Cosmological implications from observations of Type Ia Supernovae

Bruno Leibundgut

European Southern Observatory
Karl-Schwarzschild-Strasse 2
D–85748 Garching
Germany
bleibundgut@eso.org

Annual Review of Astronomy and Astrophysics 2001, 39, 67

Abstract

Distant Type Ia Supernovae (SNe Ia) appear fainter than their local counterparts. Independent of what explanation will eventually be found to be correct, this implies a significant change in how we see the distant universe and what we understand of these stellar explosions.

The observational characteristics of nearby SNe Ia show some differences from event to event. Despite their considerable range in observed peak luminosity, they can be normalized by their light curve shape. Through this normalization, SNe Ia can be used as exquisite distance indicators. The Hubble diagram of nearby Type Ia Supernovae, demonstrating the linear cosmic expansion at small scales, is the simplest observational proof for the standard character of these objects. Compared with Friedmann models of the universe, the distant supernovae are too faint for a freely coasting, 'empty,' universe, barring other influences that could dim the events. This result is independent of the absolute calibration of the peak luminosity, which is needed to derive the Hubble constant. Possible non-cosmological explanations could be gray dust, with properties that do not change the color of the objects significantly, evolution of the explosions, or de-amplification by gravitational lensing. Current indications are that none of these alternatives alone can explain the dimness of the distant supernovae.

The intrinsic colors of the distant SNe Ia are typically bluer when compared with the local sample. This in itself makes the dust hypothesis less likely. On the other hand, it could be a signature of evolutionary trends that could influence the peak luminosity. This trend is contrary to the observations in the local sample, where bluer objects typically are more luminous. However, current lack of understanding of the explosion physics and the radiation transport of SNe Ia encumbers any investigation of evolutionary changes. Any change of the peak luminosity of SNe Ia must be inferred from indirect observations, such as light curve shape, colors, and spectral evolution. At the moment, many of the distant supernovae do not have the required data set for a detailed investigation of these parameters.

The near-uniform light curves and spectral evolution of Type Ia Supernova can be used as accurate cosmic clocks to demonstrate the time dilation as predicted from expanding world models. The test has been performed both through photometry and spectroscopy and is fully consistent with the predictions.

The supernova results can currently be reconciled only with cosmological models which provide some form of acceleration. The simplest such models either include the cosmological constant or refer to a decaying particle field ('quintessence').

Combined with recent measurements of the Cosmic Microwave Background that indicate a flat geometry of the universe, and the low matter density, as derived from bulk flows and the evolution of galaxy clusters, the supernovae define a fairly narrow likelihood region for Ω_M and Ω_Λ. With these new values for the cosmological parameters the long-standing problem of the dynamical age of the universe appears to be solved. On the other hand, the size of the acceleration, if interpreted as a cosmological constant, is in clear contradiction to predictions from particle theories. In addition, we would live in a very privileged period when the matter density and the cosmological constant are equal contributors to the cosmic expansion.

Contents

1 Introduction

There are few results in astronomy and astrophysics that sparked such a heated and animated discussion as did the announcement that distant type Ia supernovae (SNe Ia) indicate an accelerated expansion of the universe. The basic observation consists in the fact that the distant supernovae appear fainter than expected in a freely coasting universe. These results were announced independently by two different research groups and have given rise to a flurry of research activities to interpret and explain them. The range of contributions spans from thrilling new cosmological explanations to alternative interpretations of absorption due to dust at large redshifts which could block some of the supernova light and mimic a cosmological effect.

After the initial burst of excitement the observational task is now to rigorously explore the systematics of the measurements and the possible alternative explanations. Among the most exciting proposals is the postulate of a new form of 'dark energy,' i.e. energy with a negative pressure, like the cosmological constant (Einstein 1917, Weinberg 1989, Carroll et al. 1992, Turner & Tyson 1999) or 'quintessence' (Caldwell et al. 1998) with a decaying particle field providing the acceleration (for a review of some of these alternatives see Kamionkowski & Kosowsky 1999). Other proposed explanations identify the faintness of the distant supernovae as due to dust absorption (Aguirre 1999a, 1999b, Totani & Kobayashi 1999), luminosity evolution of the supernovae, either intrinsic because of the different age of the progenitor stars or because of different chemical compositions of the precursor object (e.g. Höflich et al. 1998, 2000, Umeda et al. 1999, Nomoto et al. 1999). Further possibilities include changes in the properties of the observed supernova ensemble from nearby sample to the distant set.

Type Ia Supernovae have long been proposed as good distance indicators for cosmology, first through their standard candle character, i.e. identical peak luminosity, and later normalized by corrections from light curves shapes. Supernovae as cosmological tools have been described in many papers and reviews (e.g. Branch & Tammann 1992, Branch 1998, Saha et al. 1999, Gibson et al. 2000, Parodi et al. 2000).

Type Ia Supernovae are characterized by the absence of hydrogen in their spectra (e.g. Minkowski 1964, Harkness & Wheeler 1990, Filippenko 1997). They are most likely the thermonuclear explosion of a white dwarf (Woosley & Weaver 1986, Hillebrandt & Niemeyer 2000). By now, a fairly large range of peak luminosity has been observed for SNe Ia, but a normalization of the peak luminosity by the light curve shape makes them suitable distance indicators (Phillips 1993, Hamuy et al. 1996b, Riess et al. 1996, 1998, Perlmutter et al. 1997, Phillips et al. 1999, Parodi et al. 2000). It should be noted that the peak luminosity further correlates with supernova color (Riess et al. 1996, Tripp 1998, Phillips et al. 1999, Saha et al. 1999, Parodi et al. 2000), line strengths (Nugent et al. 1995), ejecta velocities (Mazzali et al. 1998), and morphology and colors of the host galaxies (Filippenko 1989, Hamuy et al. 1995, 1996a, 2000, Schmidt et al. 1998, Branch et al. 1996).

Different methods for the light curve shape corrections, however, do not compare well with each other; significant differences in the implementations of the corrections have been found (Drell et al. 2000, Leibundgut 2000a). The impact of these corrections on the cosmological interpretations will be discussed further in section 2.

The range in peak luminosity is presumed to be connected to significant differences in the amount of radioactive ^{56}Ni produced in the explosion itself (Cappellaro et al. 1997, Bowers et al. 1997, Contardo et al. 2000). Nickel represents the power source for the optical emission through its decay to radioactive ^{56}Co and further to stable ^{56}Fe (Colgate & McKee 1969, Clayton 1974). A range of over a factor of two in nickel mass has been determined for most SNe Ia, with some extreme cases possibly differing up to a factor of 10 (Contardo et al. 2000).

It has to be stressed that despite the successful application of SNe Ia to cosmology the exact physics of the explosions and the radiation transport are not very well understood (for reviews see Woosley & Weaver 1986, Hillebrandt & Niemeyer 2000, Leibundgut 2000a). First explanations of the luminosity–decline relation have been proposed and most of them point to the Ni mass as the relevant parameter (Höflich et al. 1996, Pinto & Eastman 2000), but the exact reason for the differences in the explosions is not clear. All proposed models are so far parametric and have no physical underpinning.

This makes the situation for SNe Ia as distance indicators less favorable. In particular, discussions of evolution or other effects that possibly could change the supernovae as a function of cosmological age and redshift are severely hampered by the lack of a clear theoretical understanding of the phenomenon (cf. section 4.1).

Several excellent reviews on Type Ia Supernovae have been published recently. Monographs can be found in Ruiz-Lapuente et al. (1997), Niemeyer & Truran (1999), and Livio et al. (2000). The observational status is summarized in Filippenko (1997) for spectroscopy, and light curves are extensively discussed in Leibundgut (2000a) and Meikle

(2000). Possible progenitor systems (Branch et al. 1995, Renzini 1996, Livio 1999), supernova rates (van den Bergh & Tammann 1991), and the status of explosion models (Hillebrandt & Niemeyer 2000) are covered in more specific reviews.

Two regimes for the cosmological use of SNe Ia should be distinguished. The first is relevant for the determination of the Hubble constant at redshifts where the cosmic expansion is still linear, i.e. the effects of curvature are negligible. At these distances SNe Ia can actually test the linearity of the expansion to a high degree (Sandage & Tammann 1982, Tammann & Leibundgut 1990, Tammann & Sandage 1995, Hamuy et al. 1996b, Riess et al. 1996, Saha et al. 1997), which in turn is proof that they can be used as reliable distance indicators. In the second regime, at larger redshifts ($z > 0.2$) the combination of the distinct cosmological models and evolution of the SN Ia peak luminosity can no longer be separated cleanly (e.g. Drell et al. 2000), and one has to resort to indirect evidence for the lack of evolution of the supernovae. A further difference between the determination of the current expansion rate, Hubble's constant H_0, and the measurement of the change of this parameter in the past, often referred to as the deceleration q_0, is the need to know the absolute luminosity of the objects for H_0. While the observation of H_0 requires an absolute measurement, and hence the value of the peak luminosity of SNe Ia, the second on q_0 is relative and independent of the absolute luminosity of SNe Ia, which however is assumed to be constant.

The use of SNe Ia to determine the Hubble constant is based on the absolute peak luminosity and the fact that all SNe Ia can be normalized through their light curve shapes. Over the last decade all determinations of the Hubble constant from supernovae have yielded a consistent value around 65 km s^{-1} Mpc^{-1} with about a 10% uncertainty (Hamuy et al. 1996b, Riess et al. 1996, Saha et al. 1997, 1999, Tripp 1998, Tripp & Branch 1999, Phillips et al. 1999, Suntzeff et al. 1999, Jha et al. 1999, Gibson et al. 2000, Parodi et al. 2000). This determination hinges on the distances to nearby galaxies provided by the Cepheids, which calibrates the absolute peak luminosity of SNe Ia. Any changes in this distance scale, such as a different distance to the Large Magellanic Cloud or a change in the period-luminosity correlation for Cepheids (e.g. Gibson & Stetson 2000, Freedman et al. 2001), will change the value of H_0 accordingly.

For the cosmological interpretation of the distant SNe Ia this review is restricted to Friedmann models with homogeneous and isotropic metric, i.e. a Robertson-Walker metric. The framework of world models with a cosmological constant has been laid out clearly by Carroll et al. (1992). They also proposed a number of tests but did not include one for luminosity distance indicators. This has been remedied by Goobar & Perlmutter (1995) who pointed out that the degeneracy of such distance indicators can be lifted if a large enough redshift range can be observed. The degeneracy can also be broken by combining the supernova result with other measurements, most notably the fluctuations in the cosmic microwave background (CMB) and the power of large scale structure in the universe (cf. section 5).

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 ($z \lesssim 0.1$) 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}). The speed of light c enters as a form factor. This is typically shown in a Hubble diagram, $m\ vs.\ \log(cz)$.

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

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

(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 as 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.

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

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

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

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

$S(\chi)$ takes the form

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

The cosmic deceleration in these models is defined as

$$q_0 = \frac{\Omega_M}{2} - \Omega_\Lambda. \qquad (2)$$

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 (Fig. 1, cf. also Schmidt et al. 1998, Riess et al. 1998, Perlmutter et al. 1997, 1999a). The magnitude differences between the various cosmological models are more apparent in this diagram. 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.

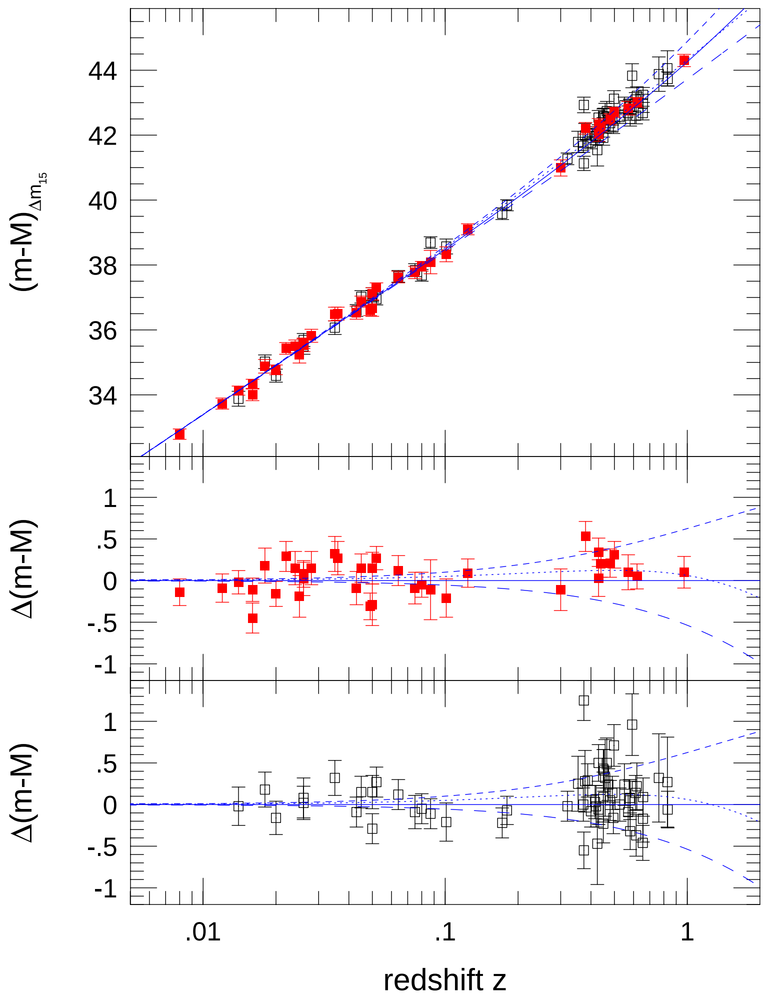

Figure 1: Hubble diagram of Type Ia Supernovae. The upper panel shows the classical Hubble diagram with distance modulus vs. redshift. All data have been normalized to the Δm_{15} method. Lines of four cosmological models are drawn: full line for an empty universe ($\Omega_M = 0$, $\Omega_\Lambda = 0$), long-dashes for an Einstein-de Sitter model ($\Omega_M = 1$, $\Omega_\Lambda = 0$), dashed line for an universe dominated by the vacuum ($\Omega_M = 0$, $\Omega_\Lambda = 1$), and the dotted line for a flat universe ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$). The lower panels are normalized to an empty universe and show the data of the High-z SN Search Team (filled squares; Riess et al. 1998) and the Supernova Cosmology Project (open squares; Perlmutter et al. 1999a).

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 2).

We emphasize again 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 cosmological parameters 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.

Although the topic is still very young there are already a few reviews in the literature. The reader is referred to the articles by Riess (2000), Leibundgut (2000b), and Filippenko & Riess (2000) for specific discussions of the supernova results and Turner & Tyson (1999) and Bahcall et al. (1999) for more general overviews.

2 Observational material

2.1 Nearby SNe Ia

The quest for uniform and consistent data sets has driven supernova searches for the last 10 years. Large and homogeneous samples of multi-filter light curves had been missing until the Calán/Tololo search (Hamuy et al. 1995, 1996c) and the data collection at the CfA (Riess et al. 1999a) were published. The Hamuy et al. (1996c) sample has been used by the Supernova Cosmology Project (SCP; Perlmutter et al. 1995, 1997, 1998, 1999a) as well as the High-z Supernova Search Team (Schmidt et al. 1998, Riess et al. 1998, 2000, Garnavich et al. 1998a, 1998b), but the latter has included several objects from the CfA sample as well (Riess et al. 1998). The nearby supernovae are used for the derivation of the light curve shape corrections and to anchor the model lines in the Hubble diagram.

Note that there is a difference in the treatment of the corrections for light curve shape between the various applied methods. The Δm_{15} (Phillips 1993, Hamuy et al. 1995, 1996d, Phillips et al. 1999) and the Multi-Color Light Curve Shape (MLCS) methods (Riess et al. 1996, 1998) are applied to correct for the change in the absolute maximum luminosity of the supernovae. The stretch factor, on the other hand, has been introduced to normalize the observed apparent peak magnitude (Perlmutter et al. 1995, 1997). The former assumes that there are intrinsic luminosity differences among SNe Ia. This is also the adopted physical picture for these events (e.g. Höflich et al. 1996, Pinto & Eastman 2000, 2000b, Contardo et al. 2000, Leibundgut 2000), whereas the latter is used simply as a normalization procedure. For the cosmological application of SNe Ia this difference is not relevant, but it leads to different presentations of the Hubble diagrams (e.g. Riess et al. 1998, Perlmutter et al. 1999a) and complicates a direct comparison between the two data sets. However, it is possible to combine the two samples after the corrections have been applied. For the distance modulus the application of the correction is symmetric; hence, we can derive a distance modulus for the SCP data set by comparing their local sample, which comes from Hamuy et al. (1996c), with the distance moduli derived in Riess et al. (1998). The 16 objects in common yield a normalized absolute magnitude for the SCP sample of $M_B = -19.30 \pm 0.12$ and $M_B = -19.41 \pm 0.12$ when compared to the MLCS and Δm_{15} samples, respectively. These values reflect the choices of the distance scales in Hamuy et al. and Riess et al. The range discussed in the literature is considerably larger than indicated by the errors (e.g. Saha et al. 1999, Gibson et al. 2000). The reason to choose these values for the absolute luminosity is simply to make the data sets compatible with each other. Note that the difference in the absolute magnitudes also implies an offset of about 0.1 magnitudes in the distance moduli derived from the MLCS and the Δm_{15} methods for these 16 objects. This offset nearly disappears when all 27 local SNe Ia are considered for the two methods (-0.07 ± 0.05). The change of the offset indicates how sensitive the relative measurements are and the great care that has to be applied when comparing the nearby and the distant SN Ia samples. It should also be noted that the systematic differences in the correction methods (Leibundgut 2000a) do not have an effect on this determination, but may well be important for the peak magnitudes and distance moduli used in the Hubble diagram.

To compare the SCP sample with the High-z SN sample we have normalized the SCP data set with the above values to the Δm_{15} method and plotted them in Figure 1 (for similar plots showing the MLCS version of this diagram, see also Riess (2000) and Wang (2000)).

2.2 Distant SNe Ia

The first serious attempt to observe distant supernovae was undertaken during the late 1980s by a Danish-British collaboration. Two distant supernovae were discovered by this group: SN 1988U, a Type Ia Supernova at z=0.31 (Nørgaard-Nielsen et al. 1989) and SN 1988T at z=0.28, which according to the very limited photometric information available, most probably was a Type II supernova (Hansen et al. 1989).

A new search was initiated by Perlmutter et al. (1991) to explore SNe Ia at high redshift and use them to measure global cosmological parameters. This search resulted in a number of discoveries which have been reported in several papers (Perlmutter et al. 1995, 1997, 1998, 1999a). So far, a total of 148 supernovae have been reported in IAU circulars. Of these, 69 objects have a secure classification as a SN Ia (in the range $0.1 < z < 1.2$) and can be used for distances. In addition, there have been 6 core-collapse, i.e. Type II and Type Ib/Ic, supernovae discovered at slightly lower redshifts ($z < 0.6$). A recent extension of the SCP to nearby supernovae, in collaboration with other groups - the Near-Earth Asteroid Tracking project (IAUC 7122), the Nearby Galaxies Supernova Search (IAUC 7125), the Spacewatch Program (IAUC 7134), the EROS collaboration (IAUC 7136), and the European Supernova Cosmology Consortium (IAUC 7182) - has already produced a sizeable number of SNe Ia (36 reported; $z < 0.5$) and core-collapse SNe (8 discovered; $z < 0.4$).

The High-z Supernova Search Team started later and discovered its first SN Ia in 1995 (Leibundgut et al. 1996, Riess et al. 1997, 1998, 2000, Schmidt et al. 1998, Garnavich et al. 1998a, 1998b). Since then a total of 141 discoveries have been reported with 76 secure SN Ia classifications ($0.05 < z < 1.2$) and 27 core-collapse SNe ($z < 0.5$). The data for the Calán/Tololo Supernova Survey have been collected by members of the High-z SN

Search Team (Hamuy et al. 1996c, Suntzeff et al. 1999, Phillips et al. 1999). Many team members are further involved in other local supernova searches (e.g. the Lick Observatory Supernova Search (Li et al. 1999, 2000), the Center for Astrophysics (Riess et al. 1999a, Jha et al. 1999) and the Mount Stromlo and Siding Spring Abell Cluster Search (Reiss et al. 1998, Germany et al. 2000).

A few supernovae have been observed independently at higher redshifts (Gilliland et al. 1999, Mannucci & Ferrara 1999), but without spectral classification. Repeated observations of the Hubble Deep Field North (e.g. Ferguson et al. 2000) have revealed two objects which appeared between 1995 and 1997 associated with galaxies at $z = 0.95$ and $z = 1.7$. The higher-redshift object appeared in an early-type galaxy which could favor a SN Ia identification. The photometry spanning a very limited time baseline is consistent with light curves of SNe Ia (Riess et al. 2001).

Spectroscopy of all distant objects is required for the classification of the supernovae. Few spectra have been published so far (Schmidt et al. 1998, Riess et al. 1998, Perlmutter et al. 1998, Coil et al. 2000). The quality of the spectroscopy is normally good enough to classify the objects, but detailed, quantitative comparisons are still lacking and will have to await better data. Another obstacle is that the defining Si II $\lambda\lambda 6347$, 6371Å doublet (e.g. Harkness & Wheeler 1990, Filippenko 1997) is redshifted out of the optical range at $z{\approx}0.5$ and becomes very difficult to observe. Hence, the secure classification often has to rely on more subtle features of SN Ia spectroscopy (Filippenko 1997, Coil et al. 2000).

Not all detected supernovae are suitable for distance determinations. Since the distances are tied to the maximum luminosity of the objects, the peak of the light curve has to be determined. Even for many nearby objects this is not possible. Out of the 29 plus 22 SNe reported by Hamuy et al. (1996c) and Riess et al. (1999a), respectively, only 27 could be used by Riess et al. (1998) for the determination of the light curve shape parameters and the peak brightness. Perlmutter et al. (1997) used only 18 objects from the Hamuy et al. (1996c) catalog. The published data on distant SNe is even smaller. The SCP has described 42 objects, while the High-z SN Search Team has so far published light curves and spectra of 13 objects. There is a fair fraction of distant objects that have no redshift observed. In some cases, the host galaxy has not been detected, which is especially true for the most distant objects. Also, to determine a good light curve shape correction and provide the peak brightness of the object, the light curves must be sampled sufficiently. In many cases, this can not be achieved because of the limited available observing time. Distant SNe are typically discovered in bunches of a dozen or more and a stringent selection has to take place to optimally use the limited observing resources. The balancing of sample size and number of good photometric observations is very important. The search strategies for distant supernovae favor the discovery of objects before peak luminosity (Perlmutter et al. 1995, Schmidt et al. 1998), but some objects are not suitable as they are blended with a high-surface brightness host, the object could not be classified spectroscopically, or the light curve coverage is insufficient for a reliable light curve shape determination. Hence, the number of objects used for distances is significantly smaller than the discoveries reported in the IAU Circulars.

The data analysis for these faint objects, often superposed on a host galaxy, can be difficult. The correct treatment of the observational errors is delicate and complicated. Both groups have adopted a strategy where a high signal-to-noise template image of the galaxy, obtained typically one year after the supernova outburst, is subtracted from the images containing the supernova. On the remaining image, regular photometry is performed. The accuracy of the photometry is checked by recovering artificial stars placed in the images and re-deriving their magnitudes.

Further corrections applied to the data are for redshift, which is done through phase-dependent, cross-filter K-corrections (Kim et al. 1996, Schmidt et al. 1998), absorption (Galactic and in the host galaxy), time dilation in the light curve (Leibundgut et al. 1996, Goldhaber et al. 1997, 2001, Riess et al. 1997) and light curve shape corrections (Phillips et al. 1999, Riess et al. 1998, Perlmutter et al. 1997). The uncertainties in these corrections are either not an issue, i.e. exactly determined (time dilation), or mostly not too large. However, systematic uncertainties, especially in the reddening law and the light curve corrections, should not be neglected.

The K-corrections have been derived from nearby supernovae and are applied to the distant supernovae. This implicitely assumes that the spectral characteristics of the distant supernovae are not significantly different from the nearby ones. These K-corrections are slightly different from the original concept (e.g. Oke & Sandage 1968) as they do not transfer the observer frame into the rest frame filter directly: howevev, they are calculated for filters that match the observer frame to the rest frame as closely as possible (Kim et al. 1996). For instance, the R filter is a good match of the B filter for objects at a redshift of 0.5. This keeps the relative K-corrections rather small for good matches of the filters and redshifts (Schmidt et al. 1998). The K-corrections further depend on the subtype of the SN Ia and are thus interlinked with the determination of the light curve shape parameter.

The colors of distant SNe Ia are largely unknown. To obtain this vital information is expensive in observing time. The High-z team has systematically observed all objects in at least two filters (corresponding as closely as possible to rest frame B and V). After their first campains the SCP has followed this procedure as well. Published data are still rare (Schmidt et al. 1998, Garnavich et al. 1998a, Riess et al. 1998, 2000). The absorption is determined either implicitly in the MLCS method (Riess et al. 1996, 1998) or through a direct color comparison in the SN rest frame for the Δm_{15} method (Hamuy et al. 1996d, Phillips et al. 1999). This again assumes that there is no color evolution from the local to the distant objects. The uncertainties are not negligible and can amount to about 0.1 magnitude. A further uncertainty here is the exact form of the reddening law. This is one of the major incertitudes in the interpretation of the distant supernovae (see discussion in section 4.2). The SCP distant sample has only been presented as a reddening histogram, without listing the individual colors (Perlmutter et al. 1999a). The available measurements indicate though that the colors are similar to the ones of nearby SNe Ia. However, there are clear indications that the distant SNe Ia of the High-z sample might have somewhat bluer colors than their local counterparts (Falco et al. 1999).

We show this effect in Figure 2 where the distant SNe Ia clearly have a bluer color than the limit found for the nearby objects (Phillips et al. 1999). The distant objects have a mean color of about -0.06 ± 0.03. This is still consistent with the intrinsic color derived for the nearby sample (-0.05) but is considerably bluer than the observed mean of the nearby sample (0.02 ± 0.01). Three of the nine distant objects have been assigned a reddening (Riess et al. 1998). This diagram will be further discussed in §4.

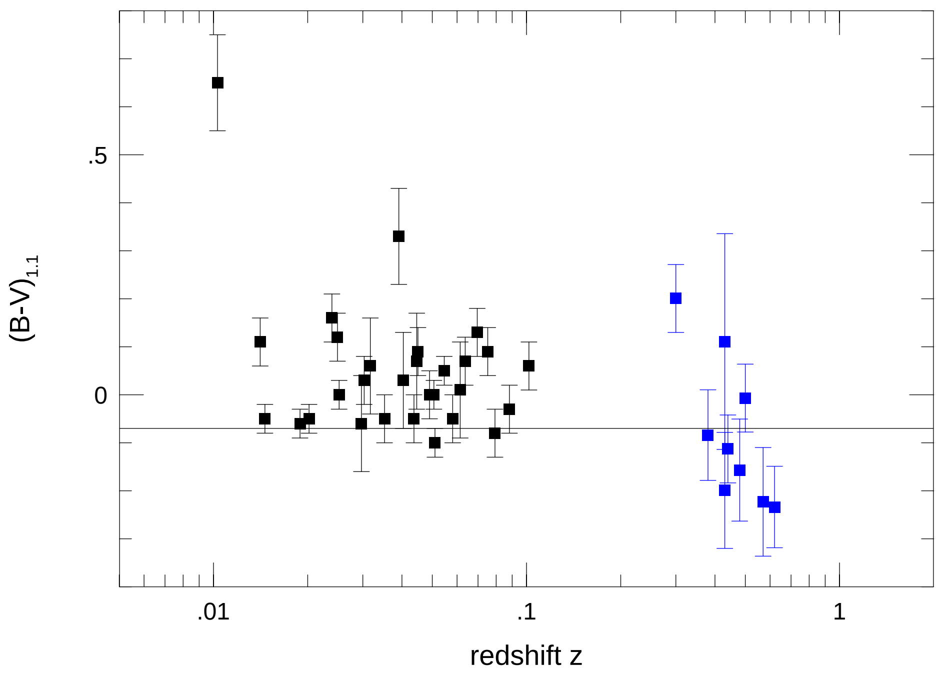

Figure 2: The observed colors of SNe Ia as a function of redshift. The data are from Phillips et al. (1999) for the low-redshift and Riess et al. (1998) for the high-z sample. The line shows the intrinsic color as defined for the nearby SNe Ia in Phillips et al. (1999).

3 Results

The proposal to use supernovae to determine the cosmological parameters was made over half a century ago (Wilson 1939). Several cosmological aspects can be tested with SNe Ia at significant redshifts. The time variability and the nearly identical light curves of the events make them ideal tracers for time dilation caused by the expansion of the universe. Their use as distance indicators provides a handle on the global cosmological parameters, in particular the de- or acceleration of the expansion. But SNe Ia are also the most distant individual stars observed. As such they will provide a stellar probe for evolution and the chemical enrichment history of the universe. Although the last few items are still on the horizon, it is not inconceivable that we will soon be able to achieve such measurements.

3.1 Time dilation

Type Ia Supernovae are perfect probes to detect time dilation, which is a firm prediction of cosmological expansion models (Wilson 1939, Tammann 1978, Colgate 1979, Leibundgut 1990, Leibundgut et al. 1996, Goldhaber et al. 1997, Riess et al. 1997). The light curve and spectral evolution of a distant supernova act like a clock. Comparing a distant object with nearby ones, we can directly observe the behavior of this clock in different inertial frames. If the universe expands, then the change in the scale parameter translates into the observed redshift and is directly proportional to a change in clock rates. This classical test is taught in textbooks (e.g. Weinberg 1972, Peebles 1993, Peacock 1999). In an expanding universe the change from the observer's frame to the rest frame of the object is equal to $(1+z)$. The proposal to use supernovae for this test has been made many times (e.g. Wilson 1939, Rust, 1974, Tammann 1978, Colgate 1979, Leibundgut 1990, Hamuy et al. 1993), but the data quality was not sufficient (Leibundgut 1990) until the new samples of distant supernovae became available. For a supernova at a redshift of 0.5 we observe a light curve that is only two thirds as fast as the local ones. All it takes is a single object at such a redshift to prove that this prediction is correct. SN 1995K (z=0.48) provided the data for the light curve (Leibundgut et al. 1996) and two spectra of SN 1996bj (z=0.57; Riess et al. 1997) were used for this time dilation test. The light curve and the spectral evolution are all fully consistent with the predicted stretch. Another test is to look at the distribution of measured light curve widths of the nearby and the distant sample. For the available data sets, they are identical after the correction for time dilation (Goldhaber et al. 1997, 2001, Riess et al. 1998, Perlmutter et al. 1999a, Drell et al. 2000). All these tests indicate that the observations are fully consistent with time dilation.

The supernova result has, however, also been interpreted in other, non-expanding cosmologies (Narlikar & Arp 1997, Segal 1997).

Other signatures of time dilation are the uniformity of the cosmic microwave background (Mather et al. 1990, Peebles et al. 1991) or the direct observation of surface brightness dimming (Sandage & Perelmuter 1990a, 1990b, 1991, Pahre et al. 1996, Bender et al. 1998). To produce the observed smooth microwave background in a non-expanding universe requires a process that works as well as adiabatic expansion. Surface brightness dimming has been shown for galaxies, but evolution of the galaxies, which is still uncertain, has to be accounted for.

3.2 Cosmology

The observational result of the Type Ia Supernovae can be stated in the following short form: "The distant SNe Ia appear fainter than a standard candle in a freely coasting, i.e. empty, Friedmann model of the universe." It should be emphasized that this is a purely observational statement (as can be seen in Figure 1). Averaging over the distant supernovae, we find that they are 0.20 ± 0.06 magnitudes fainter at $z \approx 0.5$ than in an empty universe, when the Δm_{15} correction method is used for the High-z data set. The same difference decreases to 0.14 ± 0.06 for the MLCS treatment. Both analyses produce a significant result. The SCP sample has somewhat smaller values, 0.06 ± 0.04, which might have to do with the slightly different normalization by the nearby SNe Ia and the larger redshift range of their sample. This illustrates the importance of the nearby supernova sample. A solid local comparison sample is crucial to interpret the data from the distant supernovae.

The interpretation of this result rests on some critical assumptions. The most likely explanations are an acceleration of the cosmic expansion, dimming by dust and evolution of the supernova luminosity. A priori, all these interpretations are equally likely. It is also conceivable that Fig. 1 shows a combination of several effects.

As can be seen the effect is rather small and its strength depends on the exact analysis. This is worrisome and indicates that the data are not yet good enough for a robust deduction. The uncertainties arise as much from the nearby sample as from the distant data. The light curve corrections have in all three analyses been derived from the original

Calán/Tololo sample (Hamuy et al. 1996c), with some additions from the CfA sample (Riess et al. 1999a) in the case of the High-z team (Riess et al. 1998). Yet the magnitude corrections of the same supernovae in the three analyses differ significantly (Leibundgut 2000a). Not only is the scatter rather large (σ = 0.19 magnitudes for 27 SNe Ia for a comparison of the corrections between Δm_{15} and MLCS), but the methods have a different scale for the corrections. The ratio of the magnitude corrections is significantly different from unity, if they would be similar (0.29 ± 0.04 between the corrections for Δm_{15} and the stretch method). A analogous result was derived by Drell et al. (2000) for the nearby and the distant samples and interpreted as a signature of evolution, but since the effect already appears in the nearby sample, I think that this is not by itself enough to argue for evolution of the supernovae (however, see section 4.1). Also, there are significant changes when the corrections are calculated for all available filters (typically *BVRI*) and epochs, compared to when they are restricted (in the case of the High-z team) to *B* and *V* and epochs less than 40 days after maximum. This was done in Riess et al. (1998) to match the corrections to the available data of the distant supernovae. In particular, the absorption determination in this case suffers from the limited wavelength range.

Another major uncertainty is the reliability with which the light curve correction can be obtained. The distant objects have to be followed several magnitudes below the peak brightness to have a good measure of the light curve shape. This in itself turns the problem from one of measuring faint ($R \approx 23$) objects superposed onto a host galaxy background to one of accurately determining point sources two magnitudes fainter on the same background. Good spatial resolution can greatly improve the photometry of the supernovae (e.g. compare the images presented in Garnavich et al. 1998a with the ones in Riess et al. 1998). Systematic effects are not excluded as the background can 'contaminate' the measurement. A very illustrative example is given by Perlmutter et al. (1998) where the ground-based light curve clearly has a different shape from the one measured with HST. The light curve correction applied for such a supernova could deviate from the correct one and shift its normalization.

If the observed faintness of the distant supernovae has a cosmological origin, then Fig. 1 has a profound impact on our view of the universe, the forces which govern its evolution, and its future. The distant supernovae are then at larger distances than even in a freely coasting universe, i.e., one with a constant expansion rate. The data indicate at the 2σ level an accelerated expansion between a redshift of $z \approx 0.5$ and now. An Einstein-de Sitter model is excluded at 8σ (Riess et al. 1998, Perlmutter et al. 1999a).

To have an accelerated expansion implies that some force is counteracting the gravitational attraction due to the matter in the universe. The most favored proposals currently are the old-fashioned cosmological constant, Λ, (Einstein 1917, Weinberg 1972, Carroll et al. 1992), which is connected in modern particle theories to the energy of the vacuum, or another field with a similar property, specifically a negative pressure, which could evolve in time (Caldwell et al. 1998).

The fact that no solution for a universe with a positive matter density is found clearly points to the need to introduce this extra component in the universe. Using equation 1 probability distributions between Ω_M and Ω_Λ can be derived (e.g. Goobar & Perlmutter 1995, Riess et al. 1998, Perlmutter et al. 1997, 1999a; Fig. 3). Since luminosity distances are roughly a measure of the de- or acceleration, q_0 is degenerate for combinations of Ω_M and Ω_Λ (cf. equation 2; Goobar & Perlmutter 1995). With the current small range of observed redshifts, the probability regions are inclined along $\Omega_\Lambda \approx 1.3\Omega_M + (0.3 \pm 0.2)$ (Perlmutter et al. 1999a). Nevertheless, at face value, the supernova results exclude any world model with matter but without a contribution by a cosmological constant or a similar force.

Note that undetected dust and evolution have the effect of moving the probability region downwards (Riess et al. 1998, Perlmutter et al. 1999a, Drell et al. 2000, Wang 2000), in the direction of smaller Ω_Λ and higher Ω_M. This is equivalent to moving the supernovae closer.

There have been several different statistical treatments and investigations of the supernova data (Drell et al. 2000, Wang 2000, Podariu & Ratra 2000, Gott et al. 2001), testing and questioning various assumptions in the early analyses. Although some of the interpretations tend to increase the error bars, all investigations arrive at the same conclusion: the need for a cosmological constant barring any systematic effect, like dust or evolution (§ 4).

From Fig. 3 it is clear that the supernovae do not provide a good estimate of the individual cosmological parameters, but constrain the region where the parameters lie into a narrow strip in the diagram. This means that estimates of these parameters have to include other measurements. The complementarity of the luminosity distances and angular size measurements, like the CMB, have been pointed out by several authors (White 1998, Eisenstein et al. 1998, Lineweaver 1998, Bahcall et al. 1999).

The supernova result is concordant with other recent determinations of global cosmological parameters (e.g. Lineweaver 1998, Eisenstein et al. 1998, Garnavich et al. 1998b, Turner & Tyson 1999, de Bernardis et al. 2000, Riess 2000). A particularly attractive feature is the relaxation of the constraint of the dynamical age of the universe, which becomes large enough to accommodate the oldest known stars. As can be seen in Fig. 3 the dynamical age $t_0 \times H_0$ is much closer to 1 than to the 2/3 as required by an Einstein-de Sitter model.

4 Alternative explanations

A few alternative interpretations of the supernova result have been proposed. It is conceivable that a combination of these effects can explain part or all of the observed dimming of the distant supernovae. The main contenders right now are evolution of the supernova luminosity and absorption of the SNe Ia by dust. Each of these is discussed in turn, and the tests applied – and their weaknesses – are presented. The final word on some of these tests is still out and will have to await more and improved data. A number of exotic explanations have been brought forward as well. Although I believe that they are unlikely explanations they are presented here for completeness.

The supernova data have been scrutinized in particular for effects of dust (Aguirre 1999a, 1999b, Aguirre & Haiman 2000, Totani & Kobayashi 1999, Totani 2000) and evolution (Drell et al. 2000).

4.1 Evolution

Because we are observing objects that exploded several billion years ago, it is possible that evolution has changed the explosions or their observable outcome. There are two

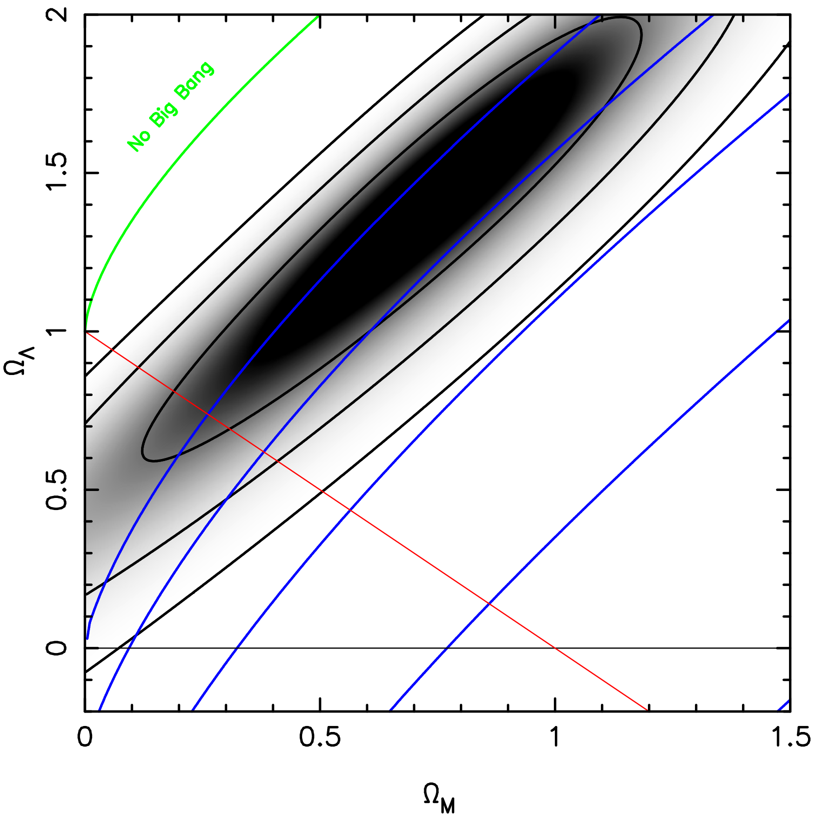

Figure 3: Likelihood region as defined by the SNe Ia in the $\Omega_\Lambda vs.\Omega_M$ plane. A total of 79 SNe Ia have been included in this figure. 27 local and 10 distant SNe Ia from Riess et al. (1998) and 42 objects from Perlmutter et al. (1999). The Δm_{15} method has been used. Contours indicate 68.3%, 95.4%, and 99.7% probability. The region in the upper left corner is excluded for Big Bang models. The line for a flat $(\Omega_M + \Omega_\Lambda = 1)$ universe is indicated. The thin, light gray lines give ages in units of H_0^{-1}. They mark 0.7, 0.8, 0.9 and 1.0 starting from right. Clearly $t_0 \times H_0 \approx 1$ is favored by the supernova data.

different processes which must be considered. The objects themselves may have changed, as is well known for galaxies, or the average properties of the overall sample could have evolved. For the cosmological interpretation a change of the SN Ia peak luminosity is the most important parameter to investigate.

It has been the goal of the observations to check for any differences between the nearby and the distant supernovae and their sample properties (Schmidt et al. 1998, Riess et al. 1998, 2000, Coil et al. 2000). Colors have been determined not only for the estimation of the absorption, but also to investigate the color evolution (Schmidt et al. 1998, Riess et al. 2000). The light curve shape is another important check which only recently has become possible by extending the observations to rest-frame I filters. The characteristic second maximum of the I (and redder) light curves is also present in the distant supernovae indicating that they are similar to their nearby counterparts (Riess et al. 2000). Spectroscopy is a powerful tool to search for differences (Riess et al. 1997, Coil et al. 2000), but the data are not quite good enough to investigate details in line shapes and strengths.

So far the distant SNe Ia resemble the nearby objects in most measured aspects, although some discrepancies have been noted.

4.1.1 Supernova evolution

There have been a few proposals on possible evolutionary changes between distant and nearby objects. Since the favored model consists of a thermonuclear explosion of a Chandrasekhar-mass white dwarf (Woosley & Weaver 1986, Nomoto et al. 1984, Arnett 1996, Hillebrandt & Niemeyer 2000) where the core was incinerated from carbon and oxygen to nuclear statistical equilibrium (mostly iron-group elements; Arnett 1996, Iwamoto et al. 1999, Brachwitz et al. 2000), changes in the nuclear burning physics are not likely. Although this model is not predicting a standard candle behavior – it can explain changes in the production of the ^{56}Ni power source in the explosions (e.g. Hillebrandt & Niemeyer 2000) – it is difficult to see how such a uniform configuration can produce significant systematic changes in the explosion. It should also be noted that there are still several contenders for the explosion models (for recent reviews see Hillebrandt & Niemeyer 2000, Leibundgut 2000a). The explosion physics, in particular the nucleosynthesis, are always the same and should not change as a function of age. However, this is a largely untested assumption so far.

There is one class of explosions, the sub-Chandrasekhar shell detonations (Livne & Glasner 1990, Livne & Arnett 1995, Woosley & Weaver 1994), in which the explosion is triggered in a surface layer, that potentially could produce systematic differences between distant and nearby objects. In this case, the mass of the progenitor could determine the peak luminosity. In these models the more massive explosions are expected to produce brighter supernovae (Arnett 1996, Livne & Arnett 1995). However, because we observe younger progenitors at high redshift, we would expect the distant objects to be on average brighter, which is contrary to the observations.

Most investigations into SN Ia systematics have concentrated on changes in the chemical composition of the progenitor star (Höflich et al. 1998, 2000, Umeda et al. 1999, Kobayashi et al. 2000). Here the composition of the fuel (carbon and oxygen) could potentially change the energy of the explosion.

These changes could be caused by the different age of the progenitor systems or an altogether different progenitor evolution. Since there is little known about the progenitors, theoretical investigations are difficult. However, it could be argued that since the nearby supernovae emerge from progenitors of all ages, the observed range should encompass all possible explosion configurations with the normalization applied through the corrections being universal. Calculations of the effect on the spectrum, however, indicate that there would be almost no change at the observed wavebands (Höflich et al. 1998).

A recent claim that the rise times to maximum for distant objects is different than for the nearby ones (Riess et al. 1999b) has been contested on statistical grounds (Aldering et al. 2000). The rise times for the distant SNe Ia appear about 2 days shorter (Riess et al. 1999b, Aldering et al. 2000), but the statistical uncertainties are near 1.2 days.

Another discrepancy emerging is the color of the distant objects. Figure 2 demonstrates what had been pointed out by Falco et al. (1999): the distant SNe Ia appear clearly bluer than the nearby objects. The significance of this change is not yet obvious. In the nearby samples, the bluer objects at maximum are typically the brighter ones (Phillips et al. 1999). Figure 2 has been corrected for the light curve shape dependence, yet the distant objects are still bluer. Further indications of this effect were also seen in the $B-I$ color of SN 1999Q at z=0.46 (Riess et al. 2000).

Should the intrinsic color for higher redshift supernovae indeed be bluer, then the derived reddening based on the colors of the nearby supernovae would be underestimated even for a galactic absorption law (cf. discussion in § 4.2). This means that the derived distances would be too small for the observed brightness.

It has also been argued that the color at maximum is governed by the opacity, which in turn depends on the temperature of the supernova (Pinto & Eastman 2000). This explanation had been invoked to explain why the brighter objects have a slower evolution (Höflich et al. 1996). However, the distant and nearby sample of SNe Ia agree very well in their light curve shapes. If the colors of the distant objects indeed are bluer, then we have a clear deviation from one of the established correlations for nearby SNe Ia, namely between the color and light curve shape (e.g. Hamuy et al. 1996a, 1996d, Phillips et al. 1999). The light curve shape dependence is observed in the High-z sample, but it is apparently absent in the published SCP sample. It should be noted that these measurements are difficult to attain. The light curve shape can only be determined with observations when the supernovae are fading into the glare of their host galaxies. Obtaining reliable colors is also becoming more difficult with increasing redshifts as the rest frame V light moves into the near infrared where the brightness of the night sky increases substantially. Future observations will have to address this point in much more detail than what has been possible so far.

Although many salient points are raised, none of them is compelling at the moment. The simple inclusion of evolution as a free parameter in the fitting necessarily broadens the probability distribution in the Ω_M–Ω_Λ plane, as this additional parameter tries to take up the apparent faintness of the distant supernovae.

4.1.2 Sample evolution

A slightly different effect comes from a changing composition of the nearby and the distant sample. For a perfect standard candle there would, of course, be no such effect, but since one is dealing with corrections and a non-negligible distribution in luminosity, the composition of the samples is important. In this case, not the supernovae change but the mean quantities may shift because of a different composition of the sample. This is different from other sample effects, such as Malmquist bias. An example would be that the relative frequency of bright and faint SNe Ia would change as a function of redshift. The luminosity corrections can compensate for all obvious and known effects, such as morphology of the parent galaxy (Schmidt et al. 1998), but more subtle discrepancies still have to be investigated.

The most thorough study so far has been carried out by Drell et al. (2000), in which several observable quantities have been compared. In particular, differences in the distances and absorption values for individual, distant supernovae are interpreted as due to the correction methods being sensitive to subtle physical effects. It can be shown, however, that the nearby sample alone shows large deviations of the decline parameter for the same supernovae, which indicates a problem of robustness between the methods (Leibundgut 2000a). In addition, the claim that the distant SNe are not as luminous as the nearby ones (Drell et al. 2000) is not supported by the data. The overall range of luminosities appears indeed smaller for the distant SNe Ia, but the scatter is not necessarily smaller and the result still depends on only a small number of distant objects (cf. Drell et al. 2000). The overall distribution of the decline parameters is similar for the nearby and the distant samples (Riess et al. 1998, Perlmutter et al. 1999a) and there is no obvious discrepancy. The other effect claimed by Drell et al. (2000) is a change in the absolute luminosity from the nearby to the distant supernovae. Their comparison of the two samples seems to demonstrate a lack of faint distant supernovae. This is to be expected as the distant supernovae are selected from a magnitude limited sample and only the more luminous objects are found.

A striking discrepancy is that none of the very slowly declining and, hence, very luminous objects observed in the nearby sample have been discovered at large distances. Objects like SN 1991T (Filippenko et al. 1992, Phillips et al. 1992) have not been observed so far in the distant sample. This is clearly contrary to what is expected from a Malmquist bias and points to some changes in the relative rates of these particular SNe Ia.

If the age of the supernova progenitor is an important parameter for the explosion, we could expect that we observe predominantly supernovae coming from younger progenitor systems at high redshifts. This could mean that we are not observing the full range in luminosity, which seems to be indicated by the above statement that we are not detecting the most luminous SNe Ia at large distances. But the normalization appears to remove such sampling discrepancies successfully.

The power of the light curve shape corrections is that they remove most of these sample issues by normalizing the nearby and distant supernovae to the same luminosity. This in itself assumes of course that there was no change of the light curve shape *vs.* luminosity relation as a function of redshift. So far, no such change has been observed, but we must remain vigilant for any signs of such a variation.

4.2 Dust

Intervening dust particles scatter and absorb light and can decrease the brightness of an object behind the dust screen. The treatment of dust has been a most difficult and thorny endeavor in astronomy. Understanding dust absorption is at the heart of many astrophysical problems and the distant supernovae are no exception. The small magnitude offset observed for the distant SNe Ia can easily be explained by a small change in the reddening law and, hence, the dust properties.

A full understanding of the reddening of nearby SNe Ia (or galaxies in general) has not been achieved yet. Two groups have tried to derive the reddening law, rather than adopt the Galactic reddening, and have reached slightly different results. In one case a standard reddening law has been measured by assuming that all SNe Ia show the same color evolution from about 30 to 90 days after maximum (corresponding roughly to 50 and 110 days after explosion), when the supernova has turned optically thin and the cooling ashes are observed (Phillips et al. 1999). At that phase the supernova is powered by the radioactive decay of ^{56}Co and the temperature evolution should be very similar for all objects. This makes the assumption of a unique color for these objects well justified. At the same time the color changes more slowly than at maximum making the measurement more reliable. This method derived a 'standard' reddening law for the SNe Ia in the local universe (Phillips et al. 1999). Another study explored the color near maximum and found slight deviations from the standard law (Riess et al. 1996). It has become customary to adopt an intrinsic color for SNe Ia (e.g. $(B-V)_0 = -0.05 \pm 0.012$; Phillips et al. 1999, $B-V)_0 = -0.012 \pm 0.05$; Parodi et al. 2000).

It is essential to measure the colors of distant supernovae to have any indication of reddening. The colors are then used to correct for any absorption using a standard reddening law. The two basic assumptions here are a standard absorption and no color evolution. Since there is also a dependence of the color on light curve shape (e.g. Riess et al. 1996, 1998, Tripp 1998, Phillips et al. 1999) and the distant objects have to be corrected for the redshift, the absorption is now determined together with the K-correction and the light curve shape (Riess et al. 1998, Perlmutter et al. 1999a).

4.2.1 Intergalactic dust

The hypothesis that small changes in the average size of the dust grains affects the distant supernovae has been explored in a series of papers (Aguirre 1999a, 1999b, Aguirre & Haiman 2000). The basic assumption is that there is a way to distribute dust from the production sites in galaxies more or less uniformly into intergalactic space. In this process, the minimum size of the dust grain is increased to about 0.1μm (for a graphite and silicate mixture), which makes the dust opacity sufficiently wavelength independent ('gray') to have gone unnoticed in the current observations of the distant SNe Ia.

It should be noted that deviations from the Galactic reddening law have been observed. A sample of nearby starburst galaxies, e.g., shows a clearly smaller selective to total extinction in the optical than what is observed in the Galaxy (Calzetti 1997). Other, although still rather preliminary, examples are measurements of absorption in lensing galaxies (Falco et al. 1999).

Given the star formation histories currently favored (e.g. Madau et al. 1996, Steidel et al. 1999), not enough metals are observed in gas and stars of galaxies. At the same time, the hot gas in clusters of galaxies is rich in metals (particularly iron; Renzini 1997). The idea is then to bind the metals in dust and strip it from the galaxies by either radiation pressure, superwinds produced by core-collapse supernova explosions, or galaxy mergers (Aguirre 1999b). Small grains can be destroyed by sputtering in the interstellar medium and the intergalactic gas. This would remove grains smaller than about 0.05μm. Radiation pressure is the favored mechanism as the shocks in the superwinds and the mergers preferentially destroy larger grains. The wavelength dependence of silicates and graphites is a strong function of the minimal grain sizes and by removing the small grains gray dust can be produced with a lower cutoff of about 0.1μm. Such dust could make the supernova data consistent with an open universe, but not an Einstein-de Sitter model (Aguirre 1999b). An important consequence of such gray dust would be a strong far-infrared background as the radiation is thermalized (Aguirre & Haiman 2000). The recent detection of a diffuse FIR background (Puget et al. 1996, Fixsen et al. 1998, see Hauser and Dwek, this volume) limits the amount of dust that could be responsible for this emission. This upper limit is further reduced by the detection of resolved sources at sub-mm wavelengths (Barger et al. 1999). There is still some margin left for intergalactic dust, enough to explain an open universe with the SN Ia data, but future sub-mm surveys could further reduce this as more resolved sources are discovered (Aguirre & Haiman 1999).

Improved observations of distant supernovae can also resolve this issue. With an increased wavelength base, the effects even of gray dust will become detectable. By observing rest-frame *UBVRI* light curves, we can check for the influence of gray dust. A prototype analysis of a single object, SN 1999Q, has indicated that the influence of gray dust is small, although a conclusive result could not be derived (Riess et al. 2000). Future multi-wavelength observations of distant SNe Ia will provide an answer to this critical issue.

4.2.2 Chemical evolution of dust

Chemical evolution is clearly observed to higher redshifts (e.g. Lu et al. 1996, Pettini et al. 1997, 2000) and it is not inconceivable that the dust properties have changed as well between z=0.5 and now. In fact, such a change is expected and a simple model predicts an average change of $A_B \approx 0.1$ to 0.2 mag over this range (Totani & Kobayashi 1999). This is just about the difference by which the distant SNe Ia appear dimmer. However, this effect only works in cases where no reddening correction is attempted (Perlmutter et al. 1997, 1999a) and can not explain the faintness of a sample where the colors have been used to estimate the amount of absorption (Riess et al. 1998). The criticism of the latter sample is that the reddening determination is uncertain (not better than 10% for individual supernovae) and with the small sample, systematic effects could not be measured. While this is true to some degree, a convincing explanation how the systematics could creep into the measurements still must be found. One possible example could be the fact that the rest-frame V photometry is often not as frequent as the rest-frame B data (cf. Riess et al. 1998; their Fig. 3) and hence, the color determination could suffer some systematic shift that is not present for the nearby SN sample. Such an effect, however, still must be demonstrated.

It should be noted also that most distant SNe Ia are on average at larger distances from their galaxy centers than are nearby ones (e.g. Howell et al. 2000). There are two reasons for this. Strongly absorbed distant SNe Ia are less likely to be detected in the searches and hence do not enter the sample. Also, the spectroscopic observations for the classification of the SNe concentrate on well-separated objects to limit the contamination from the host galaxy. At the large galactocentric distances, absorption is expected to play much less of a role. This is partially supported by the reddening determinations of Riess et al. (1998), where only two objects with significant absorption have been identified. Of course, the blue colors are another indication of little, if any, reddening for most distant SNe Ia. In a few cases, no host galaxy has been detected for the distant SNe.

Since the distant SNe Ia appear bluer (Fig. 2) the dust explanations are less appealing at the moment. Only if they are coupled with evolution (cf. § 4.1) could any form of known or proposed dust also become a viable explanation for the faintness of the distant SNe Ia.

4.3 Gravitational lensing

As the supernova light propagates through the universe to the observer, it can be deflected by massive objects. The gravitational lensing effect is well know and studied (e.g. Blandford & Narayan 1992, Mellier 2000). Any object at a considerable distance will suffer to some degree from gravitational lensing. For the supernovae, any brightness bias that is introduced by lensing could change the cosmological conclusions. As it turns out, most distant sources are dimmed as light is scattered out of the line of sight and only very few objects near deep potential wells are amplified (Kantowski et al. 1995, Wambsganss et al. 1997). Any systematic shift of the peak brightness of distant SNe Ia could explain the observed faintness of the distant objects (Kantowski et al. 1995). Note that this effect should also increase the observed scatter in peak luminosity, if significant.

The influence of gravitational lensing is the only one that can not be measured directly from supernova observations. The crucial quantity is how much matter is locked in compact objects. In the extreme case where all matter is clumped in macroscopic objects, the effect is strongest and leads to a general de-amplification of all distant objects of 0.15 magnitudes for objects at z=0.5 and a universe with Ω_M=1 (Holz & Wald 1998). For more realistic cases, where the matter is clumped on galaxy scales, the effect is diminished but results in a widening of the probability contours for Ω_M and Ω_Λ (Holz 1998). In universes where the matter is distributed continuously, the distant supernovae are not affected strongly ($<$4% at z=1; Wambsganss et al. 1997, Holz 1998, Metcalf 1999). This has been the assumption in the derivation of the results presented in § 3.

4.4 Exotic explanations

The interpretation of the supernova results are based on our current understanding of astrophysics and cosmology. The previous alternative explanations focused on the astrophysical assumptions. The supernova results can, of course, also be interpreted in world models that are based on assumptions deviating from the Friedmann models. The main motivation for these approaches is to explain the faintness of the distant supernovae without a cosmological constant.

One of the fundamental assumptions of the Friedman models is their homogeneity and isotropy. Giving up one of these assumptions means that it is possible to fit the supernova result in a different way. This has been done for the case of a Lemaître-Tolman-Bondi model and other inhomogeneous models (Célérier 2000). In these models the universe is inhomogeneous out to scales of at least $z\approx1$ to accommodate the supernova data but not to conflict with CMB measurements. First analyses which try to investigate the supernova samples in different directions on the sky seem to indicate, however, that the cosmological isotropy is supported by those data (Kolatt & Lahav 2001).

In a quasi-steady state cosmology a combination of acceleration due to the formation of matter and the particular gray dust proposed by Aguirre (1998) can reproduce the supernova observations (Banerjee et al. 2000). Because this world model has an oscillating scale parameter the supernova result would not be extraordinary in such a framework.

Changing the value of physical constants, such as the gravitational constant, the fine-structure constant, the speed of light, or the value of Planck's constant, can of course have dramatic effects on the results. If indications of a varying fine-structure constant α (Webb et al. 1999) are confirmed (but see Carilli et al. 2000), then the observed value of the cosmological constant may be explainable in some theories, in which the speed of light varies (Barrow & Magueijo 2000). In such a theory, the fact that c was larger in the past mimics the effect of a larger distance. Since $\alpha = \frac{e^2}{\hbar c}$, where e is the electron charge and

$\hbar$ Planck's constant, a change of c also changes α. However, the suggested change in the fine-structure constant is far too small to explain the apparent acceleration as a change in the speed of light with time (Barrow & Magueijo 2000). For a consistent interpretation the theory of gravity has to be changed.

5 Combination with other cosmological measurements

The degeneracy of the cosmological parameters Ω_M and Ω_Λ as measured through luminosity distances is orthogonal to the one from angular-size distances measured by the cosmic microwave background (Zaldarriaga et al. 1997, White 1998, Eisenstein et al. 1998). The power of such combined analyses has been amply demonstrated (Lineweaver 1998, Garnavich et al. 1998b, Efstathiou et al. 1999, Bahcall et al. 1999, Turner & Tyson 1999).

The combination of the supernova measurements with results from the CMB fluctuations and determinations of the mass density from galaxy clusters and flow fields has turned out to be a powerful tool to constrain Ω_M and Ω_Λ. It is the complementarity of the three measurements that provides such strong constraints. These measurements are completely independent, use different astrophysical objects, are applied at largely different scales, and constrain the cosmological parameters in different ways. Any combination of two out of the three measurements in itself requires a cosmological constant (e.g. Turner & Tyson 1999, Bahcall et al. 1999).

The combination of Ω_M and Ω_Λ favored by these measurements has an additional nice feature. The dynamical age $t_0 \times H_0$ is close to one (Figure 3) and, depending on the Hubble constant, ages from 12.5 ($H_0 = 75$ km s^{-1} Mpc^{-1}) to 17 Gyr ($H_0 = 55$ km s^{-1} Mpc^{-1}) are derived. These are all comfortably larger than the currently oldest stellar components of the universe (Vandenbergh et al. 1996, Chaboyer et al. 1998).

With a flat universe, as favored by the CMB measurements, the SN result can further be used to evaluate the equation of state parameter of the universe (White 1998, Garnavich et al. 1998b, Perlmutter et al. 1999b, Wang & Garnavich 2001). In a generalized form the luminosity distance can be derived for any energy component present in the universe (e.g. Schmidt et al. 1998). The equation of state, i.e. the dependence of pressure and density, of each of these energy forms determines their contribution to the cosmological model. The equation-of-state parameter $\omega = \frac{p}{\rho}$, where p is the pressure and ρ the energy density, is used to characterize the different components. Non-relativistic matter is pressure-less and has $\omega = 0$. Relativistic matter, like radiation, has $\omega = \frac{1}{3}$. The cosmological constant has $\omega = -1$, which carries the sign of a repulsive force. Some forms of topological defects (textures and strings) have negative ω as well.

The current SNe Ia data constrain the overall ω to values below $-\frac{1}{3}$ (Garnavich et al. 1998b, Perlmutter et al. 1999b, Efstathiou 1999, Wang & Garnavich 2001). This is a direct derivative from the accelerated expansion. The goal post has in the meantime been shifted again. Given the current propositions, we would like to be able to distinguish between a pure cosmological constant and some form of 'quintessence.' For a decaying scalar field the equation of state parameter should change over time and become observable as a function of redshift provided the measurements can be made accurately enough (Saini et al. 2000, Wang & Garnavich 2001, but see Maor et al. 2000).

The apparent size of the cosmological constant in a flat universe raises difficult questions about our picture of particle physics. The cosmological constant acts like a vacuum density, but in particle physics, the energy scales are all orders of magnitude larger than suggested by the supernova measurements (e.g. Carroll et al. 1992, Straumann 1999). This is one of the main reasons to move to 'quintessence'-type models. However, the two proposals correspond to completely different physical interpretations of the observations. The cosmological constant is an extension to the field equations of general relativity (Einstein 1917), while the 'quintessence' field is an addition to the energy-momentum tensor in these equations. One is an extension of the theory while the other postulates a new particle component.

The size of Ω_Λ is another puzzle when one considers that Ω_M is proportional to $(1+z)^3$. This means that the relative contribution changes by a large factor for relatively small changes in redshift. The decelerating contribution of Ω_M to the expansion of the universe is decreasing rapidly and will be negligible very soon. This has been another argument to favor decaying particle fields that could be tuned with appropriate forms for the particle potential. However, this does not provide an explanation for these potential forms.

6 Outlook

The observations of Type Ia Supernovae out to redshifts of about 1 have provided tantalizing evidence for an accelerated expansion of the universe. Although there are so far no strong indications that this measurement may be flawed, it requires more rigorous testing. In particular, any questions about supernova evolution will have to be tackled and answered. Dust appears to be a less likely explanation, considering the overall trend to bluer rest-frame colors of the distant SNe Ia (cf. section 2). A very powerful test is of course the observation of the early deceleration due to matter and the transition when the universe turned to an accelerated expansion. For a flat universe with about $\Omega_M \sim 0.3$ this should occur near $z = 0.8$ (Riess et al. 1998, Leibundgut 1999, Riess 2000, cf. Fig. 1). Although the first SNe Ia have been observed above $z = 1$ (Aldering 1998, Tonry et al. 1999, Gilliland et al. 1999, Coil et al. 2000) they have not yet been published on a Hubble diagram. Future campaigns will have to concentrate on these redshift ranges.

Such a non-monotonic behavior of the derived luminosity distances would be difficult to explain by other first-order effects. Evolution would have to be tuned to mimic such a behavior. Also dust and its distribution would have to change in a very particular fashion, but would be completely excluded, if SNe Ia are observed relatively brighter again at $z>1$. Although it is possible to imagine such scenarios, they would be contrived.

Should such a turnover not be observed, the supernova cosmology will have to be reexamined even more carefully and with a very critical eye. The non-monotonic evolution is a solid prediction and can become the 'smoking gun' for supernova cosmology.

This is also a critical redshift range for the distinction between a cosmological constant and other forms of 'dark energy.' The predictions for time-dependent contributions to the dark energy depend on the exact form of the potential of the scalar field and may have turnovers at different redshifts. Overall, the requirement that the contribution of the dark energy be small and only significant now, however, will provide only small diversions from the predictions of a pure cosmological constant out to $z \approx 1$. It is not yet clear whether large samples of supernovae can determine such a time-dependent effect. Although some people believe that it will be possible to measure a temporal change of the equation of state parameter (Saini et al. 2000, Chiba & Nakamura 2000, Podariu et al. 2001, Weller & Albrecht 2001, Wang & Garnavich 2001) others do not (Maor et al. 2001). These studies all assume that a large sample of well-observed supernovae will become available. A proposal to obtain several thousand SN Ia light curves with a dedicated satellite, the SuperNova Acceleration Probe (SNAP) has been made (Deustua et al. 2000). Such a large and homogeneous data set with supernovae distributed over a considerable range of redshifts can be used to map out the exact form of the acceleration for a significant fraction of the history of the universe.

There are many open questions regarding the supernova physics and they will have to be addressed in the near future (e.g. Leibundgut 2000a). SNe Ia show significant differences in the nickel masses synthesized in the explosions and their radiation transport problem is largely not understood. As long as we do not understand the explosions better, there remain doubts whether the standard candle behavior of SNe Ia also holds at high redshifts. The small measured luminosity range after normalization, i.e. their small scatter around the Hubble line in the linear portion of the Hubble diagram, gives strong empirical indications that they are very useful and reliable distance indicators (Branch & Tammann 1992, Tammann & Sandage 1995, Hamuy et al. 1996b, Riess et al. 1996, Perlmutter et al. 1997, Phillips et al. 1999, Suntzeff et al. 1999, Jha et al. 1999, Saha et al. 1999, Parodi et al. 2000, Hernandez et al. 2000).

From the above it is clear that some of the most fundamental advances in the question of supernova cosmology will be made by observing nearby bright objects. With the explosions on a better theoretical basis and the radiation physics understood our confidence in the cosmological measurements should improve considerably. The observations of the distant objects will not improve dramatically until larger telescopes become available. It is only with the next generation large ground-based telescope that we will be able to make detailed physical investigations of the distant objects. NGST should greatly extend the sensitivity into the near-infrared region, which is severely hampered by the bright sky background from the ground. It will discover and observe many more distant supernovae over an extended redshift range (e.g. Dahlén & Fransson 1999).

Another possible application of distant SNe Ia is the determination of the nature of dark matter. The distribution of the lensing magnification can tell us on which scales the dark matter is clumped. With an established peak luminosity of SNe Ia, the magnifications can be determined individually. This, in principle, could be a powerful method (Metcalf & Silk 1999), which could only be achieved with SNe Ia. However, this assumes that all evolutionary and other astrophysical effects are well understood and can either be ignored or corrected.

Supernovae at high redshifts are further important stellar tracers into the early universe. As such they can provide important information on the star formation history (Ruiz-Lapuente & Canal 1998, Madau et al. 1998, Dahlén & Fransson 1999, Nomoto et al. 2000). Currently we have no knowledge of supernova rates outside the local universe. Attempts have been made (Pain et al. 1996, Reiss 2000, Hardin et al. 2000), but they are very limited and can not constrain the models. The predictions are tightly bound to the cosmic star formation rate. The core-collapse supernovae, with their 'short fuse,' should be a near-immediate tracer of the formation of massive stars. An exciting proposition to observe core-collapse supernovae at very high redshifts ($z > 3$) has been made by Chugai et al. (2000), who proposed to observe the shock breaking out at the surface of these giant stars. These are the brightest moments of a core-collapse supernova and the UV radiation is shifted into the optical range at these redshifts. Time dilation will further prolong the appearance of this shock from about a day to a few days.

The research with distant supernovae has just started. The cosmological measurements need refinement and verification. Just increasing the sample of distant supernovae will not contribute much over the current knowledge. Future campaigns will have to target specific questions, like gray dust and evolution, or try to find the relatively brighter SNe Ia above $z \approx 1$. Eventually, we will have to find the answer to what really drives the expansion of the universe. If the cosmological constant is indeed correct, we are left with a vacuum energy incompatible with the predictions of current particle physics theories. For a particle field like the proposed 'quintessence,' we face the problem that we keep introducing more and more particles without a direct identification in the observed world. The mystery described in Carroll et al. (1992) has not been solved with the apparent cosmic acceleration. Rather, it has deepened.

Acknowledgements

Much of this exciting work has been done by the High-z Supernova Search Team and the Supernova Cosmology Project. The continuous discussion within the High-z SN Team as well as with members of the SCP are gratefully acknowledged. Comments on the manuscript by Jesper Sollerman, Jason Spyromilio, Alex Filippenko, and Allan Sandage have improved the presentation considerably. I would like to thank Adam Riess for substantial help in preparing Figure 3. Parts of this review have been written during stays at the Leiden Observatory and the European Center for Theoretical Studies in Nuclear Physics and Related Studies in Trento. I thank George Miley, Marijn Franx and Wolfgang Hillebrandt for their support.

References

Aguirre, A.N. 1999a. *Ap. J.* 512:L19–22

Aguirre, A.N. 1999b. *Ap. J.* 525:583–593

Aguirre, A.N., Haimann, Z. 2000. *Ap. J.* 532:28–36

Aldering, G., Knop, R., Nugent, P. 2000. *Astron. J.* 119:2110–2117

Aldering, G. 1998. IAU Circ. 7046

Arnett, D. 1996. *Supernovae and Nucleosynthesis. An investigation of the history of matter, from the Big Bang to the present.* Princeton: Princeton University Press

Bahcall, N.A., Ostriker, J.P., Perlmutter, S., Steinhardt, P.J. 1999. *Science* 284:1481–1488

Banerjee, S.K., Narlikar, J.V., Wickramasinghe, N.C., Hoyle, F., Burbidge, G. 2000. *Astron. J.* 119:2583–2588

Barger, A.J., Cowie, L.L., Sanders, D.B. 1999. *Ap. J.* 518:L5–8

Barrow, J.D., Magueijo, J. 2000. *Ap. J.* 532:L87–90

Bender, R., Saglia, R.P., Ziegler, B., Belloni, P., Greggio, L., Hopp, U., Bruzual, G. 1998. *Ap. J.* 493:529–535

Blandford, R.D., Narayan, R. 1992. *Annu. Rev. Astron. Astrophys.* 30:311–358

Bowers, E.J.C., Meikle, W.P.S., Geballe, T.R., Walton, N.A., Pinto, P.A., Dhillon, V.S., Howell, S.B., Harrop-Allin, M. K. 1997. *MNRAS* 290:663–679

Brachwitz, F., et al. 2000. *Ap. J.* 536:934–947

Branch, D. 1998. *Annu. Rev. Astron. Astrophys.* 36:17–55

Branch, D., Livio, M., Yungelson, L. R., Boffi, F. R., Baron, E. 1995. *Pub.Ast.Soc.Pac.* 107:1019–1029
Branch, D., Romanishin, W., Baron, E. 1996. *Ap. J.* 465:73–78 (Erratum:*Ap. J.* 467:473–474)
Branch, D., Tammann, G.A. 1992. *Annu. Rev. Astron. Astrophys.* 30: 359–389
Caldwell, R.R., Dave, R., Steinhardt, P.J. 1998. *Phys. Rev. Lett.* 80:1582–1585
Calzetti, D. 1997. *Astron. J.* 113:162–184
Cappellaro, E., Mazzali, P.A., Benetti, S., Danziger, I.J., Turatto, M., Della Valle, M., Patat, F. 1997. *Astron. Astrophys.* 328:203–210
Carilli, C.L., et al. 2000. *Phys. Rev. Lett.* 85:5511–5514; Erratum. 2001. *Phys. Rev. Lett.* 86:1910
Carroll, S.M., Press, W.H., Turner, E.L 1992. *Annu. Rev. Astron. Astrophys.* 30:499–542
Célérier, M.-N. 2000. *Astron. Astrophys.* 353:63–71
Chaboyer, B., DeMarque, P., Kernan, P. J., Krauss, L. M. 1998. *Ap. J.* 494:96–110
Chiba, T., Nakamura, T. 2000. *Phys. Rev. D* 62:121301
Chugai, N.N., Blinnikov, S.I., Lundqvist, P. 1999. In *Future Directions of Supernova Research: Progenitors to Remnants,* eds. S. Cassisi and P. Mazzali, Mem. Soc. Astr. It. 71:383–88
Clayton, D. D. 1974. *Ap. J.* 188:155–157
Coil, A.L., et al. 2000. *Ap. J.* 544:L111–114
Colgate, S.A. 1979. *Ap. J.* 232:404–408
Colgate, S.A., McKee, C. 1969. *Ap. J.* 157:623–644
Contardo, G., Leibundgut, B., Vacca, W.D. 2000. *Astron. Astrophys.* 359:876–886
Dahlén, T., Fransson, C. 1999. *Astron. Astrophys.* 350:349–367
de Bernardis, P., et al. 2000. *Nature* 404:955–959
Deustua, S.. et al. 2000. AAS Abstract 196:3212
Drell, P.S., Loredo, T.J., Wasserman, I. 2000. *Ap. J.* 530:593–617
Efstathiou, G. 1999. *MNRAS* 310:842–850
Efstathiou, G., Bridle, S.L., Lasenby, A.N., Hobson, M.P., Ellis, R.S. 1999. *MNRAS* 303:L47–52
Einstein, A. 1917. *Sitzungsber. Königl. Preuss. Akad. Wiss.* 142–152
Eisenstein, D.J., Hu, W., Tegmark, M. 1998. *Ap. J.* 504:L57–60
Falco, E.E., et al. 1999. *Ap. J.* 523:617–632
Ferguson, H.C., Dickinson, M., Williams, R. 2000. 38:667–715
Filippenko, A. V. 1989. *Pub.Ast.Soc.Pac.* 101:588–593
Filippenko, A. V. 1997. *Annu. Rev. Astron. Astrophys.* 35:309–355
Filippenko, A. V., Riess, A. G. In *Particle Physics and Cosmology: Second Tropical Workshop*, ed. J. F. Nieves, pp. 227–246. New York: American Institute of Physics
Filippenko, A. V., et al. 1992. *Ap. J.* 384:L15–18
Fixsen, D.J., Dwek, E., Mather, J.C., Bennett, C.L., Shafer, R.A. 1998. *Ap. J.* 508:123–128
Freedman, W.L., et al. 2001. *Ap. J.* 553:47–72
Garnavich, P.M., et al. 1998a. *Ap. J.* 493:L53–57
Garnavich, P.M., et al. 1998b. *Ap. J.* 509:74–79
Germany, L.M., Reiss, D.J., Sadler, E.M., Schmidt, B.P., Stubbs, C.W. 2000. *Ap. J.* 533:320–328
Gibson, B.K., Stetson, P.B. 2000. *Ap. J.* 547:L103–106
Gibson, B.K., et al. 2000. *Ap. J.* 529:723–744
Gilliland, R.L., Nugent, P.E., Phillips, M.M. 1999. *Ap. J.* 521:30–49
Goldhaber, G., et al. 1997. In *Thermonuclear Supernovae,* eds. P. Ruiz-Lapuente, R. Canal, J. Isern, pp. 486:777–784. Dordrecht: Kluwer
Goldhaber, G., et al. 2001. *Ap. J.* , in press (astro-ph/0104382)
Goobar, A., Perlmutter, S. 1995. *Ap. J.* 450:14–18
Gott, J.R., Vogeley, M.S., Podariu, S., Ratra, B. 2001. *Ap. J.* 549:1–17
Hamuy, M., Phillips, M.M., Wells, L.A., Maza, J. 1993. *Pub.Ast.Soc.Pac.* 105:787–793
Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., Avilés, R. 1995. *Astron. J.* 109:1–13
Hamuy, M., Phillips, M. M., Schommer, R. A., Suntzeff, N. B., Maza, J., Avilés, R. 1996a. *Astron. J.* 112:2391–2397
Hamuy, M., Phillips, M. M., Suntzeff, N. B., Schommer, R. A., Maza, J., Avilés, R. 1996b. *Astron. J.* 112:2398–2407
Hamuy, M., et al. 1996c. *Astron. J.* 112:2408–2437

Hamuy, M., Phillips, M. M., Suntzeff, N. B., Schommer, R. A., Maza, J., Smith, R. C., Lira, P., Avilés, R. 1996d. *Astron. J.* 112:2438–2447
Hamuy, M., Trager, S.C., Pinto, P.A., Phillips, M.M., Schommer, R.A., Ivanov, V., Suntzeff, N.B. 2000. *Astron. J.* 120:1479–1486
Hansen, L., Jørgensen, H.E., Nørgaard-Nielsen, H.U., Ellis, R.S., Couch, W.J. 1989. *Astron. Astrophys.* 211:L9–11
Hardin, D., et al. 2000. *Astron. Astrophys.* 362:419–425
Harkness, R.P., Wheeler, J.C. 1990. In *Supernovae*, ed. A.G. Petschek, 1–29. New York: Springer
Heckmann, O. 1942. *Theorien der Kosmologie.* Berlin: Springer
Hernandez, M., et al. 2000. *MNRAS* 319:223–234
Hillebrandt, W., Niemeyer, J.C. 2000. *Annu. Rev. Astron. Astrophys.* 38:191–230
Höflich, P., Khokhlov, A.M., Wheeler, J.C., Phillips, M.M., Suntzeff, N.B., Hamuy, M. 1996. *Ap. J.* 472:L81–84
Höflich, P., Nomoto, K., Umeda, H., Wheeler, J. C. 2000. *Ap. J.* 528:590–596
Höflich, P., Wheeler, J.C., Thielemann, K.-F. 1998. *Ap. J.* 495:617–629
Holz, D.E. 1998. *Ap. J.* 506:L1–5
Holz, D.E., Wald, R.M. 1998. *Phys. Rev. D* 58:063501
Howell, D.A., Wang, L., Wheeler, J.C. 2000. *Ap. J.* 230:166–171
Hoyle, F., Sandage, A. 1956. *Pub.Ast.Soc.Pac.* 68:301–307
Humason, M. L., Mayall, N. U., Sandage, A.R. 1956. *Astron. J.* 61:97–161
Iwamoto, K., Brachwitz, F., Nomoto, K., Kishimoto, N., Umeda, H., Hix, W.R., Thielemann, R.-K. 1999. *Ap. J. Suppl.* 125:439–462
Jha, S., et al. 1999. *Ap. J. Suppl.* 125:73–97
Kamionkowsi, M., Kosowsky, A. 1999. *Annu. Rev. Nucl. Part. Sci.* 49:77–123
Kantowski, R., Vaughan, T., Branch, D. 1995, *Ap. J.* 447:35–42
Kim, A., Goobar, A., Perlmutter, S. 1996. *Pub.Ast.Soc.Pac.* 108:190–201
Kobayashi, C., Tsujimoto, T., Nomoto, K. 2000. *Ap. J.* 539:26–38
Kolatt, T.S., Lahav, O. 2001. *MNRAS* 323:859–864
Leibundgut, B. 1990. *Astron. Astrophys.* 229:1–6
Leibundgut, B. 1999. In *Supernovae and Cosmology*, eds. L. Labhardt, B. Binggeli, R. Buser, pp. 61–74. Basel: University of Basel
Leibundgut, B. 2000a. *Astron. Astrophys. Rev.* 10:179–209
Leibundgut, B. 2000b. in *From Extra-Solar Planets to Cosmology: The VLT Inaugural Symposium*, ed. J. Bergeron, A. Renzini, pp. 43–51. Heidelberg: Springer
Leibundgut, B., et al. 1996. *Ap. J.* 466:L21–L24
Li, W., et al. 1999. *Astron. J.* 117:2709–2724
Li, W., Filippenko, A.V., Treffers, R.R., Riess, A.G., Hu, J., Qiu, Y.L. 2001. *Ap. J.* 546:719–733
Livio, M., Panagia, N., Sahu, K. (ed.) 2000. *Supernovae and Gamma-Ray Bursts*, Cambridge: Cambridge University Press
Livio, M.: 1999. In *Type Ia Supernovae: Theory and Cosmology*, eds. J.C. Niemeyer, J.W. Truran, pp. 33–48. Cambridge: Cambridge University Press
Livne, E., Arnett, D. 1995. *Ap. J.* 452:62–74
Livne, E., Glasner, A. 1990. *Ap. J.* 361:244–250
Lineweaver, C.H. 1998. *Ap. J.* 505:L69–73
Lu, L., Sargent, W.L.W., Barlow, T.A., Churchill, C.W., Vogt, S.S. 1996. *Ap. J. Suppl.* 107:475–519
Madau, P., Della Valle, M., Panagia, N. 1998. *MNRAS* 297:L17–22
Madau, P., Ferguson, H.C., Dickinson, M.E., Giavalisco, M., Steidel, C.C., Fruchter, A. 1996. *MNRAS* 283:1388–1404
Mannucci, F., Ferrara, A. 1999. *MNRAS* 305:L55–58
Maor, I., Brustein, R., Steinhardt, P.J. 2000. *Phys. Rev. Lett.* 86:6–9
Mather, J., et al. 1990. *Ap. J.* 354:L37–40
Mattig, W. 1958. *Astron. Nachr.* 184:109–111
Mattig, W. 1968, *Zeitschr. Astroph.* 69:418–428
Mazzali, P. A., Cappellaro, E., Danziger, I. J., Turatto, M., Benetti, S. 1998. *Ap. J.* 499:L49–52
McVittie, G.C. 1938. *Observatory* 61:209–214
Meikle, W. P. S. 2000. *MNRAS* 314:782–792

Mellier, Y. 1999. *Annu. Rev. Astron. Astrophys.* 37:127–189
Metcalf, R.B. 1999. *MNRAS* 305:746–754
Metcalf, R.B., Silk, J. 1999. *Ap. J.* 519:L1–4
Minkowski, R., 1964. *Annu. Rev. Astron. Astrophys.* 2:247–266
Narlikar, J.V., Arp, H.C. 1997. *Ap. J.* 482:L119–120
Niemeyer, J.C., Truran, J.W. (eds.) 1999. *Type Ia Supernovae: Theory and Cosmology*, Cambridge: Cambridge University Press
Nomoto, K., Thielemann, F.-K., Yokoi, K. 1984. *Ap. J.* 286:644–658
Nomoto, K., Umeda, H., Kobayashi, C., Hachisu, I., Kato, M., Tsujimoto, T. 1999. In *Cosmic Explosions*, eds. S. Holt, W. Zhang, pp. 35–52. New York: American Institute of Physics
Nørgaard-Nielsen, H.U., Hansen, L., Jørgensen, H.E., Salamanca, A.A., Ellis, R.S., Couch, W. J. 1989. *Nature* 339:523–525
Nugent, P., Phillips, M. M., Baron, E., Branch, D., Hauschildt, P. 1995. *Ap. J.* 455:L147–150
Oke, J.B., Sandage, A. 1968. *Ap. J.* 154:21–32
Pahre, M.A., Djorgovski, S.G., de Carvalho, R.R. 1996. *Ap. J.* 456:L79–82
Pain, R., et al. 1996. *Ap. J.* 473:356–364
Parodi, B.R., Saha, A., Sandage, A., Tammann, G.A. 2000. *Ap. J.* 540:634–651
Peacock, J.A. 1999. *Cosmological Physics.* Cambridge: Cambridge University Press
Peebles, P.J.E. 1993. *Principles of Physical Cosmology.* Princeton: Princeton University Press
Peebles, P.J.E., Schramm, D.N., Turner, E.L., Kron, R.G. 1991. *Nature* 352:769–776
Perlmutter, S., Marvin, H.J., Muller, R.A., Pennypacker, C.R., Sasseen, T.P., Smith, C.K., Wang, L.P. 1991, in *Supernovae*, ed. S. Woosley, pp. 727–730. New York: Springer
Perlmutter, S., et al. 1995. *Ap. J.* 440:L41–44
Perlmutter, S., et al. 1997. *Ap. J.* 483:565–581
Perlmutter, S., et al. 1998. *Nature* 391:51–54
Perlmutter, S., et al. 1999a. *Ap. J.* 517:565–586
Perlmutter, S., Turner, M.S., White, M. 1999b. *Phys. Rev. Lett.* 83:670–673
Pettini, M., Ellison, S.L., Steidel, C.C., Shapley, A.E., Bowen, D.V. 2000. *Ap. J.* 532:65–76
Pettini, M., Smith, L.J., King, D.L., Hunstead, R.W. 1997. *Ap. J.* 486:665–680
Phillips, M.M. 1993. *Ap. J.* 413:L105–108
Phillips, M.M., Wells, L.A., Suntzeff, N.B., Hamuy, M., Leibundgut, B., Kirshner, R.P., Foltz, C.B. 1992. *Astron. J.* 103:1632–1637
Phillips, M.M., Lira, P., Suntzeff, N.B., Schommer, R.A., Hamuy, M., Maza, J. 1999. *Astron. J.* 118:1766–1776
Pinto, P.A., Eastman, R.G. 2000. *Ap. J.* 530:757–776
Podariu, S., Ratra, B. 2000. *Ap. J.* 532:109–117
Podariu, S., Nugent, P., Ratra, B. 2001. *Ap. J.* 553:39–46
Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, F., Burton, W.B., Desert, F.-X., Hartmann, D. 1996. *Astron. Astrophys.* 308:L5–8
Reiss, D.J. 2000. *The Rate of Supernovae in the Nearby and Distant Universe.* PhD Thesis, Seattle: University of Washington
Reiss, D.J., Germany, L.M., Schmidt, B.P., Stubbs, C.W. 1998. *Astron. J.* 115:26–36
Renzini, A. 1996. In *Supernovae and Supernova Remnants*, eds. R. McCray, Z. Wang, pp. 77–85. Cambridge: Cambridge University Press
Renzini, A. 1997. *Ap. J.* 488:35–43
Riess, A.G. 2000. *Pub.Ast.Soc.Pac.* 112:1284–1299
Riess, A.G., Press, W.H., Kirshner, R.P. 1996a. *Ap. J.* 473:88–109
Riess, A.G., et al. 1997. *Astron. J.* 114:722–729
Riess, A.G., et al. 1998. *Astron. J.* 116:1009–1038
Riess, A.G., et al. 1999a. *Astron. J.* 117:707–724
Riess, A.G., et al. 1999b. *Astron. J.* 118:2668–2674
Riess, A.G., et al. 2000. *Ap. J.* 536:62–67
Riess, A.G., et al. 2001. *Ap. J.* , in press (astro-ph/0104455)
Robertson, H. P. 1955, *Pub.Ast.Soc.Pac.* , 67, 82–98
Ruiz-Lapuente, P., Canal, R. 1998. *Ap. J.* 497:L57–60
Ruiz-Lapuente, P., Canal, R., Isern, J. (eds.) 1997, *Thermonuclear Supernovae.* Dordrecht: Kluwer

Rust, B. W. 1974. *The use of supernovae light curves for testing the expansion hypothesis and other cosmological relations*, PhD Thesis, Oak Ridge: Oak Ridge National Laboratory
Saha, A, Sandage, A., Labhardt, L., Tammann, G.A., Macchetto, F.D., Panagia, N. 1997. *Ap. J.* 486:1–20
Saha, A, Sandage, A., Tammann, G.A., Labhardt, L., Macchetto, F.D., Panagia, N. 1999. *Ap. J.* 522:802–838
Saini, T.D., Raychaudhury, S., Sahni, V., Starobinsky, A.A. 2000. *Phys. Rev. Lett.* 85:1162-1165
Sandage, A. 1961. *Ap. J.* 133:355–392
Sandage, A. 1988. *Annu. Rev. Astron. Astrophys.* 26:561–630
Sandage, A., Perelmuter, J.-M. 1991. *Ap. J.* 370:455–473
Sandage, A., Tammann, G. A. 1982. *Ap. J.* 256:339–345
Schmidt, B.P., et al. 1998. *Ap. J.* 507:46–63
Segal, I.E. 1997. *Ap. J.* 482:L115–117
Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M., Pettini, M. 1999. *Ap. J.* 519:1–17
Straumann, N. 1999. Eur.J.Phys. 20:419–427
Suntzeff, N.B., et al. 1999. *Astron. J.* 117:1175–1184
Tammann, G. A. 1978. In *Astronomical Uses of the Space Telescope*, eds. F. Macchetto, F. Pacini & M. Tarenghi, pp. 329–343. Garching: ESO
Tammann, G. A., Leibundgut, B. 1990. *Astron. Astrophys.* 236:9-14
Tammann, G. A., Sandage, A. 1995. *Ap. J.* 452:16–24
Tonry, J., et al. 1999. IAU Circ. 7312
Totani, T. 2000. In *Sources and detection of dark matter in the universe*, ed. D. Cline, pp. 53–65. New York: Springer
Totani, T., Kobayashi, C. 1999. *Ap. J.* 526:L65–68
Tripp, R. 1998. *Astron. Astrophys.* 331:815–820
Tripp, R., Branch, D. 1999. *Ap. J.* 525:209-214
Turner, M.S., Tyson, J.A. 1999. *Rev. Mod. Phys.* 71:145–164
Umeda, H., Nomoto, K., Kobayashi, C., Hachisu, I., Kato, M. 1999. *Ap. J.* 522:L43–47
Vandenberg, D. A., Bolte, M., Stetson, P. B. 1996. *Annu. Rev. Astron. Astrophys.* 34:461–510
van den Bergh, S., Tammann, G. A. 1991. *Annu. Rev. Astron. Astrophys.* 29:363–407
Wambsganss, J., Cen, R., Xu, G., Ostriker, J.P. 1997. *Ap. J.* 475:L81–84
Wang, Y. 2000. *Ap. J.* 536:531–539
Wang, Y., Garnavich, P. M. 2001. *Ap. J.* 552:445–451
Webb, J.K., Flambaum, V.V., Churchill, C.W., Drinkwater, M.J.,Barrow, J.D. 1999. *Phys. Rev. Lett.* 82:884–887
Weinberg, S. 1972. *Gravitation and cosmology: principles and applications of the general theory of relativity*, New York: Wiley
Weinberg, S. 1989. *Rev. Mod. Phys.* 61: 1–23
Weller, J., Albrecht, A. 2001. *Phys. Rev. Lett.* 86:1939–1942
White, M. 1998. *Ap. J.* 506:495–501
Wilson, O.C. 1939. *Ap. J.* 90:634–635
Woosley, S.E., Weaver, T.A. 1986. *Annu. Rev. Astron. Astrophys.* 24:205–253
Woosley, S.E., Weaver, T.A. 1994. *Ap. J.* 423:371–379
Zaldarriaga, M., Spergel, D.N., Seljak, U. 1997. *Ap. J.* 488:1-13