simultaneous fits to light curve templates.

The most distant supernova in the sample, SN 1997ck, is at a redshift of $z = 0.97$ as deduced from a spectrum which shows a single, narrow emission line, identified as [O II], from the galaxy. The time dilation in the light curve indicates a redshift of 1.1 ± 0.2 for the best fitting light curve of a nearby SN Ia (SN 1991T). At this redshift the V band is shifted beyond $1\mu m$ and no data could be obtained. Hence we have no indication whether dust absorption is affecting this object. The following analysis of the B light curve assumes negligible absorption.

Figure 1 indicates the position of these supernovae in comparison with nearby SNe Ia (Hamuy et al. 1996). B and V observations have been combined for the points of the High-z sample. This diagram has the advantage

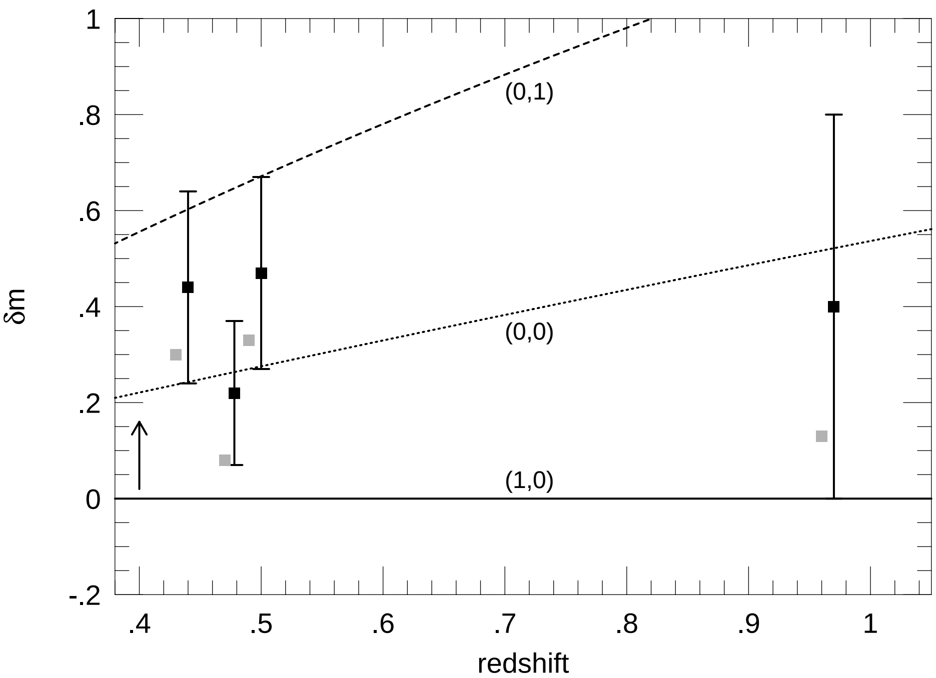

Figure 3. Same as Fig. 1 but after application of the light curve correction. The arrow indicates the shift due to the zero-point change (0.14 magnitudes). The faint dots indicate the former position of the data(shifted in redshift for clarity). The errors have increased slightly due to the additional uncertainty of the light curve fitting.

that both filter measurements can be combined in the same graph. This also means that the observations in two filters, apart from their necessity for accurate photometry and the check for absorption, increases the number of observations in the data set thus constraining the uncertainty. The figure also displays the supernovae reported by the Berkeley group (Perlmutter et al. 1997).

The diagram in Figure 1 assumes a perfect standard candle, i.e. no light curve shape correction has been applied. It uses the zero-point given in equations 4 and 5 of Hamuy et al. (1996). There is a large overlap between the two data sets, but a clear lack of bright supernovae in the High-z sample. We find values for Ω_M and Ω_Λ by χ^2 fitting. Only for the uncorrected B data do we find an acceptable solution (χ^2 minimum), if the cosmological constant is ignored. The best value in this case is $\Omega_M = 0.1 \pm 0.6$. The best solution is found for $\Omega_M = 0.6$ and $\Omega_\Lambda = 0.6$ (corresponding to $q_0 = -0.3$) with a very large uncertainty in both parameters. For the V filter data we find no solution with $\Omega_\Lambda = 0$ and $\Omega_M \geq 0$. The best solution lies near $\Omega_M = 0.5$ and $\Omega_\Lambda = 0.7$ ($q_0 = -0.45$). The original result for the Berkeley set was close to $\Omega_M = 0.9$, $\Omega_\Lambda = 0.1$ (Perlmutter et al. 1997).

The picture changes, when we apply the correction for the light curve shape. The model lines shift by 0.14 magnitudes due to the change of the zero-point provided by the local sample (Hamuy et al. 1996; equations 7 and 8). At the same time we have to correct the distant supernovae for their light curves. With the exception of SN 1997ck, which seems to have been similar to SN 1991T in light curve shape, all SNe are best approximated by the template light curve of nearby SNe Ia (cf. Garnavich et al. 1997). Thus, any light curve corrections for these objects are small (< 0.1 mag). The correction of the B maximum brightness of SN 1997ck is 0.13 magnitudes assuming it was identical to SN 1991T.

The global effect is illustrated in Figure 3. The arrow indicates the shift of the data points due to the change of the zero-point of the lines. After the correction all points scatter around the line for an open universe ($\Omega_M = 0, \Omega_\Lambda = 0$). A Λ-dominated universe is now favored with best fits of $(\Omega_M, \Omega_\Lambda) = (0.3, 0.6)$ for the B data and $(\Omega_M, \Omega_\Lambda) = (0.3, 0.9)$ for V. These values correspond to $q_0 = -0.45$ and $q_0 = -0.75$, respectively. The value for Ω_M has decreased in the B solution, because SN 1997ck, being identified as overluminous, has undergone a larger correction than the other supernovae. The photometric uncertainty in the measurement of this high-z supernova, however, reduces its contribution in the χ^2-fit. Thus the signal is produced mainly by the 3 supernovae near $z \approx 0.45$ and not by SN 1997ck, as is obvious from the fits to the V data. Note that any reddening of SN 1997ck would make this supernova even brighter. We have to emphasize that the number of objects is still small and it is certainly premature to draw definite conclusions.

Since we do not have access to the individual photometry of the Berkeley supernovae we can not perform the same analysis on their data. It should be pointed out, however, that two of their SNe lie outside the observed range of decline rates and have been excluded in their analysis. The correction of the remaining objects nearly cancels the offset of the zero-point shift as they arrive at almost the same result for the uncorrected and the corrected sample. This is surprising considering the effect of the zero-point alone (Fig. 3). A direct comparison of the two data samples is not possible, but we can compare SNe which have similar redshifts. SN 1992bi had almost the same redshift ($z = 0.458$) as SN 1995K and undergoes a large correction, but was excluded from the subsequent analysis, because it displayed a slower decline rate than observed for any local SN Ia (Perlmutter et al. 1997). More interesting might be the comparison of SN 1997ce with SN 1994al ($z = 0.420$) and SN 1994G ($z = 0.425$). SN 1994G has a spectrum identifying the object as a genuine SN Ia, while the galaxy spectrum of SN 1994al is described as consistent with an elliptical or S0 galaxy, which would identify this object also as a SN Ia. The observed rest-frame B magnitudes at peak are 22.8 (SN 1994al) and 22.3 (SN 1994G). These have to be compared to the peak magnitude of SN 1997ce which is 22.9. Thus, we have a very good agreement between SN 1994al and SN 1997ce, but SN 1994G deviating by about 0.5 magnitudes. Even after corrections for the light curve shape the close agreement between SN 1994al and SN 1997ce remains, and SN 1994G still is an outlier (Table 1 of Perlmutter et al. 1997). It is puzzling to find that our result changes so dramatically (almost entirely due to the shift of the zero-point of the local sample), while the analysis of Perlmutter et al. (1997) did not result in a similar signal when they applied their light curve correction method.

4. Conclusions

The regular behavior of SNe Ia has already provided proof of another prediction of models of an expanding universe. Time dilation contributes significantly to the filter light curves and the spectral evolution of distant supernovae (Wilson 1939, Tammann 1979). The light curves of SN 1995K are dilated exactly by the factor $(1+z)$ predicted for an expanding universe (Leibundgut et al. 1996). The Berkeley data set has been investigated for time dilation with similar conclusions (Goldhaber et al. 1997). In cases like SN 1997ck, where there is the detection of a single line in the galaxy spectrum, the time dilation can be used for consistency checks, although one has to assume that the object indeed is a SN Ia. Retarded spectral evolution, consistent with time dilation, has been observed in SN 1996bj at a redshift of 0.574 (Riess et al. 1997). Nevertheless, there remain proposals of static universe models which conform with the observed time dilation (Narlikar & Arp 1997, Segal 1997).

With sufficient control the difficulties of SNe Ia to measure the current state of the deceleration can be overcome. Light curves in two filters and spectroscopy near maximum light can identify extinction or peculiar SNe Ia, which may prevent the correct application of the standard candle paradigm. Only a very careful characterization of all measurable aspects of the sample of distant supernovae and its comparison with the nearby set can lead to a successful measurement of q_0. The influence of uncertainties introduced by the local sample should not be underestimated. They are sizeable contributions to the error with which q_0 can be determined.

The largest systematic uncertainty is the application of luminosity corrections. This is a rather intricate problem which is discussed in connection with SNe Ia based determinations of H_0, but applies equally to q_0. Our analysis of the small SN sample available shows that the light curve corrections produce a different result than a simple comparison of peak magnitudes. For SNe Ia with light curve shapes deviating only slightly from the average this effect is entirely in the offset of the zero-point of the local supernova sample. For SNe Ia which are overluminous as indicated by their light curves, the standard candle paradigm only produces an upper limit for q_0. The existing data at this point clearly favor an open universe and even a contribution of a cosmological constant, although the errors are still considerable.

As discussed the difference between an empty and a flat universe is 0.54 magnitudes at $z = 1$ (Fig. 1). This means that the influence of the zero-point decreases and a measurement at larger redshifts is less sensitive to these systematics. The difficulty will be to obtain the accurate photometry to reliably measure the light curve shape and apply the corrections. The High-z SN Search has already discovered and followed supernovae at these redshifts. We confirm in our analysis the result presented in Garnavich et al. (1997). The distant objects are essential to measure Ω_M and Ω_Λ independently (Goobar & Perlmutter 1995).

Due to Malmquist bias one is more likely to overestimate q_0 than to find too small a value. On the other hand, any residual photometry errors which would tend to widen the light curves would lead to the adoption of too bright a luminosity for the supernovae.

Type Ia Supernovae may be the closest we know to a cosmological standard candle, yet the magnitude differences for different dynamical states of the universe are very small and a tight control of the samples is indispensable. In principle all the required information can be gathered by the observations. The knowledge of the progenitor systems and the exact radiation physics are pivotal ingredients still missing from our picture of these explosions (Branch et al. 1995). With such an understanding the inference of the standard candle character and possible evolutionary scenarios can be tested. Until then we have to rely on the control provided by careful observations and analysis.

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