Carnegie Observatories Astrophysics Series, Vol. 2:
Measuring and Modeling the Universe, 2004
ed. W. L. Freedman (Cambridge: Cambridge Univ. Press)

Evidence from Type Ia Supernovae for an Accelerating Universe and Dark Energy

ALEXEI V. FILIPPENKO
Department of Astronomy, University of California, Berkeley

Abstract

I review the use of Type Ia supernovae (SNe Ia) for cosmological distance determinations. Low-redshift SNe Ia ($z \lesssim 0.1$) demonstrate that the Hubble expansion is linear, that $H_0 = 65 \pm 2$ (statistical) km s^{-1} Mpc^{-1}, and that the properties of dust in other galaxies are similar to those of dust in the Milky Way. The light curves of high-redshift ($z = 0.3$–1) SNe Ia are stretched in a manner consistent with the expansion of space; similarly, their spectra exhibit slower temporal evolution (by a factor of $1+z$) than those of nearby SNe Ia. The measured luminosity distances of SNe Ia as a function of redshift have shown that the expansion of the Universe is currently accelerating, probably due to the presence of repulsive dark energy such as Einstein's cosmological constant (Λ). Combining our data with existing measurements of the cosmic microwave background (CMB) radiation and with the results of large-scale structure surveys, we find a best fit for Ω_m and Ω_Λ of about 0.3 and 0.7, respectively. Other studies (e.g., masses of clusters of galaxies) also suggest that $\Omega_m \approx 0.3$. The sum of the densities, ~ 1.0, agrees with the value predicted by most inflationary models for the early Universe: the Universe is flat on large scales. A number of possible systematic effects (dust, supernova evolution) thus far do not seem to eliminate the need for $\Omega_\Lambda > 0$. Most recently, analyses of SNe Ia at $z = 1.0 - 1.7$ provide further support for current acceleration, and give tentative evidence for an early epoch of deceleration. Current projects include the search for additional SNe Ia at $z > 1$ to confirm the early deceleration, and the measurement of a few hundred SNe Ia at $z = 0.2 - 0.8$ to determine the equation of state of the dark energy, $w = P/(\rho c^2)$.

1.1 Introduction

Supernovae (SNe) come in two main varieties (see Filippenko 1997b for a review). Those whose optical spectra exhibit hydrogen are classified as Type II, while hydrogen-deficient SNe are designated Type I. SNe I are further subdivided according to the appearance of the early-time spectrum: SNe Ia are characterized by strong absorption near 6150 Å (now attributed to Si II), SNe Ib lack this feature but instead show prominent He I lines, and SNe Ic have neither the Si II nor the He I lines. SNe Ia are believed to result from the thermonuclear disruption of carbon-oxygen white dwarfs, while SNe II come from core collapse in massive supergiant stars. The latter mechanism probably produces most SNe Ib/Ic as well, but the progenitor stars previously lost their outer layers of hydrogen or even helium.

It has long been recognized that SNe Ia may be very useful distance indicators for a number of reasons; see Branch & Tammann (1992), Branch (1998), and references therein. (1) They are exceedingly luminous, with peak M_B averaging -19.2 mag if $H_0 = 65$ km s^{-1} Mpc^{-1}. (2) "Normal" SNe Ia have small dispersion among their peak absolute magnitudes ($\sigma \lesssim 0.3$ mag). (3) Our understanding of the progenitors and explosion mechanism of SNe Ia is on a reasonably firm physical basis. (4) Little cosmic evolution is expected in the peak luminosities of SNe Ia, and it can be modeled. This makes SNe Ia superior to galaxies as distance indicators. (5) One can perform *local* tests of various possible complications and evolutionary effects by comparing nearby SNe Ia in different environments.

Research on SNe Ia in the 1990s has demonstrated their enormous potential as cosmological distance indicators. Although there are subtle effects that must indeed be taken into account, it appears that SNe Ia provide among the most accurate values of H_0, q_0 (the deceleration parameter), Ω_m (the matter density), and Ω_Λ [the cosmological constant, $\Lambda c^2/(3H_0^2)$].

There have been two major teams involved in the systematic investigation of high-redshift SNe Ia for cosmological purposes. The "Supernova Cosmology Project" (SCP) is led by Saul Perlmutter of the Lawrence Berkeley Laboratory, while the "High-Z Supernova Search Team" (HZT) is led by Brian Schmidt of the Mt. Stromlo and Siding Springs Observatories. I have been privileged to work with both teams (see Filippenko 2001 for a personal account), but my primary allegiance is now with the HZT.

1.2 Homogeneity and Heterogeneity

Until the mid-1990s, the traditional way in which SNe Ia were used for cosmological distance determinations was to assume that they are perfect "standard candles" and to compare their observed peak brightness with those of SNe Ia in galaxies whose distances had been independently determined (e.g., with Cepheid variables). The rationale was that SNe Ia exhibit relatively little scatter in their peak blue luminosity ($\sigma_B \approx 0.4$–0.5 mag; Branch & Miller 1993), and even less if "peculiar" or highly reddened objects were eliminated from consideration by using a color cut. Moreover, the optical spectra of SNe Ia are usually rather homogeneous, if care is taken to compare objects at similar times relative to maximum brightness (Riess et al. 1997, and references therein). Over 80% of all SNe Ia discovered through the early 1990s were "normal" (Branch, Fisher, & Nugent 1993).

From a Hubble diagram constructed with unreddened, moderately distant SNe Ia ($z \lesssim 0.1$) for which peculiar motions should be small and relative distances (as given by ratios of redshifts) are accurate, Vaughan et al. (1995) find that

$$\langle M_B(\mathrm{max})\rangle \;=\; (-19.74 \pm 0.06) + 5\log(H_0/50)\ \mathrm{mag}.$$

In a series of papers, Sandage et al. (1996) and Saha et al. (1997) combine similar relations with *Hubble Space Telescope (HST)* Cepheid distances to the host galaxies of seven SNe Ia to derive $H_0 = 57 \pm 4$ km s^{-1} Mpc^{-1}.

Over the past two decades it has become clear, however, that SNe Ia do *not* constitute a perfectly homogeneous subclass (e.g., Filippenko 1997a,b). In retrospect this should have been obvious: the Hubble diagram for SNe Ia exhibits scatter larger than the photometric errors, the dispersion actually *rises* when reddening corrections are applied (under the assumption that all SNe Ia have uniform, very blue intrinsic colors at maximum; van den Bergh & Pazder 1992; Sandage & Tammann 1993), and there are some significant outliers whose anomalous magnitudes cannot possibly be explained by extinction alone.

Spectroscopic and photometric peculiarities have been noted with increasing frequency in well-observed SNe Ia. A striking case is SN 1991T; its pre-maximum spectrum did not exhibit Si II or Ca II absorption lines, yet two months past maximum brightness the spectrum was nearly indistinguishable from that of a classical SN Ia (Filippenko et al. 1992b; Phillips et al. 1993). The light curves of SN 1991T were slightly broader than the SN Ia template curves, and the object was probably somewhat more luminous than average at maximum. Another well-observed, peculiar SNe Ia is SN 1991bg (Filippenko et al. 1992a; Leibundgut et al. 1993; Turatto et al. 1996). At maximum brightness it was subluminous by 1.6 mag in V and 2.5 mag in B, its colors were intrinsically red, and its spectrum was peculiar (with a deep absorption trough due to Ti II). Moreover, the decline from maximum was very steep, the I-band light curve did not exhibit a secondary maximum like normal SNe Ia, and the velocity of the ejecta was unusually low. The photometric heterogeneity among SNe Ia is well demonstrated by Suntzeff (1996) with objects having excellent $BVRI$ light curves.

1.3 Cosmological Uses: Low Redshifts

Although SNe Ia can no longer be considered perfect "standard candles," they are still exceptionally useful for cosmological distance determinations. Excluding those of low luminosity (which are hard to find, especially at large distances), most of the nearby SNe Ia that had been discovered through the early 1990s were *nearly* standard (Branch et al. 1993; but see Li et al. 2001b for more recent evidence of a higher intrinsic peculiarity rate). Also, after many tenuous suggestions (e.g., Pskovskii 1977, 1984; Branch 1981), Phillips (1993) found convincing evidence for a correlation between light curve shape and the luminosity at maximum brightness by quantifying the photometric differences among a set of nine well-observed SNe Ia, using a parameter [$\Delta m_{15}(B)$] that measures the total drop (in B magnitudes) from B-band maximum to t = 15 days after B maximum. In all cases the host galaxies of his SNe Ia have accurate relative distances from surface brightness fluctuations or from the Tully-Fisher relation. The intrinsically bright SNe Ia clearly decline more slowly than dim ones, but the correlation is stronger in B than in V or I.

Using SNe Ia discovered during the Calán/Tololo survey ($z \lesssim 0.1$), Hamuy et al. (1995, 1996b) confirm and refine the Phillips (1993) correlation between peak luminosity and $\Delta m_{15}(B)$. Apparently the slope is steep only at low luminosities; thus, objects such as SN 1991bg skew the slope of the best-fitting single straight line. Hamuy et al. reduce the scatter in the Hubble diagram of normal, unreddened SNe Ia to only 0.17 mag in B and 0.14 mag in V; see also Tripp (1997). Yet another parameterization is the "stretch" method of Perlmutter et al. (1997) and Goldhaber et al. (2001): the B-band light curves of SNe Ia appear nearly identical when expanded or contracted temporally by a factor $(1+s)$, where the value of s varies among objects. In a similar but distinct effort, Riess, Press, & Kirshner (1995) show that the luminosity of SNe Ia correlates with the detailed *shape* of the overall light curve.

By using light curve shapes measured through several different filters, Riess, Press, & Kirshner (1996a) extend their analysis and objectively eliminate the effects of interstellar extinction: a SN Ia that has an unusually red $B-V$ color at maximum brightness is assumed to be *intrinsically* subluminous if its light curves rise and decline quickly, or of normal luminosity but significantly *reddened* if its light curves rise and decline more slowly. With a set of 20 SNe Ia consisting of the Calán/Tololo sample and their own objects, they show that the dispersion decreases from 0.52 mag to 0.12 mag after application of this "multi-color light curve shape" (MLCS) method. The results from a recent, expanded set of nearly 50 SNe Ia

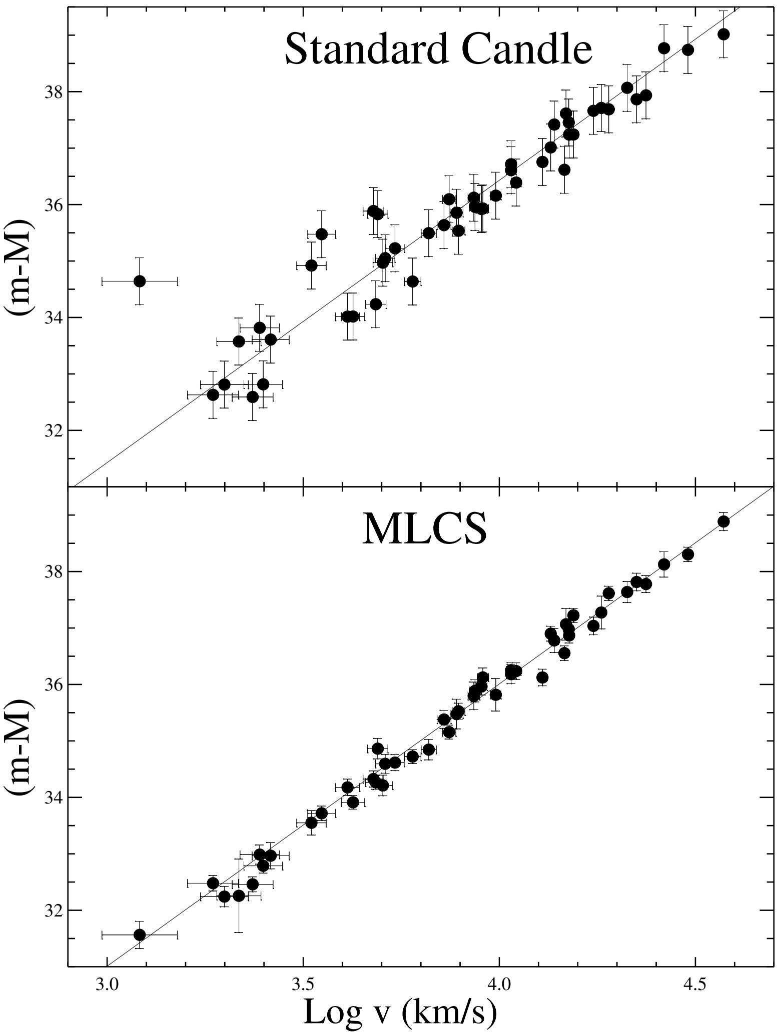

Fig. 1.1. Hubble diagrams for SNe Ia (A. G. Riess 2002, private communication) with velocities (km s^{-1}) in the *COBE* rest frame on the Cepheid distance scale. *Top:* The objects are assumed to be *standard candles* and there is no correction for extinction; the result is $\sigma = 0.42$ mag and $H_0 = 58 \pm 8$ km s^{-1} Mpc^{-1}. *Bottom:* The same objects, after correction for reddening and intrinsic differences in luminosity. The result is $\sigma = 0.15$ mag and $H_0 = 65 \pm 2$ (statistical) km s^{-1} Mpc^{-1}.

indicate that the dispersion decreases from 0.44 mag to 0.15 mag (Fig. 1.1). The resulting Hubble constant is 65 ± 2 (statistical) km s^{-1} Mpc^{-1}, with an additional systematic and zero-point uncertainty of ± 5 km s^{-1} Mpc^{-1}. Riess et al. (1996a) also show that the Hubble flow is remarkably linear; indeed, SNe Ia now constitute the best evidence for linearity. Finally, they argue that the dust affecting SNe Ia is *not* of circumstellar origin, and show quantitatively that the extinction curve in external galaxies typically does not differ from that in the Milky Way (cf. Branch & Tammann 1992, but see Tripp 1998).

The advantage of systematically correcting the luminosities of SNe Ia at high redshifts rather than trying to isolate "normal" ones seems clear in view of evidence that the luminosity of SNe Ia may be a function of stellar population. If the most luminous SNe Ia occur in young stellar populations (e.g., Hamuy et al. 1996a, 2000; Branch, Baron, & Romanishin 1996; Ivanov, Hamuy, & Pinto 2000), then we might expect the mean peak luminosity of high-z SNe Ia to differ from that of a local sample. Alternatively, the use of Cepheids (Population I objects) to calibrate local SNe Ia can lead to a zeropoint that is too luminous. On the other hand, as long as the physics of SNe Ia is essentially the same in young stellar populations locally and at high redshift, we should be able to adopt the luminosity correction methods (photometric and spectroscopic) found from detailed studies of low-z SNe Ia.

Large numbers of nearby SNe Ia are now being found by my team's Lick Observatory Supernova Search (LOSS) conducted with the 0.76-m Katzman Automatic Imaging Telescope (KAIT; Li et al. 2000; Filippenko et al. 2001; see http://astro.berkeley.edu/∼bait/kait.html). CCD images are taken of ~ 1000 galaxies per night and compared with KAIT "template images" obtained earlier; the templates are automatically subtracted from the new images and analyzed with computer software. The system reobserves the best candidates the same night, to eliminate star-like cosmic rays, asteroids, and other sources of false alarms. The next day, undergraduate students at UC Berkeley examine all candidates, including weak ones, and they glance at all subtracted images to locate SNe that might be near bright, poorly subtracted stars or galactic nuclei. LOSS discovered 20 SNe (of all types) in 1998, 40 in 1999, 38 in 2000, 69 in 2001, and 82 in 2002, making it by far the world's most successful search for nearby SNe. The most important objects were photometrically monitored through $BVRI$ (and sometimes U) filters (e.g., Li et al. 2001a, 2003; Modjaz et al. 2001; Leonard et al. 2002a,b), and unfiltered follow-up observations (e.g., Matheson et al. 2001) were made of most of them during the course of the SN search. This growing sample of well-observed SNe Ia should allow us to more precisely calibrate the MLCS method, as well as to look for correlations between the observed properties of the SNe and their environment (Hubble type of host galaxy, metallicity, stellar population, etc.).

1.4 Cosmological Uses: High Redshifts

These same techniques can be applied to construct a Hubble diagram with high-redshift SNe Ia, from which the value of $q_0 = (\Omega_m/2) - \Omega_\Lambda$ can be determined. With enough objects spanning a range of redshifts, we can determine Ω_m and Ω_Λ independently (e.g., Goobar & Perlmutter 1995). Contours of peak apparent R-band magnitude for SNe Ia at two redshifts have different slopes in the Ω_m–Ω_Λ plane, and the regions of intersection provide the answers we seek.

1.4.1 The Search

Based on the pioneering work of Norgaard-Nielsen et al. (1989), whose goal was to find SNe in moderate-redshift clusters of galaxies, the SCP (Perlmutter et al. 1995a, 1997) and the HZT (Schmidt et al. 1998) devised a strategy that almost guarantees the discovery of many faint, distant SNe Ia "on demand," during a predetermined set of nights. This "batch" approach to studying distant SNe allows follow-up spectroscopy and photometry to be scheduled in advance, resulting in a systematic study not possible with random discoveries. Most of the searched fields are equatorial, permitting follow-up from both hemispheres. The SCP was the first group to convincingly demonstrate the ability to find SNe in batches.

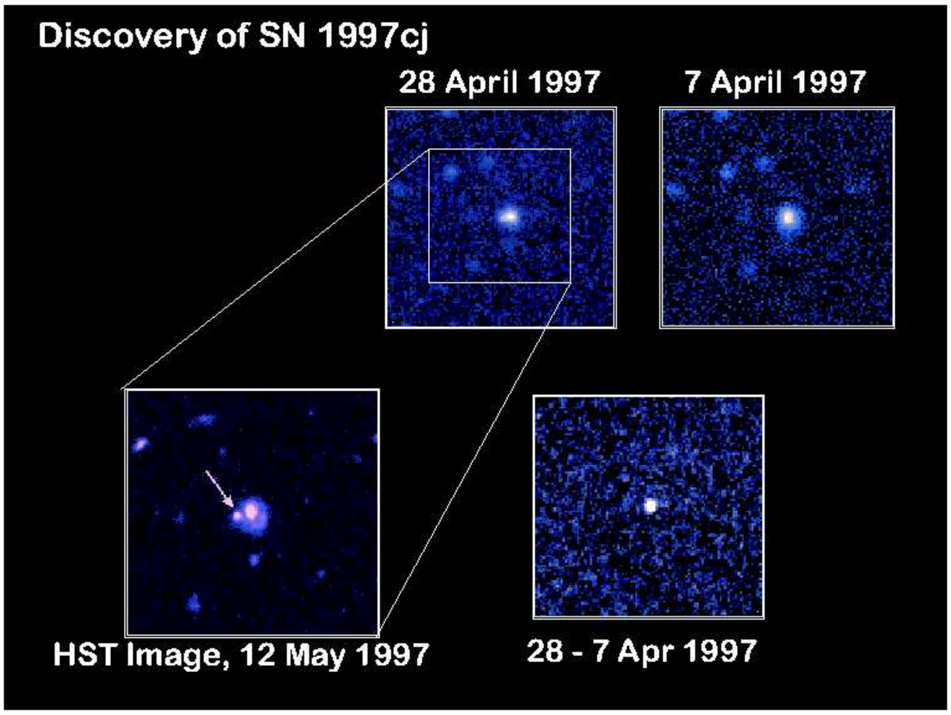

Fig. 1.2. Discovery image of SN 1997cj (28 April 1997), along with the template image and an *HST* image obtained subsequently. The net (subtracted) image is also shown.

Our approach is simple in principle. Pairs of first-epoch images are obtained with wide-field cameras on large telescopes (e.g., the Big Throughput Camera on the CTIO 4-m Blanco telescope) during the nights around new moon, followed by second-epoch images 3–4 weeks later. (Pairs of images permit removal of cosmic rays, asteroids, and distant Kuiper-belt objects.) These are compared immediately using well-tested software, and new SN candidates are identified in the second-epoch images (Fig. 1.2). Spectra are obtained as soon as possible after discovery to verify that the objects are SNe Ia and determine their redshifts. Each team has already found over 150 SNe in concentrated batches, as reported in numerous *IAU Circulars* (e.g., Perlmutter et al. 1995b, 11 SNe with $0.16 \lesssim z \lesssim 0.65$; Suntzeff et al. 1996, 17 SNe with $0.09 \lesssim z \lesssim 0.84$). The observed SN Ia rate at $z \approx 0.5$ is consistent with the low-z SN Ia rate together with plausible star-formation histories (Pain et al. 2002; Tonry et al. 2003), but the error bars on the high-z rate are still quite large.

Intensive photometry of the SNe Ia commences within a few days after procurement of the second-epoch images; it is continued throughout the ensuing and subsequent dark runs. In a few cases *HST* images are obtained. As expected, most of the discoveries are *on the rise or near maximum brightness*. When possible, the SNe are observed in filters that closely match the redshifted B and V bands; this way, the K-corrections become only a second-order effect (Kim, Goobar, & Perlmutter 1996; Nugent, Kim, & Perlmutter 2002). We try to obtain excellent multi-color light curves, so that reddening and luminosity corrections can be applied (Riess et al. 1996a; Hamuy et al. 1996a,b).

Although SNe in the magnitude range 22–22.5 can sometimes be spectroscopically confirmed with 4-m class telescopes, the signal-to-noise ratios are low, even after several hours of integration. Certainly Keck or the VLT are required for the fainter objects (22.5–24.5 mag). With the largest telescopes, not only can we rapidly confirm a substantial number of candidate SNe, but we can search for peculiarities in the spectra that might indicate evolution of SNe Ia with redshift. Moreover, high-quality spectra allow us to measure the age of a SN: we have developed a method for automatically comparing the spectrum of a SN Ia with a library of spectra corresponding to many different epochs in the development of SNe Ia (Riess et al. 1997). Our technique also has great practical utility at the telescope: we can determine the age of a SN "on the fly," within half an hour after obtaining its spectrum. This allows us to decide rapidly which SNe are best for subsequent photometric follow-up, and we immediately alert our collaborators on other telescopes.

1.4.2 Results

First, we note that the light curves of high-redshift SNe Ia are broader than those of nearby SNe Ia; the initial indications (Leibundgut et al. 1996; Goldhaber et al. 1997), based on small numbers of SNe Ia, are amply confirmed with the larger samples (Goldhaber et al. 2001). Quantitatively, the amount by which the light curves are "stretched" is consistent with a factor of $1+z$, as expected if redshifts are produced by the expansion of space rather than by "tired light" and other non-expansion hypotheses for the redshifts of objects at cosmological distances. [For non-standard cosmological interpretations of the SN Ia data, see Narlikar & Arp (1997) and Hoyle, Burbidge, & Narlikar (2000).] We also demonstrate this *spectroscopically* at the 2σ confidence level for a single object: the spectrum of SN 1996bj ($z = 0.57$) evolved more slowly than those of nearby SNe Ia, by a factor consistent with $1+z$ (Riess et al. 1997). Although one might be able to argue that something other than universal expansion could be the cause of the apparent stretching of SN Ia light curves at high redshifts, it is much more difficult to attribute apparently slower evolution of spectral details to an unknown effect.

The formal value of Ω_m derived from SNe Ia has changed with time. The SCP published the first result (Perlmutter et al. 1995a), based on a single object, SN 1992bi at $z = 0.458$: $\Omega_m = 0.2 \pm 0.6 \pm 1.1$ (assuming that $\Omega_\Lambda = 0$). The SCP's analysis of their first seven objects (Perlmutter et al. 1997) suggested a much larger value of $\Omega_m = 0.88 \pm 0.6$ (if $\Omega_\Lambda = 0$) or $\Omega_m = 0.94 \pm 0.3$ (if $\Omega_{\mathrm{total}} = 1$). Such a high-density universe seemed at odds with other, independent measurements of Ω_m. However, with the subsequent inclusion of just one more object, SN 1997ap at $z = 0.83$ (the highest known for a SN Ia at the time; Perlmutter et al. 1998), their estimates were revised back down to $\Omega_m = 0.2 \pm 0.4$ if $\Omega_\Lambda = 0$, and $\Omega_m = 0.6 \pm 0.2$ if $\Omega_{\mathrm{total}} = 1$; the apparent brightness of SN 1997ap had been precisely measured with *HST*, so it substantially affected the best fits.

Meanwhile, the HZT published (Garnavich et al. 1998a) an analysis of four objects (three of them observed with *HST*), including SN 1997ck at $z = 0.97$, at that time a redshift record, although they cannot be absolutely certain that the object was a SN Ia because the spectrum is too poor. From these data, the HZT derived that $\Omega_m = -0.1 \pm 0.5$ (assuming $\Omega_\Lambda = 0$) and $\Omega_m = 0.35 \pm 0.3$ (assuming $\Omega_{\mathrm{total}} = 1$), inconsistent with the high Ω_m initially found

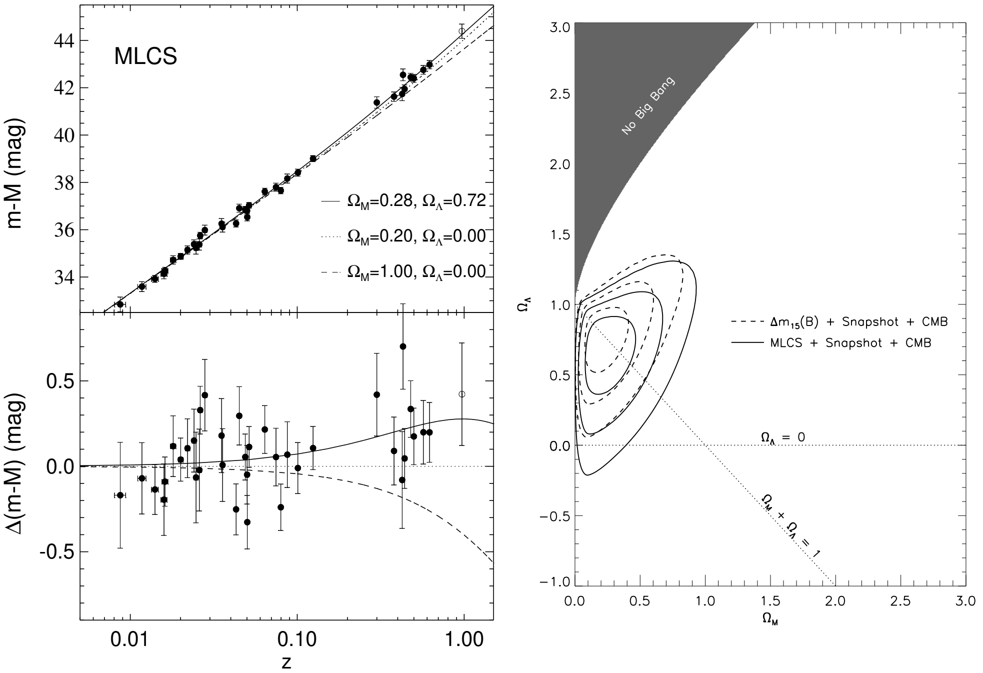

Fig. 1.3. *Left:* The upper panel shows the Hubble diagram for the low-z and high-z HZT SN Ia sample with MLCS distances; see Riess et al. (1998b). Overplotted are three world models: "low" and "high" Ω_m with $\Omega_\Lambda = 0$, and the best fit for a flat universe ($\Omega_m = 0.28$, $\Omega_\Lambda = 0.72$). The bottom panel shows the difference between data and models from the $\Omega_m = 0.20$, $\Omega_\Lambda = 0$ prediction. Only the 10 best-observed high-z SNe Ia are shown. The average difference between the data and the $\Omega_m = 0.20$, $\Omega_\Lambda = 0$ prediction is ~ 0.25 mag. *Right:* The HZT's combined constraints from SNe Ia (left) and the position of the first acoustic peak of the CMB angular power spectrum, based on data available in mid-1998; see Garnavich et al. (1998b). The contours mark the 68.3%, 95.4%, and 99.7% enclosed probability regions. Solid curves correspond to results from the MLCS method; dotted ones are from the $\Delta m_{15}(B)$ method; all 16 SNe Ia in Riess et al. (1998b) were used.

by Perlmutter et al. (1997) but consistent with the revised estimate in Perlmutter et al. (1998). An independent analysis of 10 SNe Ia using the "snapshot" distance method (with which conclusions are drawn from sparsely observed SNe Ia) gave quantitatively similar conclusions (Riess et al. 1998a). However, none of these early data sets carried the statistical discriminating power to detect cosmic acceleration.

The SCP's next results were announced at the 1998 January AAS meeting in Washington, DC. A press conference was scheduled, with the stated purpose of presenting and discussing the then-current evidence for a low-Ω_m universe as published by Perlmutter et al. (1998; SCP) and Garnavich et al. (1998a; HZT). When showing the SCP's Hubble diagram for SNe Ia, however, Perlmutter also pointed out tentative evidence for *acceleration*! He stated that the conclusion was uncertain, and that the data were equally consistent with no acceleration; the systematic errors had not yet been adequately assessed. Essentially the same conclusion was given by the SCP in their talks at a conference on dark matter, near Los Angeles, in February 1998 (Goldhaber & Perlmutter 1998).

Although it chose not to reveal them at the same 1998 January AAS meeting, the HZT already had similar, tentative evidence for acceleration in their own SN Ia data set. The HZT continued to perform numerous checks of their data analysis and interpretation, including fairly thorough consideration of various possible systematic effects. Unable to find any significant problems, even with the possible systematic effects, the HZT reported detection of a *nonzero* value for Ω_Λ (based on 16 high-z SNe Ia) at the Los Angeles dark matter conference in February 1998 (Filippenko & Riess 1998), and soon thereafter submitted a formal paper that was published in September 1998 (Riess et al. 1998b). Their original Hubble diagram for the 10 best-observed high-z SNe Ia is given in Figure 1.3 (*left*). With the MLCS method applied to the full set of 16 SNe Ia, the HZT's formal results were $\Omega_m = 0.24 \pm 0.10$ if $\Omega_{\rm total} = 1$, or $\Omega_m = -0.35 \pm 0.18$ (unphysical) if $\Omega_\Lambda = 0$. If one demanded that $\Omega_m = 0.2$, then the best value for Ω_Λ was 0.66 ± 0.21. These conclusions did not change significantly when only the 10 best-observed SNe Ia were used (Fig. 1.3, *left*; $\Omega_m = 0.28 \pm 0.10$ if $\Omega_{\rm total} = 1$).

Another important constraint on the cosmological parameters could be obtained from measurements of the angular scale of the first acoustic peak of the CMB (e.g., Zaldarriaga, Spergel, & Seljak 1997; Eisenstein, Hu, & Tegmark 1998); the SN Ia and CMB techniques provide nearly complementary information. A stunning result was already available by mid-1998 from existing measurements (e.g., Hancock et al. 1998; Lineweaver & Barbosa 1998): the HZT's analysis of the SN Ia data in Riess et al. (1998b) demonstrated that $\Omega_m + \Omega_\Lambda = 0.94 \pm 0.26$ (Fig. 1.3, *right*), when the SN and CMB constraints were combined (Garnavich et al. 1998b; see also Lineweaver 1998, Efstathiou et al. 1999, and others).

Somewhat later (June 1999), the SCP published almost identical results, implying an accelerating expansion of the Universe, based on an essentially independent set of 42 high-z SNe Ia (Perlmutter et al. 1999). Their data, together with those of the HZT, are shown in Figure 1.4 (*left*), and the corresponding confidence contours in the Ω_Λ vs. Ω_m plane are given in Figure 1.4 (*right*). This incredible agreement suggested that neither group had made a large, simple blunder; if the result was wrong, the reason must be subtle. Had there been only one team working in this area, it is likely that far fewer astronomers and physicists throughout the world would have taken the result seriously.

Moreover, already in 1998–1999 there was tentative evidence that the "dark energy" driving the accelerated expansion was indeed consistent with the cosmological constant, Λ. If Λ dominates, then the equation of state of the dark energy should have an index $w = -1$, where the pressure (P) and density (ρ) are related according to $w = P/(\rho c^2)$. Garnavich et al. (1998b) and Perlmutter et al. (1999) already set an interesting limit, $w \lesssim -0.60$ at the 95% confidence level. However, more high-quality data at $z \approx 0.5$ are needed to narrow the allowed range, in order to test other proposed candidates for dark energy such as various forms of "quintessence" (e.g., Caldwell, Davé, & Steinhardt 1998).

Although the CMB results appeared reasonably persuasive in 1998–1999, one could argue that fluctuations on different scales had been measured with different instruments, and that suble systematic effects might lead to erroneous conclusions. These fears were dispelled only 1–2 years later, when the more accurate and precise results of the BOOMERANG collaboration were announced (de Bernardis et al. 2000, 2002). Shortly thereafter the MAXIMA collaboration distributed their very similar findings (Hanany et al. 2000; Balbi et al. 2000; Netterfield et al. 2002; see also the TOCO, DASI, and many other measurements). Figure 1.4 (*right*) illustrates that the CMB measurements tightly constrain $\Omega_{\rm total}$ to be close

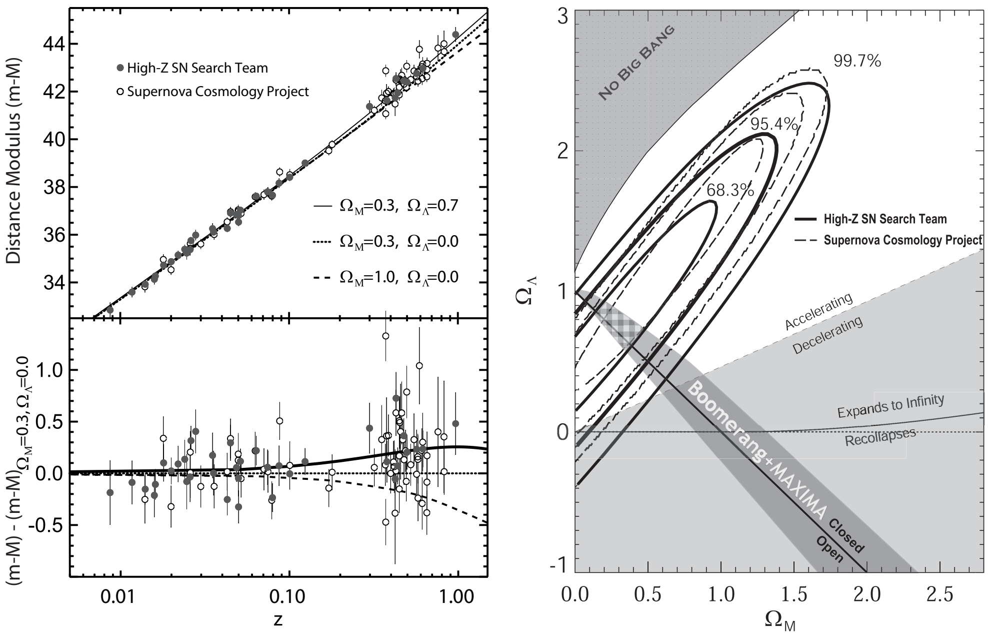

Fig. 1.4. *Left:* As in Fig. 1.3, but this time including both the HZT (Riess et al. 1998b) and SCP (Perlmutter et al. 1999) samples of low-redshift and high-redshift SNe Ia. Overplotted are three world models: $\Omega_m = 0.3$ and 1.0 with $\Omega_\Lambda = 0$, and a flat universe ($\Omega_{\rm total} = 1.0$) with $\Omega_\Lambda = 0.7$. The bottom panel shows the difference between data and models from the $\Omega_m = 0.3$, $\Omega_\Lambda = 0$ prediction. *Right:* The combined constraints from SNe Ia (left) and the position of thefirst acoustic peak of the CMB angular power spectrum, based on BOOMERANG and MAXIMA data. The contours mark the 68.3%, 95.4%, and 99.7% enclosed probability regions determined from the SNe Ia. According to the CMB, $\Omega_{\rm total} \approx 1.0$.

to unity; we appear to live in a flat universe, in agreement with most inflationary models for the early Universe! Combined with the SN Ia results, the evidence for nonzero Ω_Λ was fairly strong. Making the argument even more compelling was the fact that various studies of clusters of galaxies (see summary by Bahcall et al. 1999) showed that $\Omega_m \approx 0.3$, consistent with the results in Figures 1.3 and 1.4. Thus, a “concordance cosmology” had emerged: $\Omega_m \approx 0.3$, $\Omega_\Lambda \approx 0.7$—consistent with what had been suspected some years earlier by Ostriker & Steinhardt (1995; see also Carroll, Press, & Turner 1992).

Yet another piece of evidence for a nonzero value of Λ was provided by the Two-Degree Field Galaxy Redshift Survey (2dFGRS; Peacock et al. 2001; Percival et al. 2001; Efstathiou et al. 2002). Combined with the CMB maps, their results are inconsistent with a universe dominated by gravitating dark matter. Again, the implication is that about 70% of the mass-energy density of the Universe consists of some sort of dark energy whose gravitational effect is repulsive. Just as this review was going to press, results from the *Wilkinson Microwave Anisotropy Prove (WMAP)* appeared; together with the 2dFGRS constraints, they confirm and refine the concordance cosmology ($\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_{\rm baryon} = 0.044$, $H_0 = 71 \pm 4$ km s^{-1} Mpc^{-1}; Spergel et al. 2003).

The dynamical age of the Universe can be calculated from the cosmological parameters. In an empty Universe with no cosmological constant, the dynamical age is simply the "Hubble time" (i.e., the inverse of the Hubble constant); there is no deceleration. SNe Ia yield $H_0 = 65 \pm 2$ km s^{-1} Mpc^{-1} (statistical uncertainty only), and a Hubble time of 15.1 ± 0.5 Gyr. For a more complex cosmology, integrating the velocity of the expansion from the current epoch ($z = 0$) to the beginning ($z = \infty$) yields an expression for the dynamical age. As shown in detail by Riess et al. (1998b), by mid-1998 the HZT had obtained a value of $14.2^{+1.0}_{-0.8}$ Gyr using the likely range for $(\Omega_m, \Omega_\Lambda)$ that they measured. (The precision was so high because their experiment was sensitive to roughly the *difference* between Ω_m and Ω_Λ, and the dynamical age also varies in approximately this way.) Including the *systematic* uncertainty of the Cepheid distance scale, which may be up to 10%, a reasonable estimate of the dynamical age was 14.2 ± 1.7 Gyr (Riess et al. 1998b). Again, the SCP's result was very similar (Perlmutter et al. 1999), since it was based on nearly the same derived values for the cosmological parameters. This expansion age is consistent with ages determined from various other techniques such as the cooling of white dwarfs (Galactic disk > 9.5 Gyr; Oswalt et al. 1996), radioactive dating of stars via the thorium and europium abundances (15.2 ± 3.7 Gyr; Cowan et al. 1997), and studies of globular clusters (10–15 Gyr, depending on whether *Hipparcos* parallaxes of Cepheids are adopted; Gratton et al. 1997; Chaboyer et al. 1998). By mid-1998, the ages of the oldest stars no longer seemed to exceed the expansion age of the Universe; the long-standing "age crisis" had evidently been resolved.

1.5 Discussion

Although the convergence of different methods on the same answer is reassuring, and suggests that the concordance cosmology is correct, it is important to vigorously test each method to make sure it is not leading us astray. Moreover, only through such detailed studies will the accuracy and precision of the methods improve, allowing us to eventually set better constraints on the equation of state parameter, w. Here I discuss the systematic effects that could adversely affect the SN Ia results.

High-redshift SNe Ia are observed to be dimmer than expected in an empty Universe (i.e., $\Omega_m = 0$) with no cosmological constant. At $z \approx 0.5$, where the SN Ia observations have their greatest leverage on Λ, the difference in apparent magnitude between an $\Omega_m = 0.3$ ($\Omega_\Lambda = 0$) universe and a flat universe with $\Omega_\Lambda = 0.7$ is only about 0.25 mag. Thus, we need to find out if chemical abundances, stellar populations, selection bias, gravitational lensing, or grey dust can have an effect this large. Although both the HZT and SCP had considered many of these potential systematic effects in their original discovery papers (Riess et al. 1998b; Perlmutter et al. 1999), and had shown with reasonable confidence that obvious ones were not greatly affecting their conclusions, if was of course possible that they were wrong, and that the data were being misinterpreted.

1.5.1 Evolution

Perhaps the most obvious possible culprit is *evolution* of SNe Ia over cosmic time, due to changes in metallicity, progenitor mass, or some other factor. If the peak luminosity of SNe Ia were lower at high redshift, then the case for $\Omega_\Lambda > 0$ would weaken. Conversely, if the distant explosions are more powerful, then the case for acceleration strengthens. Theorists are not yet sure what the sign of the effect will be, if it is present at all; different assumptions lead to different conclusions (Höflich et al. 1998; Umeda et al. 1999; Nomoto et al. 2000; Yungelson & Livio 2000).

Of course, it is extremely difficult, if not effectively impossible, to obtain an accurate, independent measure of the peak luminosity of high-z SNe Ia, and hence to directly test for luminosity evolution. However, we can more easily determine whether *other* observable properties of low-z and high-z SNe Ia differ. If they are all the same, it is more probable that the peak luminosity is constant as well—but if they differ, then the peak luminosity might also be affected (e.g., Höflich et al. 1998). Drell, Loredo, & Wasserman (2000), for example, argue that there are reasons to suspect evolution, because the average properties of existing samples of high-z and low-z SNe Ia seem to differ (e.g., the high-z SNe Ia are more uniform).

The local sample of SNe Ia displays a weak correlation between light curve shape (or peak luminosity) and host galaxy type, in the sense that the most luminous SNe Ia with the broadest light curves only occur in late-type galaxies. Both early-type and late-type galaxies provide hosts for dimmer SNe Ia with narrower light curves (Hamuy et al. 1996a). The mean luminosity difference for SNe Ia in late-type and early-type galaxies is ~ 0.3 mag. In addition, the SN Ia rate per unit luminosity is almost twice as high in late-type galaxies as in early-type galaxies at the present epoch (Cappellaro et al. 1997). These results may indicate an evolution of SNe Ia with progenitor age. Possibly relevant physical parameters are the mass, metallicity, and C/O ratio of the progenitor (Höflich et al. 1998).

We expect that the relation between light curve shape and peak luminosity that applies to the range of stellar populations and progenitor ages encountered in the late-type and early-type hosts in our nearby sample should also be applicable to the range we encounter in our distant sample. In fact, the range of age for SN Ia progenitors in the nearby sample is likely to be *larger* than the change in mean progenitor age over the 4–6 Gyr lookback time to the high-z sample. Thus, to first order at least, our local sample should correct the distances for progenitor or age effects.

We can place empirical constraints on the effect that a change in the progenitor age would have on our SN Ia distances by comparing subsamples of low-redshift SNe Ia believed to arise from old and young progenitors. In the nearby sample, the mean difference between the distances for the early-type hosts (8 SNe Ia) and late-type hosts (19 SNe Ia), at a given redshift, is 0.04 ± 0.07 mag from the MLCS method. This difference is consistent with zero. Even if the SN Ia progenitors evolved from one population at low redshift to the other at high redshift, we still would not explain the surplus in mean distance of 0.25 mag over the $\Omega_\Lambda = 0$ prediction. Moreover, in a major study of high-redshift SNe Ia as a function of galaxy morphology, the SCP found no clear differences (except for the amount of scatter; see §1.5.2) between the cosmological results obtained with SNe Ia in late-type and early-type galaxies (Sullivan et al. 2004).

It is also reassuring that initial comparisons of high-z SN Ia spectra appear remarkably similar to those observed at low redshift. For example, the spectral characteristics of SN 1998ai ($z = 0.49$) appear to be essentially indistinguishable from those of normal low-z SNe Ia; see Figure 1.5 (*left*). In fact, the most obviously discrepant spectrum in this figure is the second one from the top, that of SN 1994B ($z = 0.09$); it is intentionally included as a "decoy" that illustrates the degree to which even the spectra of nearby, relatively normal SNe Ia can vary. Nevertheless, it is important to note that a dispersion in luminosity (perhaps 0.2 mag) exists even among the other, more normal SNe Ia shown in Figure 1.5

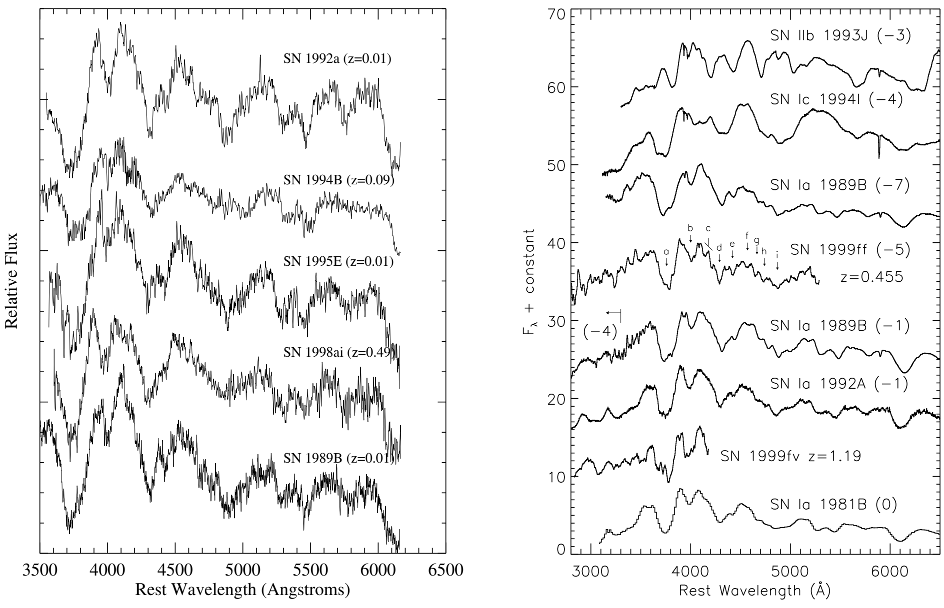

Fig. 1.5. *Left:* Spectral comparison (in f_λ) of SN 1998ai ($z = 0.49$; Keck spectrum) with low-redshift ($z < 0.1$) SNe Ia at a similar age (~ 5 days before maximum brightness), from Riess et al. (1998b). The spectra of the low-redshift SNe Ia were resampled and convolved with Gaussian noise to match the quality of the spectrum of SN 1998ai. Overall, the agreement in the spectra is excellent, tentatively suggesting that distant SNe Ia are physically similar to nearby SNe Ia. SN 1994B ($z = 0.09$) differs the most from the others, and was included as a "decoy." *Right:* Heavily smoothed spectra of two high-z SNe (SN 1999ff at $z = 0.455$ and SN 1999fv at $z = 1.19$; quite noisy below $\sim$3500 Å) are presented along with several low-z SN Ia spectra (SNe 1989B, 1992A, and 1981B), a SN Ib spectrum (SN 1993J), and a SN Ic spectrum (SN 1994I); see Filippenko (1997) for a discussion of spectra of various types of SNe. The date of the spectra relative to B-band maximum is shown in parentheses after each object's name. Specific features seen in SN 1999ff and labeled with a letter are discussed by Coil et al. (2000). This comparison shows that the two high-z SNe are most likely SNe Ia.

(*left*); thus, our spectra of SN 1998ai and other high-z SNe Ia are not yet sufficiently good for independent, *precise* determinations of peak luminosity from spectral features (Nugent et al. 1995). Many of them, however, are sufficient for ruling out other SN types (Fig. 1.5, *right*), or for identifying gross peculiarities such as those shown by SNe 1991T and 1991bg; see Coil et al. (2000).

We can help verify that the SNe at $z \approx 0.5$ being used for cosmology do not belong to a subluminous population of SNe Ia by examining restframe I-band light curves. Normal, nearby SNe Ia show a pronounced second maximum in the I band about a month after the first maximum and typically about 0.5 mag fainter (e.g., Ford et al. 1993; Suntzeff 1996). Subluminous SNe Ia, in contrast, do not show this second maximum, but rather follow a linear decline or show a muted second maximum (Filippenko et al. 1992a). As

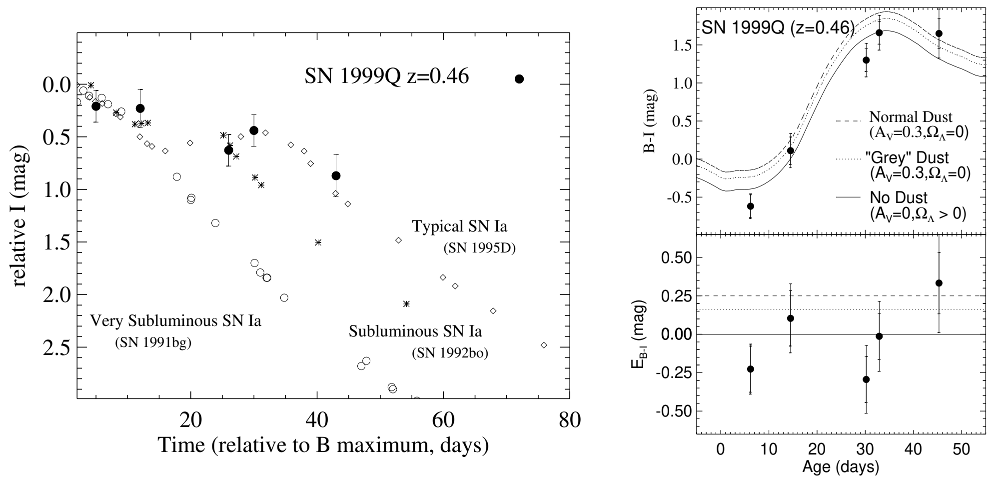

Fig. 1.6. *Left:* Restframe I-band (observed J-band) light curve of SN 1999Q (z = 0.46, 5 solid points; Riess et al. 2000), and the I-band light curves of several nearby SNe Ia. Subluminous SNe Ia exhibit a less prominent second maximum than do normal SNe Ia. *Right:* Color excess, E_{B-I}, for SN 1999Q and different dust models (Riess et al. 2000). The data are most consistent with no dust and $\Omega_\Lambda > 0$.

discussed by Riess et al. (2000), tentative evidence for the second maximum is seen from the HZT's existing J-band (restframe I-band) data on SN 1999Q ($z = 0.46$); see Figure 1.6 (*left*). Additional tests with spectra and near-infrared light curves are currently being conducted.

Another way of using light curves to test for possible evolution of SNe Ia is to see whether the rise time (from explosion to maximum brightness) is the same for high-redshift and low-redshift SNe Ia; a difference might indicate that the peak luminosities are also different (Höflich et al. 1998). Riess et al. (1999c) measured the risetime of nearby SNe Ia, using data from KAIT, the Beijing Astronomical Observatory (BAO) SN search, and a few amateur astronomers. Though the exact value of the risetime is a function of peak luminosity, for typical low-redshift SNe Ia it is 20.0 ± 0.2 days. Riess et al. (1999b) pointed out that this differs by 5.8σ from the *preliminary* risetime of 17.5 ± 0.4 days reported in conferences by the SCP (Goldhaber et al. 1998a,b; Groom 1998). However, more thorough analyses of the SCP data (Aldering, Knop, & Nugent 2000; Goldhaber et al. 2001) show that the high-redshift uncertainty of ± 0.4 days that the SCP originally reported was much too small because it did not account for systematic effects. The revised discrepancy with the low-redshift risetime is about 2σ or less. Thus, the apparent difference in risetimes might be insignificant. Even if the difference is real, however, its relevance to the peak luminosity is unclear; the light curves may differ only in the first few days after the explosion, and this could be caused by small variations in conditions near the outer part of the exploding white dwarf that are inconsequential at the peak.

1.5.2 Extinction

Our SN Ia distances have the important advantage of including corrections for interstellar extinction occurring in the host galaxy and the Milky Way. Extinction corrections based on the relation between SN Ia colors and luminosity improve distance precision for a sample of nearby SNe Ia that includes objects with substantial extinction (Riess et al. 1996a); the scatter in the Hubble diagram is much reduced. Moreover, the consistency of the measured Hubble flow from SNe Ia with late-type and early-type hosts (see §1.5.1) shows that the extinction corrections applied to dusty SNe Ia at low redshift do not alter the expansion rate from its value measured from SNe Ia in low-dust environments.

In practice, the high-redshift SNe Ia generally appear to suffer very little extinction; their $B-V$ colors at maximum brightness are normal, suggesting little color excess due to reddening. The most detailed available study is that of the SCP (Sullivan et al. 2004): they found that the scatter in the Hubble diagram is minimal for SNe Ia in early-type host galaxies, but increases for SNe Ia in late-type galaxies. Moreover, on average the SNe in late-type galaxies are slightly fainter (by 0.14 ± 0.09 mag) than those in early-type galaxies. Finally, at peak brightness the colors of SNe Ia in late-type galaxies are marginally redder than those in early-type galaxies. Sullivan et al. (2004) conclude that extinction by dust in the host galaxies of SNe Ia is one of the major sources of scatter in the high-redshift Hubble diagram. By restricting their sample to SNe Ia in early-type host galaxies (presumably with minimal extinction), they obtain a very tight Hubble diagram that suggests a nonzero value for Ω_Λ at the 5σ confidence level, under the assumption that $\Omega_{\rm total} = 1$. In the absence of this assumption, SNe Ia in early-type hosts still imply that $\Omega_\Lambda > 0$ at nearly the 98% confidence level. The results for Ω_Λ with SNe Ia in late-type galaxies are quantitatively similar, but statistically less secure because of the larger scatter.

Riess, Press, & Kirshner (1996b) found indications that the Galactic ratios between selective absorption and color excess are similar for host galaxies in the nearby ($z \leq 0.1$) Hubble flow. Yet, what if these ratios changed with lookback time (e.g., Aguirre 1999a)? Could an evolution in dust-grain size descending from ancestral interstellar "pebbles" at higher redshifts cause us to underestimate the extinction? Large dust grains would not imprint the reddening signature of typical interstellar extinction upon which our corrections rely.

However, viewing our SNe through such gray interstellar grains would also induce a *dispersion* in the derived distances. Using the results of Hatano, Branch, & Deaton (1998), Riess et al. (1998b) estimate that the expected dispersion would be 0.40 mag if the mean gray extinction were 0.25 mag (the value required to explain the measured MLCS distances without a cosmological constant). This is significantly larger than the 0.21 mag dispersion observed in the high-redshift MLCS distances. Furthermore, most of the observed scatter is already consistent with the estimated *statistical* errors, leaving little to be caused by gray extinction. Nevertheless, if we assumed that *all* of the observed scatter were due to gray extinction, the mean shift in the SN Ia distances would be only 0.05 mag. With the existing observations, it is difficult to rule out this modest amount of gray interstellar extinction.

Gray *intergalactic* extinction could dim the SNe without either telltale reddening or dispersion, if all lines of sight to a given redshift had a similar column density of absorbing material. The component of the intergalactic medium with such uniform coverage corresponds to the gas clouds producing Lyman-α forest absorption at low redshifts. These clouds have individual H I column densities less than about $10^{15}\,{\rm cm}^{-2}$ (Bahcall et al. 1996). However, they display low metallicities, typically less than 10% of solar. Gray extinction would

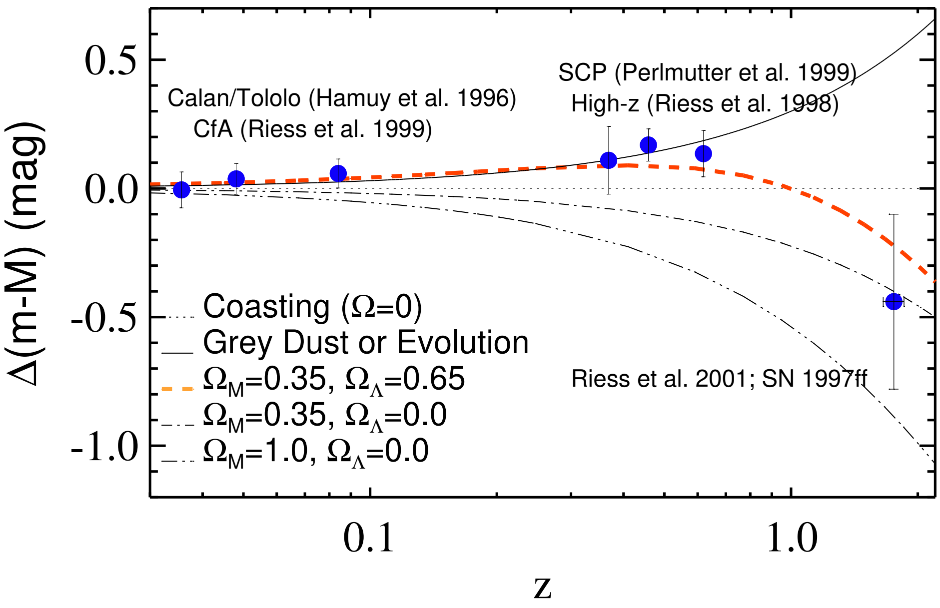

Fig. 1.7. Hubble diagram for SNe Ia relative to an empty universe ($\Omega = 0$) compared with cosmological and astrophysical models (Riess et al. 2001). Low-redshift SNe Ia are from Hamuy et al. (1996a) and Riess et al. (1999a). The magnitude of SN 1997ff at $z = 1.7$ has been corrected for gravitational lensing (Benítez et al. 2002). The measurements of SN 1997ff are inconsistent with astrophysical effects that could mimic previous evidence for an accelerating universe from SNe Ia at $z \approx 0.5$.

require larger dust grains which would need a larger mass in heavy elements than typical interstellar grain size distributions to achieve a given extinction. It is possible that large dust grains are blown out of galaxies by radiation pressure, and are therefore not associated with Lyman-α clouds (Aguirre 1999b).

But even the dust postulated by Aguirre (1999a,b) and Aguirre & Haiman (1999) is not *completely* gray, having a size of about 0.1 μm. We can test for such nearly gray dust by observing high-redshift SNe Ia over a wide wavelength range to measure the color excess it would introduce. If $A_V = 0.25$ mag, then $E(U-I)$ and $E(B-I)$ should be 0.12–0.16 mag (Aguirre 1999a,b). If, on the other hand, the 0.25 mag faintness is due to Λ, then no such reddening should be seen. This effect is measurable using proven techniques; so far, with just one SN Ia (SN 1999Q; Fig. 1.6, *right*), our results favor the no-dust hypothesis to better than 2σ (Riess et al. 2000). More work along these lines is in progress.

1.5.3 The Smoking Gun

Suppose, however, that for some reason the dust is *very* gray, or our color measurements are not sufficiently precise to rule out Aguirre's (or other) dust. Or, perhaps some other astrophysical systematic effect is fooling us, such as possible evolution of the white dwarf progenitors (e.g., Höflich et al. 1998; Umeda et al. 1999), or gravitational lensing (Wambsganss, Cen, & Ostriker 1998). The most decisive test to distinguish between Λ and cumulative systematic effects is to examine the *deviation* of the observed peak magnitude of SNe Ia from the magnitude expected in the low-Ω_m, zero-Λ model. If Λ is positive, the deviation should actually begin to *decrease* at $z \approx 1$; we will be looking so far back in time that the Λ effect becomes small compared with Ω_m, and the Universe is decelerating at that epoch. If, on the other hand, a systematic bias such as gray dust or evolution of the white dwarf progenitors is the culprit, we expect that the deviation of the apparent magnitude will continue growing, unless the systematic bias is set up in such an unlikely way as to mimic the effects of Λ (Drell et al. 2000). A turnover, or decrease of the deviation of apparent magnitude at high redshift, can be considered the "smoking gun" of Λ.

In a wonderful demonstration of good luck and hard work, Riess et al. (2001) report on *HST* observations of a probable SN Ia at $z \approx 1.7$ (SN 1997ff, the most distant SN ever observed) that suggest the expected turnover is indeed present, providing a tantalizing glimpse of the epoch of deceleration. (See also Benítez et al. 2002, which corrects the observed magnitude of SN 1997ff for gravitational lensing.) SN 1997ff was discovered by Gilliland & Phillips (1998) in a repeat *HST* observation of the Hubble Deep Field–North, and serendipitously monitored in the infrared with *HST*/NICMOS. The peak apparent SN brightness is consistent with that expected in the decelerating phase of the concordance cosmological model, $\Omega_m \approx 0.3$, $\Omega_\Lambda \approx 0.7$ (Fig. 1.7). It is inconsistent with gray dust or simple luminosity evolution, when combined with the data for SNe Ia at $z \approx 0.5$. On the other hand, it is wise to remain cautious: the error bars are large, and it is always possible that we are being fooled by this one object. The HZT and SCP currently have programs to find and measure more SNe Ia at such high redshifts. For example, SN candidates at very high redshifts (e.g., Giavalisco et al. 2002) have been found by "piggybacking" on the Great Observatories Origins Deep Survey (GOODS) being conducted with the Advanced Camera for Surveys aboard *HST*.

Less ambitious programs, concentrating on SNe Ia at $z \gtrsim 0.8$, have already been completed (HZT; Tonry et al. 2003) or are nearing completion (SCP). Tonry et al. (2003) measured several SNe Ia at $z \approx 1$, and their deviation of apparent magnitude from the low-Ω_m, zero-Λ model is roughly the same as that at $z \approx 0.5$, in agreement with expectations based on the results of Riess et al. (2001). Moreover, the new sample of high-redshift SNe Ia presented by Tonry et al., analyzed with methods distinct from (but similar to) those used previously, confirm the result of Riess et al. (1998b) and Perlmutter et al. (1999) that the expansion of the Universe is accelerating. By combining all of the available data sets, Tonry et al. are able to use 230 SNe Ia, and they place the following constraints on cosmological quantities. (1) If the equation of state parameter of the dark energy is $w = -1$, then $H_0 t_0 = 0.96 \pm 0.04$, and $\Omega_\Lambda - 1.4\Omega_m = 0.35 \pm 0.14$. (2) Including the constraint of a flat universe, they find that $\Omega_m = 0.28 \pm 0.05$, independent of any large-scale structure measurements. (3) Adopting a prior based on the 2dFGRS constraint on Ω_m (Percival et al. 2001) and assuming a flat universe, they derive that $-1.48 < w < -0.72$ at 95% confidence. These constraints are similar in precision and in value to very recent conclusions reported using *WMAP* (Spergel et al. 2003), also in combination with the 2dFGRS. Complete details on the SN Ia results, as well as figures, can be found in Tonry et al. (2003).

1.5.4 Measuring the Dark Energy Equation of State

Every energy component in the Universe can be parameterized by the way its density varies as the Universe expands (scale factor a), with $\rho \propto a^{-3(1+w)}$, and w reflects the component's equation of state, $w = P/(\rho c^2)$, where P is the pressure exerted by the component. So for matter, $w = 0$, while an energy component that does not vary with scale factor has $w = -1$, as in the cosmological constant Λ. Some really strange energies may have $w < -1$: their density increases with time (Carroll, Hoffman, & Trodden 2003)! Clearly, a good estimate of w becomes the key to differentiating between models.

The CMB observations imply that the geometry of the universe is close to flat, so the energy density of the dark component is simply related to the matter density by $\Omega_x = 1 - \Omega_m$. This allows the luminosity distance as a function of redshift to be written as

$$D_L(z) \ = \ \frac{c(1+z)}{H_0} \int_0^z \frac{[1+\Omega_x((1+\mathrm{z})^{3w}-1)]^{-1/2}}{(1+\mathrm{z})^{3/2}} \, \mathrm{dz} \ ,$$

showing that the dark energy density and equation of state directly influence the apparent brightness of standard candles. As demonstrated graphically in Figure 1.8 (*left*), SNe Ia observed over a wide range of redshifts can constrain the dark energy parameters to a cosmologically interesting accuracy.

But there are two major problems with using SNe Ia to measure w. First, systematic uncertainties in SN Ia peak luminosity limit how well $D_L(z)$ can be measured. While statistical uncertainty can be arbitrarily reduced by finding thousands of SNe Ia, intrinsic SN properties such as evolution and progenitor metallicity, and observational limits like photometric calibrations and K-corrections, create a systematic floor that cannot be decreased by sheer force of numbers. We expect that systematics can be controlled to at best 3%.

Second, SNe at $z > 1.0$ are very hard to discover and study from the ground. As discussed above, both the HZT and the SCP have found a few SNe Ia at $z > 1.0$, but the numbers and quality of these light curves are insufficient for a w measurement. Large numbers of SNe Ia at $z > 1.0$ are best left to a wide-field optical/infrared imager in space, such as the proposed *Supernova/Acceleration Probe* (*SNAP*; Nugent et al. 2000) satellite.

Fortunately, an interesting measurement of w can be made at present. The current values of Ω_m from many methods (most recently *WMAP*: 0.27; Spergel et al. 2003) make an excellent substitute for those expensive SNe at $z > 1.0$. Figure 1.8 (*left*) shows that a SN Ia sample with a maximum redshift of $z = 0.8$, combined with the current 10% error on Ω_m, will do as well as a SN Ia sample at much higher redshifts. Within a few years, the Sloan Digital Sky Survey and *WMAP* will solidify the estimate of Ω_m and sharpen w further.

Both the SCP and the HZT are involved in multi-year programs to discover and monitor hundreds of SNe Ia for the purpose of measuring w. For example, the HZT's project, ESSENCE (Equation of State: SupErNovae trace Cosmic Expansion), is designed to discover 200 SNe Ia evenly distributed in the $0.2 < z < 0.8$ range. The CTIO 4-m telescope and mosaic camera are being used to find and follow the SNe by imaging on every other dark night for several consecutive months of the year. Keck and other large telescopes are being used to get the SN spectra and redshifts. Project ESSENCE will eventually provide an estimate of w to an accuracy of $\sim$10% (Fig. 1.8, *right*).

Farther in the future, large numbers of SNe Ia to be found by the *SNAP* satellite and the Large-area Synoptic Survey Telescope (the "Dark Matter Telescope"; Tyson & Angel 2001) could reveal whether the value of w depends on redshift, and hence should give ad-

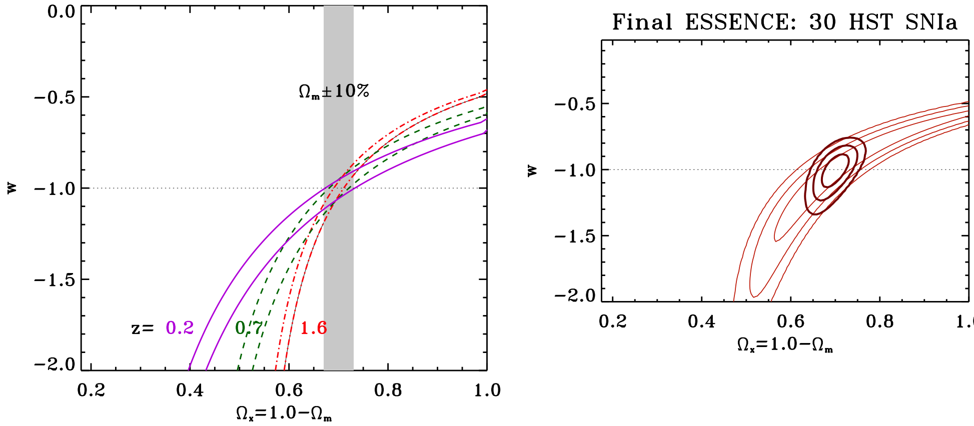

Fig. 1.8. *Left:* Constraints on Ω_x and w from SN data sets collected at $z = 0.2$ (solid lines), $z = 0.7$ (dashed lines), and $z = 1.6$ (dash-dot lines). The shaded area indicates how an independent estimate of Ω_m with a 10% error can help constrain w. *Right:* Expected constraints on w with the desired final ESSENCE data set of 200 SNe Ia, 30 of which (in the redshift range $0.6 < z < 0.8$) are to be observed with *HST*. The thin lines are for SNe alone while the thick lines assume an uncertainty in Ω_m of 7%. The final ESSENCE data will constrain the value of w to $\sim$10%.

ditional constraints on the nature of the dark energy. High-redshift surveys of galaxies such as DEEP2 (Davis et al. 2001), as well as space-based missions to map the CMB (*Planck*), should provide additional evidence for (or against) Λ. Observational cosmology promises to remain exciting for quite some time!

Acknowledgements. I thank all of my HZT collaborators for their contributions to our team's research, and members of the SCP for their seminal complementary work on the accelerating Universe. My group's work at U.C. Berkeley has been supported by NSF grant AST–9987438, as well as by grants GO–7505, GO/DD–7588, GO–8177, GO–8641, GO–9118, and GO–9352 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5–26555. KAIT was made possible by generous donations from Sun Microsystems, Inc., the Hewlett-Packard Company, AutoScope Corporation, Lick Observatory, the National Science Foundation, the University of California, and the Sylvia and Jim Katzman Foundation.

References

Aguirre, A. N. 1999a, ApJ, 512, L19
——. 1999b, ApJ, 525, 583
Aguirre, A. N., & Haiman, Z. 1999, ApJ, 525, 583
Aldering, G., Knop, R., & Nugent, P. 2000, AJ, 119, 2110
Bahcall, J. N., et al. 1996, ApJ, 457, 19
Bahcall, N. A., Ostriker, J. P., Perlmutter, S., & Steinhardt, P. J. 1999, Science, 284, 1481
Balbi, A., et al. 2000, ApJ, 545, L1
Benítez, N., Riess, A., Nugent, P., Dickinson, M., Chornock, R., & Filippenko, A. V. 2002, ApJ, 577, L1
Branch, D. 1981, ApJ, 248, 1076
——. 1998, ARA&A, 36, 17
Branch, D., Fisher, A., & Nugent, P. 1993, AJ, 106, 2383
Branch, D., & Miller, D. L. 1993, ApJ, 405, L5

Branch, D., Romanishin, W., & Baron, E. 1996, ApJ, 465, 73 (erratum: 467, 473)
Branch, D., & Tammann, G. A. 1992, ARA&A, 30, 359
Caldwell, R. R., Davé, R., & Steinhardt, P. J. 1998, Ap&SS, 261, 303
Cappellaro, E., Turatto, M., Tsvetkov, D. Yu., Bartunov, O. S., Pollas, C., Evans, R., & Hamuy, M. 1997, A&A, 322, 431
Carroll, S. M., Hoffman, M., & Trodden, M. 2003, Phys. Rev. D, 68, 023509
Carroll, S. M., Press, W. H., & Turner, E. L. 1992, ARA&A, 30, 499
Chaboyer, B., Demarque, P., Kernan, P. J., & Krauss, L. M. 1998, ApJ, 494, 96
Coil, A. L., et al. 2000, ApJ, 544, L111
Cowan, J. J., McWilliam, A., Sneden, C., & Burris, D. L. 1997, ApJ, 480, 246
Davis, M., Newman, J. A., Faber, S. M., & Phillips, A. C. 2001, in Deep Fields, ed. S. Cristiani, A. Renzini, & R. E. Williams (Berlin: Springer), 241
de Bernardis, P., et al. 2000, Nature, 404, 955
——. 2002, ApJ, 564, 559
Drell, P. S., Loredo, T. J., & Wasserman, I. 2000, ApJ, 530, 593
Efstathiou, G., et al. 1999, MNRAS, 303, L47
——. 2002, MNRAS, 330, L29
Eisenstein, D. J., Hu, W., & Tegmark, M. 1998, ApJ, 504, L57
Filippenko, A. V. 1997a, in Thermonuclear Supernovae, ed. P. Ruiz-Lapuente et al. (Dordrecht: Kluwer), 1
——. 1997b, ARA&A, 35, 309
——. 2001, PASP, 113, 1441
Filippenko, A. V., et al. 1992a, AJ, 104, 1543
——. 1992b, ApJ, 384, L15
Filippenko, A. V., Li, W. D., Treffers, R. R., & Modjaz, M. 2001, in Small-Telescope Astronomy on Global Scales, ed. W. P. Chen, C. Lemme, & B. Paczyński (San Francisco: ASP), 121
Filippenko, A. V., & Riess, A. G. 1998, Phys. Rep., 307, 31
Ford, C. H., et al. 1993, AJ, 106, 1101
Garnavich, P., et al. 1998a, ApJ, 493, L53
——. 1998b, ApJ, 509, 74
Giavalisco, M., et al. 2002, IAUC 7981
Gilliland, R. L., & Phillips, M. M. 1998, IAUC 6810
Goldhaber, G., et al. 1997, in Thermonuclear Supernovae, ed. P. Ruiz-Lapuente et al. (Dordrecht: Kluwer), 777
——. 1998a, BAAS, 30, 1325
——. 1998b, in Gravity: From the Hubble Length to the Planck Length, SLAC Summer Institute (Stanford, CA: SLAC)
——. 2001, ApJ, 558, 359
Goldhaber, G., & Perlmutter, S. 1998, Phys. Rep., 307, 325
Goobar, A., & Perlmutter, S. 1995, ApJ, 450, 14
Gratton, R. G., Fusi Pecci, F., Carretta, E., Clementini, G., Corsi, C. E., & Lattanzi, M. 1997, ApJ, 491, 749
Groom, D. E. 1998, BAAS, 30, 1419
Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., & Aviles, R. 1995, AJ, 109, 1
——. 1996a, AJ, 112, 2391
——. 1996b, AJ, 112, 2398
Hamuy, M., Trager, S. C., Pinto, P. A., Phillips, M. M., Schommer, R. A., Ivanov, V., & Suntzeff, N. B. 2000, AJ, 120, 1479
Hanany, S., et al. 2000, ApJ, 545, L5
Hancock, S., Rocha, G., Lazenby, A. N., & Gutiérrez, C. M. 1998, MNRAS, 294, L1
Hatano, K., Branch, D., & Deaton, J. 1998, ApJ, 502, 177
Höflich, P., Wheeler, J. C., & Thielemann, F. K. 1998, ApJ, 495, 617
Hoyle, F., Burbidge, G., & Narlikar, J. V. 2000, A Different Approach to Cosmology (Cambridge: Cambridge Univ. Press)
Ivanov, V. D., Hamuy, M., & Pinto, P. A. 2000, ApJ, 542, 588
Kim, A., Goobar, A., & Perlmutter, S. 1996, PASP, 108, 190
Leibundgut, B., et al. 1993, AJ, 105, 301
——. 1996, ApJ, 466, L21
Leonard, D. C., et al. 2002a, PASP, 114, 35 (erratum: 114, 1291)
——. 2002b, AJ, 124, 2490

Li, W., et al. 2000, in Cosmic Explosions, ed. S. S. Holt & W. W. Zhang (New York: AIP), 103
——. 2001a, PASP, 113, 1178
——. 2003, PASP, 115, 453
Li, W., Filippenko, A. V., Treffers, R. R., Riess, A. G., Hu, J., & Qiu, Y. 2001b, ApJ, 546, 734
Lineweaver, C. H. 1998, ApJ, 505, L69
Lineweaver, C. H., & Barbosa, D. 1998, ApJ, 496, 624
Matheson, T., Filippenko, A. V., Li, W., Leonard, D. C., & Shields, J. C. 2001, AJ, 121, 1648
Modjaz, M., Li, W., Filippenko, A. V., King, J. Y., Leonard, D. C., Matheson, T., Treffers, R. R., & Riess, A. G. 2001, PASP, 113, 308
Narlikar, J. V., & Arp, H. C. 1997, ApJ, 482, L119
Netterfield, C. B., et al. 2002, ApJ, 571, 604
Nomoto, K., Umeda, H., Hachisu, I., Kato, M., Kobayashi, C., & Tsujimoto, T. 2000, in Type Ia Supernovae: Theory and Cosmology, ed. J. C. Niemeyer & J. W. Truran (Cambridge: Cambridge Univ. Press), 63
Norgaard-Nielsen, H., et al. 1989, Nature, 339, 523
Nugent, P., 2000, in Particle Physics and Cosmology: Second Tropical Workshop, ed. J. F. Nieves (New York: AIP), 263
Nugent, P., Kim, A., & Perlmutter, S. 2002, PASP, 114, 803
Nugent, P., Phillips, M., Baron, E., Branch, D., & Hauschildt, P. 1995, ApJ, 455, L147
Ostriker, J. P., & Steinhardt, P. J. 1995, Nature, 377, 600
Oswalt, T. D., Smith, J. A., Wood, M. A., & Hintzen, P. 1996, Nature, 382, 692
Pain, R., et al. 2002, ApJ, 577, 120
Peacock, J. A., et al. 2001, Nature, 410, 169
Percival, W., et al. 2001, MNRAS, 327, 1297
Perlmutter, S., et al. 1995a, ApJ, 440, L41
——. 1995b, IAUC 6270
——. 1997, ApJ, 483, 565
——. 1998, Nature, 391, 51
——. 1999, ApJ, 517, 565
Phillips, M. M. 1993, ApJ, 413, L105
Phillips, M. M., et al. 1992, AJ, 103, 1632
Pskovskii, Yu. P. 1977, Sov. Astron., 21, 675
——. 1984, Sov. Astron., 28, 658
Riess, A. G., et al. 1997, AJ, 114, 722
——. 1998b, AJ, 116, 1009
——. 1999a, AJ, 117, 707
——. 1999c, AJ, 118, 2675
——. 2000, ApJ, 536, 62
——. 2001, ApJ, 560, 49
Riess, A. G., Filippenko, A. V., Li, W. D., & Schmidt, B. P. 1999b, AJ, 118, 2668
Riess, A. G., Nugent, P. E., Filippenko, A. V., Kirshner, R. P., & Perlmutter, S. 1998a, ApJ, 504, 935
Riess, A. G., Press, W. H., & Kirshner, R. P. 1995, ApJ, 438, L17
——. 1996a, ApJ, 473, 88
——. 1996b ApJ, 473, 588.
Saha, A., et al. 1997, ApJ, 486, 1
Sandage, A., et al. 1996, ApJ, 460, L15
Sandage, A., & Tammann, G. A. 1993, ApJ, 415, 1
Schmidt, B. P., et al. 1998, ApJ, 507, 46
Spergel, D. N., et al. 2003, ApJS, 148, 175
Sullivan, M., et al. 2004, MNRAS, in press (astro-ph/0211444)
Suntzeff, N. 1996, in Supernovae and Supernova Remnants, ed. R. McCray & Z. Wang (Cambridge: Cambridge Univ. Press), 41
Suntzeff, N., et al. 1996, IAUC 6490
Tonry, J. L., et al. 2003, ApJ, 594, 1
Tripp, R. 1997, A&A, 325, 871
——. 1998, A&A, 331, 815
Turatto, M., et al. 1996, MNRAS, 283, 1

Tyson, J. A., & Angel, R. 2001, in The New Era of Wide Field Astronomy, ed. R. Clowes et al. (San Francisco: ASP), 347
Umeda, H., et al. 1999, ApJ, 522, L43
van den Bergh, S., & Pazder, J. 1992, ApJ, 390, 34
Vaughan, T. E., Branch, D., Miller, D. L., & Perlmutter, S. 1995, ApJ, 439, 558
Wambsganss, J., Cen, R., & Ostriker, J. P. 1998, ApJ, 494, 29
Yungelson, L. R., & Livio, M. 2000, ApJ, 528, 108
Zaldarriaga, M., Spergel, D. N., & Seljak, U. 1997, ApJ, 488, 1