New Constraints on $\Omega_{\rm M}$ and Ω_Λ From an Independent Set of High-Redshift Supernovae Observed With HST[1]

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ABSTRACT

This paper presents measurements of $\Omega_{\rm M}$ and Ω_Λ from 11 supernovae with high-quality lightcurves measured with WFPC2 on HST. This is an independent set of high-redshift supernovae that confirm previous supernova evidence for an accelerating Universe. Because of the high-quality lightcurves available from photometry on WFPC2, these 11 supernovae alone provide limits on the cosmological parameters comparable in statistical weight to the previous results. Combined with earlier Supernova Cosmology Project data, the new supernovae yield a measurement of the mass density $\Omega_{\rm M} = 0.21^{+0.06}_{-0.05}$ (statistical) ± 0.05 (identified systematics), or equivalently a cosmological constant of $\Omega_\Lambda = 0.79^{+0.05}_{-0.06}$ (statistical) ± 0.05 (identfied systematics), under the assumption of a flat universe. When the supernova results are combined with an independent flat-universe measurement of $\Omega_{\rm M}$ from CMB and large scale structure data, they provide an upper limit on the dark energy equation of state parameter of $w < -0.70 \pm \sim 0.1$ (identfied systematic), if w is assumed to be constant in time. In addition to high-precision lightcurve measurements, the new data offer greatly improved color measurements of the high-redshift supernovae, and hence host-galaxy $E(B\text{-}V)$ estimates. These measurements indicate that only one or two of the 11 new supernovae suffers significant host-galaxy extinction; there is no trend of anomalous $E(B\text{-}V)$ at higher redshifts. The precision of the measurements is such that it is possi-

1. Introduction

In a series of papers cluminating in 1998, two teams reported observations of Type Ia Supernovae (SNe Ia), which gave strong evidence for an acceleration of the Universe's expansion, and hence for a non-zero cosmological constant, or dark energy density (Perlmutter *et al.* 1998; Garnavich *et al.* 1998a; Schmidt *et al.* 1998; Riess 1998; Perlmutter *et al.* 1999). These results ruled out a flat, matter-dominated ($\Omega_{\rm M} = 1$, $\Omega_\Lambda = 0$) universe. For a flat universe, motivated by inflation theory, they yielded a value for the cosmological con-

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stant of $\Omega_\Lambda \simeq 0.7$. Even in the absence of assumptions about the geometry of the Universe, the supernova results indicate at greater than 99% confidence the existence of a cosmological constant.

The supernova results combined with observations of the power spectrum of the Cosmic Microwave Background (CMB) (e.g., Jaffe *et al.* 2001) and the density of massive clusters (e.g., Turner 2001; Allen, Schmidt, & Fabian 2002; Bahcall *et al.* 2003) yield a consistent picture of a flat universe with $\Omega_\mathrm{M} \simeq 0.3$ and $\Omega_\Lambda \simeq 0.7$ (Bahcall *et al.* 1999). Each of these measurements are sensitive to different linear combinations of the parameters, and hence they complement each other. Moreover, because there are three different measurements of two parameters, the combination provides an important consistency check. While the current observations of massive clusters and high-redshift supernovae primarily probe the "recent" Universe at redshifts of $z < 1$, the CMB measurements probe the early Universe at $z \sim 1100$. That consistent results are obtained by measurements of vastly different epochs of the Universe's history is a vindication of the standard model of the expanding Universe.

In the redshift range around $z = 0.4$–0.7, the supernova results are most sensitive to a linear combination of Ω_M and Ω_Λ close to $\Omega_\mathrm{M} - \Omega_\Lambda$. In contrast, clusters are sensitive primarily to Ω_M alone, while the CMB is most sensitive to $\Omega_\mathrm{M} + \Omega_\Lambda$. Of the three cosmological measurements, the supernovae taken alone thus provide best *direct* evidence for dark energy; even under the assumption of a flat universe, it is the supernovae that indicate the presence of dark energy. Therefore, it is of importance to improve the precision of the result, to confirm the result with additional independent high-redshift supernovae, and also to limit the possible effects of systematic errors.

This paper presents 11 new supernovae discovered and observed by the Supernova Cosmology Project (SCP) at redshifts $0.35 < z < 0.86$, a range very similar to that of the 42 high-redshift supernovae reported in Perlmutter *et al.* (1999, hereafter P99). The supernovae of that paper, with one exception, were observed entirely with ground-based telescopes; the 11 supernovae of this work have complete lightcurves in both the R and I bands measured with the Wide-Field/Planetary Camera (WPFC2) on the Hubble Space Telescope (HST). The HST provides two primary advantages for photometry of point sources such as supernovae. First, from orbit, the sky background is much lower, allowing a much higher signal-to-noise ratio in a single exposure. Second, because the telescope is not limited by atmospheric seeing, it has very high spatial resolution. This helps the signal-to-noise ratio by greatly reducing the area of background emission which contributes to the noise of the source measurement, and moreover simplifies the task of separating the variable supernova signal from the host galaxy. With these advantages, the precision of the lightcurve and color measurements is so much greater for the 11 supernovae in this paper than was possible with previous ground-based observations. These 11 supernovae themselves provide a high-precision *new* set of supernovae to test the accelerating universe results.

Perlmutter *et al.* (1997, 1999) and Riess (1998) presented extensive accounts of, and bounds for, possible systematic uncertainties in the supernova measurements. One obvious possible source of systematic uncertainty that was discussed is the effect of host galaxy dust. For a given mass density, the effect of a cosmological constant on the magnitudes of high-redshift supernovae is to make their observed brightness *dimmer* than would have been the case with $\Omega_\Lambda = 0$. Dust extinction from within the host galaxy of the high-redshift supernovae could have a similar effect; however, dust extinction will also tend to redden the colors of the supernovae. Therefore, a measurement of the color of the high-redshift supernovae, compared to the known colors of SNe Ia, has been used to provide a upper limit on the effect of host-galaxy dust extinction, or a direct measurement of that extinction which may then be corrected. These color usually dominate the statistical error of photometric measurements. Previous analyses have either selected a low-extinction subset of high-redshift supernovae and not applied corrections dirctly (P99), or have used a biasing Bayesian prior on the intrinsic extinction distribution to limit the propogated uncertainties of errors in color measurements (P99, Riess 1998). The much higher precision of the HST lightcurves of this paper allow us to make high-quality, unbiased, individual host-galaxy extinction corrections to each supernova event.

In this paper, we first describe the PSF-fit photometry method used for extracting the lightcurves from the WPFC2 images. Next, we describe the lightcurve fitting procedure, including the methods used for calculating accurate K-corrections. So that all supernovae may be treated consistently, we apply the slightly updated K-correction procedure to all of the supernovae used in P99. We discuss the evidence for host-galaxy extinction (only significant for one of the 11 new supernovae) from the R-I lightcurve colors. We present the limits on the cosmological parameters Ω_M and Ω_Λ from the new dataset alone as well as combining this data set with the data of P99; this latter fit provides the best current limit on cosmological parameters from high-redshift SNe Ia. Finally, we present the limits on w, the equation of state of the dark energy, from these data, and from these data combined with recent WMAP results. Updated analyses of systematic uncertainties are presented for these measurements.

2. Observations, Data Reduction, and Analysis

2.1. WFPC2 Photometry

The supernovae discussed in this paper are listed in Table 1. They were discovered during three different supernova searches following the techniques described in Perlmutter *et al.* (1995, 1997, 1999). Two of the searches were conducted at the 4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO), in December 1997 and March/April 1998. The final search was conducted at the Canada-France-Hawaii Telescope (CFHT) on Mauna Kea in Hawaii in April/May 2000. In each case, 2–3 nights of reference images were followed 3–4 weeks later by 2–

3 nights of search images. The two images of each search field were seeing-matched and subtracted, and were searched for residuals indicating a supernova candidate. The March/April 1998 search originally targeted primarily higher-redshift supernovae to be observed by the HST, but marginal weather conditions limited the depth to which we were able to search. As a result, rather than being entirely at the higher redshift end, the 11 HST supernovae reported in this paper are at spaced approximately evenly in the range $0.3 < z < 0.8$.

Spectra were obtained at with the red-side of the LRIS (Oke *et al.* 1995) on the Keck 10m telescope, with FORS1 on Antu (VLT-UT1) (Appenzeller *et al.* 1998), and with WFOSC2 on the ESO 3.6m telescope.[23] These spectra were used to confirm the identification of the candidates as SNe Ia, and to measure the redshift of each candidate. All eleven supernovae in the set have strong confirmation as type Ia, although there is no measurement of the SiII feature (Pskovskii 1969; Branch & Patchet 1973) for the higher redshift supernovae (ANDY, PETER AND CHRIS, HELP!! WHAT SHOULD I SAY HERE ABOUT SiII6150 and SiII4??? ALSO, WHAT ABOUT Z MEASURED FROM SN ☑ FEATURES; ANY OTHERS?). Where possible, the redshift z of each candidate was measured by matching narrow features in the host galaxy of the supernovae; the precision of these measurements in z is typically 0.001. In cases where there were not sufficient host galaxy features (SN 1998aw and SN 1998ba), redshifts were measured from the supernova itself; in these cases, z is precise to typically 0.01. However, even in the latter case redshift measurements do not contribute significantly to the uncertainties in the final cosmological measurements since these are dominated by the photometric uncertainties.

Each of these supernovae was followed with two broadband filters with the Wide Field/Planetary Camera 2 (WFPC2) on the Hubble Space Telescope (HST). Table 1 lists the dates of these observations. The two filters were chosen to be those with maximum sensitivity to these faint objects, and which were as close as practical to the rest-frame B and V filters at the targeted redshifts. At the redshifts for the supernovae in this paper, the filters used approximate the ground-based R-band (F675W) and I-band (F814W) filters (with effective system transmission curves provided by the Space Telescope Science Institute). These filters roughly correspond to redshifted B- and V-band filters for the supernovae at $z < 0.7$, and redshifted U- and B- band filters for the supernovae at $z > 0.7$.

Supernovae were imaged with the Planetary Camera (PC) chip of WFPC2, which has a scale of $0.05''$/pixel. The HST images were reduced through the standard HST "On-The-Fly Reprocessing" data reduction pipeline provided by the Space Telescope Science Institute. Images were background subtracted, and images taken in the same orbit were combined to reject cosmic rays using the "crrej" procedure (a part of the STSDAS IRAF package). Photometric fluxes were extracted from the final images using a PSF-fitting procedure. Traditional PSF fitting procedures assume a single isolated point source

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[23] http://www.ls.eso.org/lasilla/sciops/efosc/

Table 1: WFPC2 Supernova Observations

SN Name	z	F675W Observations	F814W Observations
1997ek	0.863	1998-01-05 (400s,400s)	1998-01-05 (500s,700s)
		1998-01-11 (400s,400s)	1998-01-11 (500s,700s)
			1998-02-02 (1100s,1200s)
			1998-02-14 (1100s,1200s)
			1998-02-27 (1100s,1200s)
			1998-11-09 (1100s,1300s)
			1998-11-16 (1100s,1300s)
1997eq	0.538	1998-01-06 (300s,300s)	1998-01-06 (300s,300s)
		1998-01-21 (400s,400s)	1998-01-11 (300s,300s)
			1998-02-02 (500s,700s)
		1998-02-11 (400s,400s)	1998-02-11 (500s,700s)
		1998-02-19 (400s,400s)	1998-02-19 (500s,700s)
1997ez	0.778	1998-01-05 (400s,400s)	1998-01-05 (500s,700s)
		1998-01-11 (400s,400s)	1998-01-11 (500s,700s)
			1998-02-02 (1100s,1200s)
			1998-02-14 (1100s,1200s)
			1998-02-27 (100s,1200s,1100s,1200s)
1998as	0.355	1998-04-08 (400s,400s)	1998-04-08 (500s,700s)
		1998-04-20 (400s,400s)	1998-04-20 (500s,700s)
		1998-05-11 (400s,400s)	1998-05-11 (500s,700s)
		1998-05-15 (400s,400s)	1998-05-15 (500s,700s)
		1998-05-29 (400s,400s)	1998-05-29 (500s,700s)
1998aw	0.440	1998-04-08 (300s,300s)	1998-04-08 (300s,300s)
		1998-04-18 (300s,300s)	1998-04-18 (300s,300s)
		1998-04-29 (400s,400s)	1998-04-29 (500s,700s)
		1998-05-14 (400s,400s)	1998-05-14 (500s,700s)
		1998-05-28 (400s,400s)	1998-05-28 (500s,700s)
1998ax	0.497	1998-04-08 (300s,300s)	1998-04-08 (300s,300s)
		1998-04-18 (300s,300s)	1998-04-18 (300s,300s)
		1998-04-29 (300s,300s)	1998-04-29 (500s,700s)
		1998-05-14 (300s,300s)	1998-05-14 (500s,700s)
		1998-05-27 (300s,300s)	1998-05-27 (500s,700s)
1998ay	0.638	1998-04-08 (400s,400s)	1998-04-08 (500s,700s)
		1998-04-20 (400s,400s)	1998-04-20 (500s,700s)
			1998-05-11 (1100s,1200s)
			1998-05-15 (1100s,1200s)
			1998-06-03 (1100s,1200s)
1998ba	0.430	1998-04-08 (300s,300s)	1998-04-08 (300s,300s)
		1998-04-19 (300s,300s)	1998-04-19 (300s,300s)
		1998-04-29 (400s,400s)	1998-04-29 (500s,700s)
		1998-05-13 (400s,400s)	1998-05-13 (500s,700s)
		1998-05-28 (400s,400s)	1998-05-28 (500s,700s)
1998be	0.644	1998-04-08 (300s,300s)	1998-04-08 (300s,300s)
		1998-04-19 (300s,300s)	1998-04-19 (300s,300s)
		1998-04-30 (400s,400s)	1998-04-30 (500s,700s)
		1998-05-15 (400s,400s)	1998-05-15 (500s,700s)
		1998-05-28 (400s,400s)	1998-05-28 (500s,700s)
1998bi	0.740	1998-04-06 (400s,400s)	1998-04-06 (500s,700s)
		1998-04-18 (400s,400s)	1998-04-18 (500s,700s)
			1998-04-28 (1100s,1200s)
			1998-05-12 (1100s,1200s)
			1998-06-02 (1100s,1200s)
2000fr	0.543		2000-05-08 (2200s)
		2000-05-15 (600s,600s)	2000-05-15 (1100s,1100s)
		2000-05-28 (600s,600s)	2000-05-28 (600s,600s)
		2000-06-10 (500s,500s)	2000-06-10 (600s,600s)
		2000-06-22 (1100s,1300s)	2000-06-22 (1100s,1200s)
		2000-07-08 (1100s,1300s)	2000-07-08 (110s,1200s)

above a constant background. In this case, the point source was superimposed on top of the image of the host galaxy. In all cases, the supernova image was separated from the core of the host galaxy; however, in most cases the separation was not enough that an annular measurement of the background would be accurate. Because the host galaxy flux should be constant in all of the images, we used a PSF fitting procedure which fit a PSF *simultaneously* to every image of a given supernovae observed through a given photometric filter. The model we fit was:

$$f_i(x,y) = f_{0i} \times \mathrm{psf}(x - x_{0i}, y - y_{0i}) + \mathrm{bg}(x - x_{0i}, y - y_{0i}; a_j) + p_i \quad (1)$$

where $f_i(x,y)$ is the measured flux in pixel (x,y) of the ith image, (x_{0i}, y_{0i}) is the position of the supernova on the ith image, f_{0i} is the total flux in the supernova in the ith image, $\mathrm{psf}(u,v)$ is a normalized point spread function, $\mathrm{bg}(u,v)$ is a constant background parametrized by a_j, and p_i is a pedestal offset for the ith image. There are $4n+m-1$ parameters in this model, where n is the number of images (typically 2, 5, or 6 summed images) and m is the number of parameters a_j that specifies the background model (typically 3 or 6). (The -1 is due to the fact that a zeroth-order term in the background is degenerate with one of the p_i terms.) Parameters varied include f_i, x_{0i}, y_{0i}, p_i, and a_j. Due to the scarcity of objects in our images, geometric transformations between the images at different epochs using other objects on the four chips of WFPC2 allowed an *a priori* determination of (x_{0i}, y_{0i}) good to only $\sim$ 1 pixel. Allowing those parameters to vary in the fit (effectively, using the point source signature of the supernova to determine the offset of the image) provided position measurements a factor of $\sim$ 10 better. The model was fit to 7×7 or 9×9 pixel patches extracted from all of the images of a time sequence of a single supernova in a single filter. The series of f_{0i} values, corrected as described in the rest of this section, provided the data used in the lightcurve fits described in § 2.2. For one supernova (SN 1997ek) the F814W background was further constrained by a supernova-free "final reference" image taken 11 months after the supernova explosion. (Although obtaining final references to subtract the galaxy background is standard procedure for ground-based photometry of high-redshift supernovae, the higher resolution of WFPC2 provides sufficient separation between the supernova and host galaxy that such images are not always necessary, particularly in this redshift range.

A single Tiny Tim PSF (Krist & Hook 2001), corrected by an empirical electron diffusion term (Fruchter 2000), was used as $\mathrm{psf}(u,v)$ for all images of a given band. Although this is an approximation– the PSF of WFPC2 depends on the epoch of the observation as well as the position on the chip– this approximation should be a good one, especially given that for all of the observations the supernova was positioned close to the center of the PC. To verify that this approximation is valid, we reran the PSF fitting procedure with individually generated PSFs for most supernovae. The measured fluxes were not significantly different, showing differences in both directions generally within 1–2% of the supernova peak flux value, much less than our photometric uncertainties on individual data points.

One of the great advantages of the Hubble Space Telescope is its low background. However, CCD photometry of faint objects over a low background suffers from an imperfect charge transfer efficiency (CTE) effect, which can lead to a systematic underestimate of the flux of point sources. On the PC, these effects can be as large as $\sim 15\%$. The measured flux values (f_i above) extracted were corrected for the CTE of WFPC2 following the standard procedure of Dolphin (2000).[24] Because the host galaxy is a smooth background underneath the point source, it was considered as a contribution to the background in the CTE correction. For an image which was a combination of several separate exposures within the same orbit or orbits, the CTE calculation was performed assuming that each image had a measured flux whose fraction of the total flux was equal to the fraction of that individual image's exposure time to the summed image's total exposure time.

In addition to the HST data, there exists some ground-based photometry for each of these SNe. This includes the images from the search itself, as well as a limited amount of follow-up. The details of which supernovae were observed with which telescopes are given with the lightcurves in Appendix A. Ground-based photometric fluxes were extracted from images using the same aperture photometry procedure of P99. A complete lightcurve in a given filter (R or I) combined the HST data with the ground-based data (using the color correction procedure described below in § 2.3), using measured zeropoints for the ground-based data and the Vega zeropoints of Dolphin (2000) for the HST data. The uncertainties on those zeropoints (0.003 for F814W or 0.006 for F675W) were added as correlated errors between all HST data points when combining with the ground-based lightcurve. Similarly, the measured uncertainty in the ground-based zeropoint was added as a correlated error to all ground-based fluxes.

2.2. Lightcurve Fits

It is the magnitude of the supernova at its lightcurve peak that serves as a standard candle in estimating the cosmological parameters from the luminosity distance relationship. To estimate this peak magnitude, we performed template fits to the time series of photometric data for each supernova. In addition to the 11 SNe described here, lightcurve fits were also performed to the supernovae from P99, including 18 supernovae from Hamuy *et al.* (1996, hereafter H96), and eight from Riess (1999a, hereafter R99) which match the same selection criteria used for the H96 supernovae (having data within six days of maximum light and located at $cz > 4000$ km/s). Because of new templates and K-corrections (see below), lightcurve fits to the photometric data on the 42 high-redshift of supernovae P99 were redone for this paper for consistency.

Lightcurve fits were performed using a χ^2-minimization procedure based on MINUIT (James & Roos 1975). For both high and low-redshift supernovae, color corrections and K-corrections are applied (see

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[24] updated by the coefficients posted later on the author's web page in May, 2001

§ 2.3) to the photometric data. These data were then fit to lightcurve templates. Fits were performed to the combined R and I band data for each high-redshift supernova. (The exceptions are the seven high-redshift supernovae from P99 for which no I-band lightcurve is available, and which are therefore not included in the main analyses of this paper.) For low-redshift supernovae, fits were performed using only the B and V band data (which correspond to de-redshifted R and I bands for most of the high-redshift supernovae). The lightcurve model fit to the supernova has four parameters to modify the lightcurve templates: time of rest-frame B-band maximum light, peak flux in R, R-I color, and stretch s. Stretch (Perlmutter *et al.* 1997; Goldhaber *et al.* 2001) is a parameter which scales the time relative to maximum light, so that a supernova with a high stretch has a relatively slow decay from maximum, and a supernova with a low stretch has a relatively fast decay from maximum. For supernovae in the redshift range $z = 0.3$–0.7, a B template was fit to the R-band lightcurve and a V template was fit to the I-band lightcurve. For supernovae at $z > 0.7$, a U template was fit to the R-band lightcurve and a B template to the I-band lightcurve. Two of the high redshift supernovae from P99 fall at $z \sim 0.18$ (SN 1997I and SN 1997N); for these supernovae, V and R templates were fit to the R and I band data. (The peak B band magnitude was extracted by adding the intrinsic SN Ia B-V color to the fit V band magnitude at the epoch of B maximum.)

The B template used in the lightcurve fits was that of Goldhaber *et al.* (2001). For this paper, new V-band and R-band templates were generated following a procedure similar to that of Goldhaber *et al.* (2001), by fitting a smooth parametrized curve through the low-z supernova data of H96 and R99. A new U-band template was generated with data from Hamuy *et al.* (1991), Lira *et al.* (1998), Richmond *et al.* (1995), Suntzeff *et al.* (1999), and Wells *et al.* (1994). Each of these new templates was fit to the low-redshift supernova data simultaneously with a stretch fit of the B-template to the B-band data of the same supernova, thereby guaranteeing that the fit templates correspond to a stretch=1 supernova. Lightcurve templates had an initial parabola with a 20-day rise time (Aldering, Knop, & Nugent 2000), joined to a smooth spline section to describe the main part of the lightcurve, then joined to an exponential decay to describe the final tail at $>\sim$ 70 days past maximum light. The first 90 days of each of the three templates is shown in Table 2. Due to a secondary "hump" or "shoulder" $\sim$ 20 days after maximum, the R-band lightcurve does not appear to vary strictly according to the single simple stretch parameter which is so successful in describing the different U-, B-, and V-band lightcurves. Nonetheless, the lightcurve fits performed in this paper assume that the R-band template is adequately described by stretch. The effects of this on any results of this paper will be small, as the R-band template was only used for the two supernovae at $z \sim 0.18$. For one of these two supernovae, although the χ^2 for the lightcurve fit is poor, we have a very robust measurement of the peak R and I band magnitudes, and a robust stretch measurement (from the R-band lightcurve, which is a redshifted V-

Table 2: U, V, and R Lightcurve Templates Used

Day[1]	U flux[2]	V flux[2]	R flux[2]	Day[1]	U flux[2]	V flux[2]	R flux[2]
-19	6.712e-03	4.960e-03	5.779e-03	31	4.790e-02	2.627e-01	3.437e-01
-18	2.685e-02	1.984e-02	2.312e-02	32	4.524e-02	2.481e-01	3.238e-01
-17	6.041e-02	4.464e-02	5.201e-02	33	4.300e-02	2.345e-01	3.054e-01
-16	1.074e-01	7.935e-02	9.246e-02	34	4.112e-02	2.218e-01	2.887e-01
-15	1.678e-01	1.240e-01	1.445e-01	35	3.956e-02	2.099e-01	2.733e-01
-14	2.416e-01	1.785e-01	2.080e-01	36	3.827e-02	1.990e-01	2.592e-01
-13	3.289e-01	2.430e-01	2.832e-01	37	3.722e-02	1.891e-01	2.463e-01
-12	4.296e-01	3.174e-01	3.698e-01	38	3.636e-02	1.802e-01	2.345e-01
-11	5.437e-01	4.017e-01	4.681e-01	39	3.565e-02	1.721e-01	2.237e-01
-10	6.712e-01	4.960e-01	5.779e-01	40	3.506e-02	1.649e-01	2.137e-01
-9	7.486e-01	5.889e-01	6.500e-01	41	3.456e-02	1.583e-01	2.046e-01
-8	8.151e-01	6.726e-01	7.148e-01	42	3.410e-02	1.524e-01	1.962e-01
-7	8.711e-01	7.469e-01	7.725e-01	43	3.365e-02	1.471e-01	1.884e-01
-6	9.168e-01	8.115e-01	8.236e-01	44	3.318e-02	1.423e-01	1.813e-01
-5	9.524e-01	8.660e-01	8.681e-01	45	3.266e-02	1.378e-01	1.747e-01
-4	9.781e-01	9.103e-01	9.062e-01	46	3.205e-02	1.337e-01	1.687e-01
-3	9.940e-01	9.449e-01	9.382e-01	47	3.139e-02	1.299e-01	1.630e-01
-2	1.000e+00	9.706e-01	9.639e-01	48	3.072e-02	1.263e-01	1.578e-01
-1	9.960e-01	9.880e-01	9.834e-01	49	3.005e-02	1.229e-01	1.529e-01
0	9.817e-01	9.976e-01	9.957e-01	50	2.945e-02	1.195e-01	1.483e-01
1	9.569e-01	1.000e+00	1.000e+00	51	2.893e-02	1.161e-01	1.440e-01
2	9.213e-01	9.958e-01	9.952e-01	52	2.853e-02	1.128e-01	1.398e-01
3	8.742e-01	9.856e-01	9.803e-01	53	2.830e-02	1.096e-01	1.359e-01
4	8.172e-01	9.702e-01	9.545e-01	54	2.827e-02	1.064e-01	1.320e-01
5	7.575e-01	9.502e-01	9.196e-01	55	2.849e-02	1.033e-01	1.282e-01
6	6.974e-01	9.263e-01	8.778e-01	56	2.793e-02	1.003e-01	1.244e-01
7	6.375e-01	8.991e-01	8.313e-01	57	2.738e-02	9.743e-02	1.207e-01
8	5.783e-01	8.691e-01	7.821e-01	58	2.684e-02	9.467e-02	1.170e-01
9	5.205e-01	8.369e-01	7.324e-01	59	2.630e-02	9.207e-02	1.133e-01
10	4.646e-01	8.031e-01	6.842e-01	60	2.578e-02	8.964e-02	1.097e-01
11	4.113e-01	7.683e-01	6.396e-01	61	2.527e-02	8.741e-02	1.061e-01
12	3.610e-01	7.330e-01	6.007e-01	62	2.477e-02	8.538e-02	1.026e-01
13	3.145e-01	6.977e-01	5.691e-01	63	2.428e-02	8.359e-02	9.910e-02
14	2.725e-01	6.629e-01	5.444e-01	64	2.380e-02	8.207e-02	9.568e-02
15	2.356e-01	6.293e-01	5.254e-01	65	2.333e-02	8.083e-02	9.232e-02
16	2.044e-01	5.972e-01	5.113e-01	66	2.287e-02	7.927e-02	8.902e-02
17	1.783e-01	5.667e-01	5.011e-01	67	2.242e-02	7.774e-02	8.579e-02
18	1.567e-01	5.376e-01	4.938e-01	68	2.197e-02	7.624e-02	8.264e-02
19	1.388e-01	5.099e-01	4.887e-01	69	2.154e-02	7.476e-02	7.958e-02
20	1.239e-01	4.835e-01	4.848e-01	70	2.111e-02	7.332e-02	7.660e-02
21	1.115e-01	4.583e-01	4.814e-01	71	2.070e-02	7.191e-02	7.373e-02
22	1.008e-01	4.342e-01	4.776e-01	72	2.029e-02	7.052e-02	7.096e-02
23	9.144e-02	4.113e-01	4.725e-01	73	1.989e-02	6.916e-02	6.832e-02
24	8.314e-02	3.894e-01	4.653e-01	74	1.949e-02	6.782e-02	6.581e-02
25	7.583e-02	3.685e-01	4.552e-01	75	1.911e-02	6.651e-02	6.344e-02
26	6.941e-02	3.486e-01	4.414e-01	76	1.873e-02	6.523e-02	6.199e-02
27	6.380e-02	3.296e-01	4.247e-01	77	1.836e-02	6.397e-02	6.057e-02
28	5.891e-02	3.115e-01	4.058e-01	78	1.799e-02	6.274e-02	5.918e-02
29	5.467e-02	2.943e-01	3.855e-01	79	1.764e-02	6.153e-02	5.783e-02
30	5.102e-02	2.781e-01	3.645e-01	80	1.729e-02	6.034e-02	5.650e-02

1: Day is relative to the epoch of the maximum of the B-band lightcurve.

2: Relative fluxes.

band lightcurve).

Some of the high-redshift supernovae lack a supernova-free host galaxy image. These supernovae were fit with an additional variable parameter: the zero-level of the I-band lightcurve. The supernovae treated in this manner include SN 1997J, SN 1997O, SN 1997Q, SN 1997R, SN 1997S, SN 1997K, and SN 1997am. Both R and I band zero offsets were allowed to vary for SN 1994G.

The late-time lightcurve behavior may bias the result of a lightcurve fit (Aldering, Knop, & Nugent 2000); it is therefore important that the low and high-redshift supernovae be treated in as consistent a manner as possible. Few or none of the high-redshift supernovae have high-precision measurements ∼40–50 days after maximum light, so as in Perlmutter *et al.* (1997) and P99 these late-time points were eliminated from the low-redshift lightcurve data before the template fit procedure. Additionally, to allow for systematic offset uncertainties on the host galaxy subtraction, an "error floor" of 0.007 times the maximum lightcurve flux was applied; any point with an uncertainty below the error floor had its uncertainty replaced by that value (Goldhaber *et al.* 2001).

The final results of the lightcurve fits, including the effect of color corrections and K-corrections, are listed in Table 3 for the 11 supernovae of this paper. Table 4 shows the results of new lightcurve fits for the 42 high-redshift supernovae of P99, and Table 5 shows the results of lightcurve fits for the low-redshift supernovae from H96 and R99. Appendix A tabulates all of the lightcurve data and shows plots of all of the lightcurves for the SNe in this paper.

2.3. Color- and K-Corrections

In order to combine data from different telescopes, icolor corrections were applied to remove the differences in the spectral responses of the filters relative to the Bessell system (Bessell 1990). For the ground-based telescopes, the filters are close enough to the standard Bessell filters that a single linear color term (measured at each observatory with standard stars) suffices to put the data onto the Bessell system, with most corrections being smaller than 0.01 magnitudes. The WFPC2 filters are different enough from the ground-based filters, however, that a linear term is not sufficient. Moreover, the differences between a SN Ia and standard star spectral energy distribution (SED) are significant. In this case, color corrections were calculated by integrating template SN Ia spectra (described below).

In order to perform lightcurve template fitting, a cross-filter K-correction (Kim, Goobar, & Perlmutter 1996) must be applied to transform the data in the observed filter into a rest-frame magnitude in the filter used for the lightcurve template. The color correction to the nearest standard Bessell filter followed by a K-correction to a rest-frame filter is equivalent to a direct K-correction from the observed filter to the standard rest-frame filter. In practice, we perform the two steps separately so that all photometry may be combined to provide a lightcurve effectively observed through a standard (e.g.) R-band filter, which may then be K-corrected and fit with a single series of K-corrections.

Color and K-corrections were performed following the procedure of Nugent, Kim, & Perlmutter (2002). In order to per-

Table 3: Supernova Lightcurve Fits: HST Supernovae from this paper

SN	z	m_X[a]	m_B[b]	Stretch	*R*-*I*[c]	$E(B\text{-}V)$ Gal.[d]	$E(B\text{-}V)_{\rm host}$[e]	Excluded Subsets[f]
1997ek	0.863	23.39	24.58 ± 0.03	1.052 ± 0.002	0.831 ± 0.066	0.042	-0.125 ± 0.096	
1997eq	0.538	22.65	23.23 ± 0.03	0.987 ± 0.031	0.151 ± 0.034	0.044	-0.036 ± 0.038	
1997ez	0.778	23.27	24.39 ± 0.04	1.056 ± 0.038	0.696 ± 0.061	0.026	0.088 ± 0.089	
1998as	0.355	22.20	22.71 ± 0.03	0.942 ± 0.020	0.166 ± 0.032	0.037	0.082 ± 0.035	
1998aw	0.440	22.64	23.29 ± 0.02	1.025 ± 0.021	0.286 ± 0.028	0.026	0.227 ± 0.030	2,3
1998ax	0.497	22.59	23.20 ± 0.05	1.100 ± 0.034	0.123 ± 0.049	0.035	-0.003 ± 0.053	
1998ay	0.638	23.28	23.91 ± 0.08	1.054 ± 0.047	0.250 ± 0.072	0.035	-0.100 ± 0.091	
1998ba	0.430	22.34	22.94 ± 0.05	0.921 ± 0.023	0.057 ± 0.042	0.024	-0.023 ± 0.045	
1998be	0.644	23.31	23.89 ± 0.04	0.761 ± 0.033	0.406 ± 0.056	0.029	0.073 ± 0.072	
1998bi	0.740	22.95	24.00 ± 0.03	0.951 ± 0.035	0.526 ± 0.045	0.026	-0.002 ± 0.063	
2000fr	0.543	22.52	23.14 ± 0.03	1.076 ± 0.013	0.104 ± 0.032	0.030	-0.079 ± 0.036	

a: Magnitude in the observed filter at the peak of the rest-frame *B*-band lightcurve. X=*R* for $z < 0.7$, X=*I* for $z > 0.7$.

b: This value has been *K*-corrected and corrected for Galactic $E(B\text{-}V)$ extinction.

c: This is the observed *R*-*I* color at the epoch of the rest-frame *B*-band lightcurve peak.

d: Schlegel, Finkbeiner, & Davis (1998)

e: Measurement uncertainty only; no intrinsic color dispersion included.

f: The indicated supernovae were excluded from Subset 1 (full primary subset), Subset 2 (low-extinction primary subset), and/or Subset 3(low-extinction, strict SN Ia subset); see § 2.4.

form these corrections, a template SN Ia spectrum for each epoch of the lightcurve, as described in that paper, is necessary. The spectral template used in this present paper began with the template of that paper. To it was applied a smooth multiplicative function at each day to ensure that integration of the spectrum through the standard filters would produce the proper intrinsic colors for a Type Ia supernova (including a mild dependence of those intrinsic colors on stretch).

The proper intrinsic colors for the supernova spectral template were determined in the *BVRI* spectral range by smooth fits to the low-redshift supernova data of H96 and R99. For each color (*B*-*V*, *V*-*R*, and *R*-*I*), every data point from those papers was *K*-corrected and corrected for Galactic extinction. These data were plotted together, and then a smooth curve was fit to the plot of color versus date relative to maximum. This curve is given by two parameters, each of which was a function of time, and is described by a spline under tension: an "intercept" $b(t)$ and a "slope" $m(t)$. At any given date the intrinsic color is

$$color(t') = b(t') + m(t') \times 1/s \qquad (2)$$

where $t' = t/(s(1+z))$, z is the redshift of the supernova, and s is the stretch of the supernova from a simultaneous fit to the *B* and *V* lightcurves (matching the procedure used for most of the high redshift supernovae). As the goal was to determine intrinsic colors without making any assumptions about reddening, no host-galaxy extinction corrections were applied to the literature data at this stage of the analysis. Instead, host-galaxy extinction was handled by fitting the blue side ridge-line of the supernova color curves, so as to extract

Table 4: Supernova Lightcurve Fits: New Fits to Perlmutter (1999) SNe

SN	z	$m_X{}^a$	$m_B{}^b$	Stretch	R-I^c	$E(B$-$V)$ Gal.^{d}	$E(B$-$V)^e_{\rm host}$	Excluded Subsets^f
1992bi	0.458	22.13	22.81 ± 0.09	0.860 ± 0.451	—	0.010	—	1–3
1994F	0.354	22.06	22.55 ± 0.14	0.690 ± 0.142	—	0.036	—	1–3
1994H	0.374	21.31	21.84 ± 0.03	0.876 ± 0.033	—	0.031	—	1–3
1994al	0.420	22.37	22.68 ± 0.05	1.035 ± 0.147	—	0.136	—	1–3
1994am	0.372	21.81	22.33 ± 0.04	0.886 ± 0.002	—	0.031	—	1–3
1994an	0.378	22.13	22.57 ± 0.07	1.017 ± 0.119	—	0.066	—	1–3
1995aq	0.453	22.61	23.25 ± 0.07	0.870 ± 0.100	0.029 ± 0.132	0.022	-0.079 ± 0.139	1–3
1995ar	0.465	22.80	23.49 ± 0.08	0.915 ± 0.111	0.509 ± 0.233	0.022	0.433 ± 0.255	
1995as	0.498	23.03	23.68 ± 0.07	1.038 ± 0.091	0.153 ± 0.205	0.021	0.033 ± 0.222	3
1995at	0.655	22.62	23.25 ± 0.03	1.050 ± 0.064	0.350 ± 0.109	0.019	-0.003 ± 0.139	1–3
1995aw	0.400	21.79	22.28 ± 0.03	1.186 ± 0.037	-0.116 ± 0.103	0.040	-0.159 ± 0.108	
1995ax	0.615	22.54	23.21 ± 0.06	1.129 ± 0.071	0.120 ± 0.211	0.033	-0.200 ± 0.259	
1995ay	0.480	22.64	23.05 ± 0.04	0.881 ± 0.066	0.206 ± 0.164	0.114	0.021 ± 0.177	
1995az	0.450	22.46	22.66 ± 0.07	0.973 ± 0.066	0.085 ± 0.138	0.181	-0.118 ± 0.148	
1995ba	0.388	22.08	22.65 ± 0.05	0.970 ± 0.046	0.013 ± 0.106	0.018	-0.040 ± 0.112	
1996cf	0.570	22.70	23.30 ± 0.03	1.000 ± 0.050	0.152 ± 0.093	0.040	-0.078 ± 0.109	3
1996cg	0.490	22.46	23.09 ± 0.03	1.013 ± 0.041	0.299 ± 0.101	0.035	0.186 ± 0.110	3
1996ci	0.495	22.19	22.82 ± 0.02	0.966 ± 0.045	0.081 ± 0.071	0.028	-0.054 ± 0.076	
1996ck	0.656	23.09	23.76 ± 0.05	0.888 ± 0.077	0.189 ± 0.262	0.032	-0.227 ± 0.333	
1996cl	0.828	23.37	24.52 ± 0.16	0.963 ± 0.234	0.550 ± 0.188	0.035	-0.362 ± 0.265	
1996cm	0.450	22.67	23.26 ± 0.07	0.899 ± 0.065	0.212 ± 0.180	0.049	0.103 ± 0.193	3
1996cn	0.430	22.58	23.25 ± 0.03	0.892 ± 0.064	0.375 ± 0.091	0.025	0.313 ± 0.100	2,3
1997F	0.580	22.91	23.49 ± 0.06	1.050 ± 0.068	0.249 ± 0.205	0.040	0.023 ± 0.244	
1997G	0.763	23.48	24.41 ± 0.40	0.825 ± 0.096	0.094 ± 0.447	0.043	-0.708 ± 0.600	
1997H	0.526	22.69	23.25 ± 0.03	0.887 ± 0.050	0.295 ± 0.181	0.051	0.125 ± 0.203	
1997I	0.172	20.18	20.41 ± 0.01	0.965 ± 0.009	0.072 ± 0.047	0.051	0.086 ± 0.066	
1997J	0.619	23.21	23.84 ± 0.06	1.038 ± 0.124	0.167 ± 0.342	0.039	-0.160 ± 0.423	
1997K	0.592	23.78	24.42 ± 0.12	1.083 ± 0.159	0.280 ± 0.356	0.020	0.053 ± 0.429	1–3
1997L	0.550	22.90	23.52 ± 0.05	0.938 ± 0.058	—	0.025	—	1–3
1997N	0.180	20.40	20.49 ± 0.02	1.070 ± 0.016	-0.090 ± 0.096	0.031	-0.089 ± 0.130	
1997O	0.374	23.00	23.53 ± 0.07	1.045 ± 0.069	0.085 ± 0.157	0.029	0.036 ± 0.169	1–3
1997P	0.472	22.53	23.15 ± 0.04	0.890 ± 0.039	0.054 ± 0.218	0.033	-0.074 ± 0.231	
1997Q	0.430	22.01	22.61 ± 0.02	0.935 ± 0.024	0.068 ± 0.145	0.030	-0.014 ± 0.154	
1997R	0.657	23.28	23.88 ± 0.05	0.980 ± 0.065	0.354 ± 0.182	0.030	-0.013 ± 0.233	
1997S	0.612	23.03	23.89 ± 0.05	1.189 ± 0.073	-0.424 ± 0.411	0.033	-0.851 ± 0.495	
1997ac	0.320	21.43	21.89 ± 0.02	1.057 ± 0.020	0.059 ± 0.066	0.027	-0.003 ± 0.073	
1997af	0.579	22.92	23.59 ± 0.08	0.856 ± 0.052	0.007 ± 0.238	0.028	-0.268 ± 0.281	
1997ai	0.450	22.27	22.86 ± 0.07	0.926 ± 0.116	0.136 ± 0.138	0.045	0.029 ± 0.147	
1997aj	0.581	22.58	23.24 ± 0.11	0.956 ± 0.055	0.013 ± 0.173	0.033	-0.260 ± 0.205	
1997am	0.416	22.02	22.58 ± 0.07	1.030 ± 0.060	0.046 ± 0.114	0.036	-0.016 ± 0.121	
1997ap	0.830	23.18	24.36 ± 0.08	1.003 ± 0.066	0.920 ± 0.087	0.026	0.178 ± 0.131	
199fG	0.425	21.64	22.30 ± 0.16	0.924 ± 0.186	0.071 ± 0.163	0.008	0.008 ± 0.173	

a: X=R for $z < 0.7$, X=I for $z > 0.7$

b: As in Table 3

c: As in Table 3

d: Schlegel, Finkbeiner, & Davis (1998)

e: As in Table 3

f: The indicated supernovae were excluded from Subset 1 (full primary subset), Subset 2 (low-extinction primary subset), and/or Subset 3(low-extinction, strict SN Ia subset); see § 2.4.

Table 5: Supernova Lightcurve Fits: Low-z SNe from Hamuy (1996) and Riess (1999)

SN[a]	z	m_B[b]	Stretch	B-V[c]	$E(B$-$V)$ Gal.[d]	$E(B$-$V)^e_{\rm host}$	Excluded Subsets[f]
1990O	0.030	16.14 ± 0.03	1.113 ± 0.027	0.038 ± 0.027	0.098	-0.023 ± 0.028	
1990af	0.050	17.76 ± 0.01	0.752 ± 0.010	0.073 ± 0.011	0.035	0.002 ± 0.012	
1992P	0.026	16.04 ± 0.02	1.071 ± 0.027	-0.049 ± 0.019	0.020	-0.028 ± 0.019	
1992ae	0.075	18.39 ± 0.03	0.968 ± 0.026	0.075 ± 0.027	0.036	-0.031 ± 0.030	
1992ag	0.026	16.23 ± 0.02	1.061 ± 0.016	0.215 ± 0.021	0.097	0.163 ± 0.021	2,3
1992al	0.014	14.47 ± 0.01	0.960 ± 0.011	-0.055 ± 0.013	0.034	-0.045 ± 0.013	
1992aq	0.101	19.28 ± 0.05	0.895 ± 0.030	0.094 ± 0.031	0.012	-0.071 ± 0.036	
1992bc	0.020	15.09 ± 0.01	1.056 ± 0.006	-0.092 ± 0.009	0.022	-0.067 ± 0.009	
1992bg	0.036	16.61 ± 0.04	1.013 ± 0.015	0.121 ± 0.026	0.181	-0.040 ± 0.027	
1992bh	0.045	17.59 ± 0.02	1.029 ± 0.016	0.098 ± 0.018	0.022	0.083 ± 0.019	
1992bl	0.043	17.30 ± 0.03	0.820 ± 0.013	0.005 ± 0.023	0.012	-0.024 ± 0.024	
1992bo	0.018	15.77 ± 0.01	0.758 ± 0.007	0.052 ± 0.012	0.027	0.036 ± 0.012	
1992bp	0.079	18.27 ± 0.01	0.911 ± 0.015	0.067 ± 0.015	0.068	-0.089 ± 0.017	
1992br	0.088	19.33 ± 0.08	0.704 ± 0.024	0.158 ± 0.050	0.027	0.011 ± 0.056	1–3
1992bs	0.063	18.18 ± 0.04	1.050 ± 0.015	-0.016 ± 0.021	0.013	-0.070 ± 0.023	
1993B	0.071	18.35 ± 0.04	1.037 ± 0.019	0.163 ± 0.027	0.080	0.039 ± 0.029	
1993O	0.052	17.63 ± 0.01	0.930 ± 0.009	0.036 ± 0.012	0.053	-0.036 ± 0.013	
1993ag	0.050	17.80 ± 0.02	0.949 ± 0.016	0.208 ± 0.020	0.111	0.092 ± 0.021	
1994M	0.024	16.23 ± 0.03	0.887 ± 0.015	0.037 ± 0.022	0.023	0.041 ± 0.022	
1994S	0.016	14.77 ± 0.02	1.035 ± 0.026	-0.064 ± 0.019	0.018	-0.030 ± 0.019	
1995ac	0.049	17.03 ± 0.01	1.090 ± 0.013	0.014 ± 0.011	0.042	-0.032 ± 0.012	
1995bd	0.016	15.18 ± 0.01	1.040 ± 0.008	0.734 ± 0.008	0.490	0.299 ± 0.008	1–3
1996C	0.030	16.54 ± 0.04	1.125 ± 0.019	-0.002 ± 0.026	0.014	0.024 ± 0.027	
1996ab	0.125	19.52 ± 0.04	0.961 ± 0.036	0.111 ± 0.032	0.032	-0.153 ± 0.038	
1996bl	0.035	16.64 ± 0.01	1.033 ± 0.015	0.086 ± 0.012	0.099	0.009 ± 0.012	
1996bo	0.016	15.83 ± 0.01	0.862 ± 0.006	0.404 ± 0.008	0.077	0.360 ± 0.008	1–3

a: Supernovae through 1993ag are from H96, later ones from R99.

b: Measurement uncertainties as for note 2 in Table 3.

c: This is the measured B-V color at the epoch of rest-frame B-band lightcurve maximum. *d*: Schlegel, Finkbeiner, & Davis (1998)

e: Measurement error only; no intrinsic color dispersion included.

f: The indicated supernovae were excluded from Subset 1 (full primary subset), Subset 2 (low-extinction primary subset), and/or Subset 3(low-extinction, strict SN Ia subset); see § 2.4.

the unreddened intrinsic color. This ridge-line fit was performed by adding an asymmetric intrinsic error bar (twice as long to the red than to the blue), and by omitting supernovae from the fit which were systematically reddened relative to the median value.

Some of our data extends into the U-band range of the spectrum. This is obvious for supernovae at $z > 0.7$ where a U-band template is fit to the R-band data. However, even for supernovae at $z \gtrsim 0.55$, the de-redshifted R-band filter begins to overlap the U-band range of the rest-frame spectrum. Thus, it is also important to know the intrinsic U-B color so as to generate a proper spectral template. We used data from the literature in Table 6. Here, there is an insufficient number of supernova lightcurves to reasonably use the sort of ridge-line analysis used above to eliminate the effects of host-galaxy extinction in determining the intrinsic $BVRI$ colors. Instead, for U-B, we perform extinction corrections using the $E(B\text{-}V)$ values from Phillips *et al.* (1999). Based on Table 6, we adopt a U-B color of -0.4 at the epoch of rest-B maximum. Although any intrinsic uncertainty in B-V should be included in the assumed intrinsic dispersion of extinction-corrected peak magnitudes (see § 2.5), it is likely that there is a greater intrinsic dispersion in U-B. The effect on extinction-corrected magnitudes will be further increased by the greater effect of dust extinction on the bluer U-band light. The scatter of our extinction-corrected magnitudes about the best fit cosmology suggests an intrinsic uncertainty in U-B of 0.04 magnitudes. This is also consistent with the U-B data of Jha (2003) over the range of timescale stretch of our $z > 0.6$ SNe Ia, after two extreme color outliers are removed. There is no evidence of such extreme color objects in our dataset. Note that this intrinsic color dispersion is in addition to the intrinsic magnitude dispersion assumed after extinction correction.

Given a template spectrum with the proper intrinsic colors for each day relative to the date of B maximum, it must be further modified for each supernova to account for dust extinction in the supernova host galaxy, and extinction of the redshifted spectrum due to Galactic dust. Reddening effects from dust were calculated given the $E(B\text{-}V)$ parameter (measured from the lightcurve fits for the host galaxy, and given by Schlegel, Finkbeiner, & Davis (1998) for the Galaxy) and the extinction law of O'Donnell (1994).

For each supernova, this finally modified spectral template was integrated through the Bessell and WFPC2 filter transmission functions to provide color and K-corrections. The exact spectral template needed for a given data point on a given supernova is dependent on parameters of the fit: the stretch, the time of each point relative to the epoch of rest-B maximum, and the host-galaxy $E(B\text{-}V)$ (measured from the peak color of the lightcurve). Thus, color and K-corrections were performed iteratively with lightcurve fitting in order to generate the final corrections used in the fits described in § 2.2. An initial date of maximum, stretch, and host-galaxy extinction was assumed to generate K-corrections for the first iteration of the fit. The parameters resulting from that fit were used to generate new color and K-

Table 6: U-B SN Ia Colors at Epoch of B-band Maximum

SN	Raw U-B^1	Corrected U-B^2	Reference
1980N	−0.21	−0.29	Hamuy *et al.* (1991)
1989B	0.08	−0.33	Wells *et al.* (1994)
1990N	−0.35	−0.45	Lira *et al.* (1998)
1994D	−0.50	−0.52	Wu *et al.* (1995)
1998bu	−0.23	−0.51	Suntzeff *et al.* (1999)

1: This is the measured U-B value from the paper

2: This is U-B K-corrected, and corrected for host galaxy and Galactic extinction

corrections, and the whole procedure was repeated until the results of the fit converged. Generally, the fit converged within 2–3 iterations, although occasionally a few more iterations were necessary.

The $E(B$-$V)$ values quoted in Tables 3, 4, and 5 are the parameters for the extinction law of O'Donnell (1994) necessary to reproduce the observed R-I color at the epoch of the maximum of the rest-frame B lightcurve. This reproduction was performed by modifying the spectral template exactly as described above, given the intrinsic color of the supernova of the fit stretch, the Galactic extinction, and the host-galaxy $E(B$-$V)$ parameter. The modified spectrum was integrated through the Bessell R and I band filters, and $E(B$-$V)$ was varied until the R-I value produced matched the result from the lightcurve fit. (These $E(B$-$V)$ values where then used to generate the proper color and K-corrections for the next iteration of each lightcurve fit.)

2.4. Supernova Subsets

In P99, separate analyses were perfomed and compared for the supernova sample before and after removing supernovae with less secure identification as Type Ia. The results were shown to be consistent, providing a cross-check of the cosmological conslusions. For this current paper's analysis, adding and comparing eleven very-well-measured SNe Ia, we take the more securely identified SNe Ia as our primary sample. This excludes six supernoave from P99 (SNe 1992bi, 1994G, 1994al, 1995a1995aq, 1995at, and 1997K) that are very likely to be SNe Ia, but without good spectra confirmation, and one supernova (SN 1994H) that is considered a likely Type II supernova (Nugent, Kim, & Perlmutter 2002), and was removed from the primary P99 fits. Following P99, we omit two supernovae are outliers in the stretch distribution, with $s < 0.75$ (SN 1992br and SN 1994F), and three supernova which are $> 4\,\sigma$ outliers from the best-fit flat-universe cosmology (SN 1996bo, SN 1995bd, and SN 1997O). Finally, we omit any supernovae not yet omitted which do not have a color measurement (SN 1994an, SN 1994am, and SN 1997L). The resulting "full primary subset" of SNe Ia, "Subset 1", is further culled to remove likely reddened supernovae, producing a "low-extinction primary subset," Subset 2. This subset omits three supernovae with host galaxy $E(B\text{-}V) > 0.1$ and $> 3-\sigma$ above zero (SN 1992ag, SN 1996cn, and SN 1998aw).

Subset 3, the "low-extinction strict Ia subset," makes an even more stringent cut on spectral confirmation, including only those supernovae whose confirmations as Type Ia SNe are unquestionable (which includes all supernovae from this paper). The additional supernovae omitted from Subset 3 beyond those omitted from Subset 2 are SN 1995as, SN 1996cf, SN 1996cg, and SN 1996cm.

2.5. Cosmological Fit Methodology

Cosmological fits to the luminosity distance modulus equation from the Friedmann-Robertson-Walker metric followed the procedure of P99. The set of supernova redshifts (z) and K-corrected peak B-magnitudes (m_B) were fit to the equation

$$m_B = \mathcal{M} + 5 \log \mathcal{D_L}(z; \Omega_{\mathrm{M}}, \Omega_\Lambda) - \alpha(s-1) \tag{3}$$

where s is the stretch value for the supernova, $\mathcal{D_L} \equiv H_0 d_L$ is the "Hubble-constant-free" luminosity distance (Perlmutter *et al.* 1997), and $\mathcal{M} \equiv M_B - 5logH_0 + 25$ is the "Hubble-constant-free" B-band peak absolute magnitude of a $s = 1$ SN Ia. The peak magnitude of a SN Ia is mildly dependent on the lightcurve decay time scale, such that SNe with a slower decay (higher stretch) tend to be over-luminous, while SNe with a faster decay (lower stretch) tend to be under-luminous (Phillips *et al.* 1993). α is a slope that parameterizes this relationship.

There are four parameters in the fit: the mass density Ω_{M} and cosmological constant Ω_Λ, as well as the two nuisance parameters $\mathcal{M}$ and α. The four-dimensional (Ω_{M}, Ω_Λ, $\mathcal{M}$, α) space was divided into a grid, and at each grid point a χ^2 value was calculated by fitting the luminosity distance equation to the peak B-band magnitudes and redshifts of the supernovae. The range of parameter space explored included $\Omega_{\mathrm{M}} = [0, 3)$, $\Omega_\Lambda = [-1, 3)$ (for fits where host-galaxy extinction corrections are not directly applied) or $\Omega_{\mathrm{M}} = [0, 4]$, $\Omega_\Lambda = [-1, 4)$ (for fits with host-galaxy extinction corrections). No further constraints were placed on the parameters. An additional two dimensions on the grid included the relevant range for $\mathcal{M}$ and α. The probability of the whole 4-dimensional grid is normalized, and then integrated over the two dimensions corresponding to the "nuisance" parameters.

Fits were performed to the supernovae subsets described in § 2.4. These subset fits were also perfomred separately for the eleven high-redshift supernovae from this paper and for the 42 high-redshift supernoave from P99. Table 8 presents a summary of the results from these fits.

For each fit, all peak m_B values were corrected for Galactic extinction using $E(B\text{-}V)$ values from Schlegel, Finkbeiner, & Davis (1998), using the extinction law of O'Donnell (1994) integrated through the *observed* filter.[25] For fits of the low-extinction subsets, the total effective statistical uncertainty on each value of m_B in-

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[25] This supersedes P99, where an incorrect dependence of the effective on R_R for Galactic extinction was applied. This correction would decrease the flat-universe value of Ω_{M} by 0.03.

cluded the following contributions:

- the uncertainty on m_B from the lightcurve fits;
- the uncertainty on s, multiplied by α
- the covariance between m_B and s;
- a contribution from the uncertainty in the redshift due to peculiar velocity (assumed to have a dispersion of 300 km s^{-1});
- 10% of the Galactic extinction correction; and
- 0.17 magnitudes of intrinsic dispersion (H96).

Fits to the full primary subset (Subset 1), which explicitly performed host-galaxy extinction corrections, used the first five items above plus:

- the uncertainty on $E(B\text{-}V)$ multiplied by R_B;
- the covariance between $E(B\text{-}V)$ and m_B;
- 0.11 magnitudes of intrinsic dispersion (Phillips *et al.* 1999); and
- 0.04 magnitudes of intrinsic U-B dispersion (see below).

Host-galaxy extinction corrections used a value $R_B \equiv A_B/E(B\text{-}V) = 4.34$, which results from applying the extinction law of O'Donnell (1994) to a SN Ia spectrum and integrating the results through standard B and V filters. Although there is almost certainly some intrinsic dispersion either in the proper value of R_B to use, or in the true B-V color of a SN Ia (Nobili *et al.* 2003), we do not explicitly include such a term. The effects of such a dispersion should be included in the 0.11 magnitudes of intrinsic magnitude dispersion which Phillips *et al.* (1999) see after applying extinction corrections. As discussed in § 2.3, the intrinsic U-B dispersion is likely to be greater than the intrinsic B-V dispersion. For those supernovae most affected by this (i.e. those at $z > 0.7$), we included an additional uncertainty in magnitude corresponding to 0.04 magnitudes of intrinsic U-B dispersion, converted into a magnitude error using the O'Donnell extinction law. This set of statistical uncertainties is slightly different from those used in P99. For these fits, at each test value of α we propagated the stretch errors into the corrected B-band magnitude errors; in contrast, P99 used a single value of $\alpha = 1.74$ for purposes of error propagation.

3. Colors and Extinction

One notable difference between the data on the 11 WFPC2-observed supernovae in this paper and previous high-redshift supernova data is that the R-I colors have been measured to much higher precision. In the work of the SCP (P99), extinction was estimated by comparing the mean host-galaxy $E(B\text{-}V)$ values from the low and high redshift samples. Although the uncertainties on individual $E(B\text{-}V)$ values for high-redshift supernovae were large, the uncertainty on the mean of the distribution was only 0.01 magnitudes. P99 showed that there was no significant difference in the mean host-galaxy reddening between the low and high redshift sets of supernovae of the primary analysis (Fit C). This tightly constrained the systematic uncertainty on the cosmological results due to differences in extinction. Fit E of P99 and Riess (1998) did apply host-galaxy extinction corrections to each individual supernova. However, these analyses used a Bayesian prior on the color-excess distribution to modify the extinction correction. This prior was one sided, with zero probability for $E(B\text{-}V) < 0$, and a probability which sharply falls for positive values of $E(B\text{-}V) > 0.02$ magnitudes (Hatano, Branch, & Deaton 1998). Even if all $E(B\text{-}V)$ values are intrinsically close to zero, measurements will scatter to both sides of zero by an amount given by the measurement uncertainty; consequently, applying this asymmetric prior biases the measured $E(B\text{-}V)$ distribution to the red. As discussed in P99, when the uncertainties on the high and low redshift supernova $E(B\text{-}V)$ values differ, this prior can introduce a bias into the cosmological results; P99 therefore cautioned against this approach. (The validity of a prior with such small dispersion is further called into question by the observation that a number of the low-redshift supernovae in R99 were found with moderate amounts of host-galaxy extinction.) The small dispersion of the prior makes the cosmological fits appear much better constrained by reducing the propogated $E(B\text{-}V)$ measurement uncertainties, especially for SNe with $E(B\text{-}V) < 0$ (as was the case for more than half of the SNe in Riess (1998)).

The high precision measurements of the *R*-*I* color afforded by the WFPC2 lightcurves for the supernovae in this work allow a direct estimation of the host-galaxy $E(B\text{-}V)$ color excess without any need to resort to a prior assumption in the intrinsic color-excess distribution.

Figure 1 shows histograms of the host-galaxy $E(B\text{-}V)$ values from different subsets of supernovae. For the bottom two panels, overplotted is a line that treats the H96 SNe $E(B\text{-}V)$ values as a parent distribution, and shows the expected distribution for the other sets given their measurement uncertainties. Each set's distribution is consistent with the $E(B\text{-}V)$ distribution from H96, except for R99 which shows several significantly reddened supernovae. This effect arises because the R99 SNe are not from a flux-limited sample, as are the H96 and all high redshift SNe. Flux-limited surveys select against extincted SNe. For the 11 HST SNe in this paper, one is significantly reddened (with $E(B\text{-}V) > 3\,\sigma$). Table 7 lists the variance-weighted mean $E(B\text{-}V)$ values for each set. For the low-extinction Subset 1, the four sets are not significantly different. That the low-redshift supernovae are too blue indicate that the assumed *B*-*V* color at epoch of B maximum (determined from all of the low-redshift SNe from H96 and P99 following the procedure of § 2.3) may be mildly too red by ~ 0.02 magnitudes; we consider the effect that this might have

Table 7: Mean $E(B\text{-}V)$ Values

Set	All SNe	Subset 2 SNe[1]
Low z:		
H96	-0.015 ± 0.004	-0.021 ± 0.004
R99	$+0.193 \pm 0.004$	-0.011 ± 0.007
High z:		
P99	$+0.009 \pm 0.024$	-0.008 ± 0.026
This Paper	$+0.044 \pm 0.014$	-0.008 ± 0.016

1: SNe omitted from Fits 1–3 (§ 4.1, Table 8) have been omitted from these means. This excludes outliers, as well as supernovae with $E(B\text{-}V) > 3\sigma$.

on which supernovae are rejected for being reddened in § 5.3. Because it is a *difference* between the reddening high and redshift supernovae that would systeamtically affect $\Omega_{\rm M}$ and Ω_Λ, any such small offset should not affect those measurements.

For the 11 HST supernovae in this paper, if SN 1998aw is omitted, then the mean $E(B\text{-}V)$ of the set is consistent with the mean $E(B\text{-}V)$ of the Subset 2 supernovae from both low-redshift sets. Note that this conclusion is not circular; individual $E(B\text{-}V)$ error bars for the HST supernovae are typically 0.04–0.1, and hence only grossly reddened supernovae have been omitted from Subset 2. A residual difference on the mean $E(B\text{-}V)$ value is still possible, but is not detected.

The mean host-galaxy color excess calculated for the highest redshift supernovae is critically dependent on the assumed intrinsic $U\text{-}B$ color. This is obvious for supernovae at $z > 0.7$, where the $E(B\text{-}V)$ value is estimated directly from measurements of the $U\text{-}B$ rest-frame color. Even for supernovae at $z \gtrsim 0.55$, the deredshifted R filter overlaps part of the U band region of the rest-frame spectrum, and as such the assumed $U\text{-}B$ color will affect the cross-filter K-correction between observed R and rest-frame B.

Figure 2 shows $E(B\text{-}V)$ vs. z for the 11 supernovae of this paper. This figure graphically shows both that except for SN 1998aw at $z = 0.44$ (and to a lesser degree, SN 1998as at $z = 0.36$), the supernovae do not suffer from significant host-galaxy extinction. Several authors (including Leibundgut (2001) and Falco *et al.* (1999)) have suggested that there is evidence that high-redshift supernovae are bluer statistically than the low-redshift counterparts they are compared with. These data show now such effect. It is possible that the problem was cuased by an assumed intrinsic $U\text{-}B$ that was too red.

In should be noted that K-corrected magnitudes are dependent on the assumed supernova colors that went into deriving the K-corrections. If the assumed $U\text{-}B$ color is too red, that will affect the cross-filter K-correction applied to R band data at $z \gtrsim 0.5$, thereby changing derived rest frame colors. In § 5, we consider the effect of changing the $U\text{-}B$ color assumed.

4. Cosmological Results

4.1. $\Omega_{\rm M}$ and Ω_Λ

Figure 3 shows Hubble Diagrams which plot K-corrected rest-frame B-band peak magnitudes and redshifts for the new supernovae of this paper. For most supernovae, the rest-frame peak B-band magnitude was calculated from the observed and K-corrected R-band lightcurve. For supernovae at $z > 0.7$, the peak rest-frame B magnitude was calculated from the peak of the I-band lightcurve. In the upper panel, the m_B values and uncertainties from Table 3 are plotted. In the lower panel, m_B values have been corrected for host-galaxy $E(B\text{-}V)$ extinction. The error bars here are much larger because the color excess must be multiplied by R_B in order to determine the resulting uncertainty on m_B.

Figure 4 shows the measurement of $\Omega_{\rm M}$ and Ω_Λ resulting from the fits to the low-extinction primary subset (Subset 2); several parameters from these fits are tabulated in Fits 1–3 of Table 8. In Figure 4,

Fig. 1.— Histograms of $E(B\text{-}V)$ for the four sets of supernovae used in this paper. All supernovae with measured colors (i.e. excluding seven from P99) are plotted. The solid lines drawn over the bottom two panels is a simulation of the distribution expected if the H96 set represented the true distribution of SN colors, given the error bars of each set.

Table 8: Cosmological fits

Fit #	N_{SNe}	Min. χ^2	Ω_{M} for Flat[a]	Ω_Λ for Flat[a]	$\mathcal{M}$	α	High-Redshfit SNe Included in Fit[b]
Fits to Low-Extinction Subset (Subset 2)							
1	51	62	$0.22^{+0.07}_{-0.07}$	$0.78^{+0.07}_{-0.07}$	-3.48 ± 0.05	1.52 ± 0.33	P99
2	32	38	$0.18^{+0.07}_{-0.07}$	$0.82^{+0.07}_{-0.07}$	-3.47 ± 0.05	0.99 ± 0.34	New “HST” SNe from this paper
3	**61**	**76**	$\mathbf{0.21^{+0.06}_{-0.05}}$	$\mathbf{0.79^{+0.05}_{-0.06}}$	$\mathbf{-3.47 \pm 0.05}$	$\mathbf{1.25 \pm 0.29}$	**All SCP SNe**
Fits to Full Primary Subset (Subset 1), With Extinction Correction							
4	53	56	$0.19^{+0.20}_{-0.16}$	$0.81^{+0.16}_{-0.20}$	-3.47 ± 0.06	1.19 ± 0.33	P99
5	34	44	$0.16^{+0.12}_{-0.10}$	$0.84^{+0.10}_{-0.12}$	-3.47 ± 0.06	1.20 ± 0.32	New “HST” SNe from this paper
6	64	72	$0.18^{+0.11}_{-0.10}$	$0.82^{+0.10}_{-0.11}$	-3.46 ± 0.06	1.07 ± 0.32	All SCP SNe.

a: This is the intersection of the fit probability distribution with the the line that assumes $\Omega_{\mathrm{M}} + \Omega_\Lambda = 1$.

b: All fits include the low-redshift SNe from H96 and R99.

Fig. 3.— Hubble Diagram of effective m_B vs. redshift for the 11 SNe observed with WFPC2 and reported in this paper. In the upper plot, no host-galaxy $E(B\text{-}V)$ extinction corrections have been applied. Inner error bars only include the measurement error, and are generally a similar size to the plot symbols. Outer error bars include 0.17 magnitudes of intrinsic dispersion. In the lower plot, host-galaxy $E(B\text{-}V)$ extinction corrections have been applied; uncertainties have had $\delta E(B\text{-}V)\times R_B$ added in quadrature, where $\delta E(B\text{-}V)$ is the uncertainty in $E(B\text{-}V)$ and $R_B = 4.34$. Again, inner error bars represent only measurement uncertainties, while outer error bars include 0.11 magnitudes of intrinsic dispersion. Lines are for three different model cosmologies with the indicated values of $\Omega_{\rm M}$ and Ω_Λ, including the best-fit flat-universe case of $(\Omega_{\rm M}, \Omega_\Lambda) = (0.2, 0.8)$.

the same low-redshift supernovae are inlcuded in all fits, but the high-redshfit sample is studied in various combinations. The filled contours show the combined limits using all of the SCP's high redshift supernovae, both from P99 and from this paper (Fit 3). The solid lines show confidence intervals from a fit using only the high-redshift SNe from this paper Fit 2), and the dotted contours are from a fit using only the P99 SNe (Fit 1). Fit 2 provides comparable and consistent limits on $\Omega_{\rm M}$ and Ω_Λ to Fit 1 (which includes a greater number of high-redshift supernovae selected from P99).

Figure 5, and the bottom three lines of Table 8, show how the cosmological fits to the full primary subset (Subset 1) compare with host-galaxy extinction corrections applied. The top row of fits from this figure are the same low-extinction subset fits plotted in Figure 4. The second row has $E(B\text{-}V)$ host-galaxy extinctions applied using the one-sided prior used by Riess (1998) and discussed in § 3; because of bias introduced by this prior (P99), we do not recommend using these results. The third row has full extinction corrections applied to supernova Subset 1, without any prior assumptions on the intrinsic $E(B\text{-}V)$ distribution. Two points are apparent from this plot. First, using a prior does, as expected, greatly reduce the $E(B\text{-}V)$ error bars and hence tightents the constraints of the cosmological confidence regions. Second, the current set of supernovae provide much better limits on the cosmology than do the SNe Ia from previous high redshift samples when unbiased extinction corrections are applied. Whereas Figure 4 shows that the current set of supernovae give comparable limits on Ω_{M} and Ω_Λ when the low-extinction subsample is used with no host-galaxy extinction corrections, Figure 5 shows that the much higher precision color measurements from the WFPC2 data allows us directly to set much better limits on the effects of host-galaxy extinction on the cosmological results.

4.2. Combined High-Redshift Supernova Limits

Figure 6 shows the limits on Ω_{M} and Ω_Λ which combine the high-redshift supernova data of Riess (1998) together with the SCP data presented in this paper and in P99. The contours show confidence intervals from the 61 SNe of the low-extinction primary Subset 2 (used in Fit 3 of Table 8), plus the nine well-observed confirmed Type Ia supernovae from Riess (1998) (using their template fitting data); following the criteria of Subset 2, SN 1997ck has been omitted, as that supernova does not have a confirmed type identification nor a color measurement. We also omit from Riess (1998) the supernovae they measured using the "snapshot" method, and two SCP SNe (already included in the P99 set). This fit has a minimum χ^2 of 83 with 70 supernovae. Under the assumption of a flat universe, it yields a measurement of the mass density of $\Omega_{\mathrm{M}} = 0.23 \pm 0.06$, or equivalently a cosmological constant of $\Omega_\Lambda = 0.77 \pm 0.06$. However, this fit should be approached with some caution, as the nine supernovae from the Riess (1998) team were not treated in exactly the same manner as the others. The details of the template fitting will naturally have been different, which can introduces small differences (see § 5.1). More importantly, the K-corrections applied by the Riess (1998) team to derive distance moduli were almost certainly different from those used in this paper. (The fact that many of their supernovae show significant negative values of $E(B\text{-}V)$ suggests that this effect may be non-negligible.)

4.3. Dark Energy Equation of State

The fits of the previous section used a traditional Robertson-Walker cosmology where Ω_{M} is the energy density of non-relativistic matter (i.e. pressure $p = 0$), and Ω_Λ is the energy density in a cosmological constant (i.e. pressure $p = -\rho$, where ρ is the energy density). In Einstein's field equations, the gravitational effect enters in terms of $\rho + 3p$. If $w \equiv p/\rho$ is the equation of state parameter, then for matter, $w = 0$ and for vacuum energy (i.e. a cosmological constant), $w = -1$. In fact, it is possible to achieve an accelerating Universe so long as there is a component with $w <\sim -1/2$.

Fig. 5.— 68%, 95%, and 99% confidence limits on $\Omega_{\rm M}$ and Ω_Λ using different data subsets and methods for treating host-galaxy extinction corrections. The top row represents fits from

The Hubble diagram for high-redshift supernovae provide limits on the value of w (P99, Garnavich *et al.* 1998b). Figure 7 shows the the joint confidence limits on $\Omega_{\rm M}$ and w for the SCP SNe, including the 11 new "HST" SNe, under the assumption that w is constant, and that the Universe is flat, i.e. $\Omega_{\rm M} + \Omega_X = 1$ (where Ω_X is the energy density in the component with equation of state w, in units of the critical density).

The lower panel on each plot applies an additional constraint that $\Omega_{\rm M} = 0.27 \pm 0.04$, a value obtained by Bennett *et al.* (2003) which combines WMAP data with other CMB and large scale structure data. We have also combined our measurements of $\Omega_{\rm M}$ and w with other independent constraints on $\Omega_{\rm M}$, and derived 3-σ upper limits on w in each case. The results are listed in Table 9. Using the CMB and large scale structure limit from Bennett *et al.* (2003), we measure a 3-σ upper limit of $w < -0.70$ when host galaxy extinction corrections are not applied (Fit 3), or $w < -0.45$ when an unbiased host galaxy extinction correction is applied (Fit 6). Other measurements of $\Omega_{\rm M}$ provide slightly different measurements; all measurements remain consistent with a low mass ($\Omega_{\rm M} \sim 0.2$–0.3) flat universe dominated by vacuum energy ($w{=}{-1}$)— as well as with a wide variety of dark energy models.

5. Systematic Errors

The effect of most systematic errors in the $\Omega_{\rm M}$ vs. Ω_Λ plane is asymmetric in a manner similar to the asymmetry of our statistical errors. For the effects listed below, a systematic difference will tend to move the confidence ellipses primarily along their major axis. In other words, for most systematic effects, we have a larger uncertainty in $\Omega_{\rm M} + \Omega_\Lambda$ than in $\Omega_{\rm M} - \Omega_\Lambda$ (or, equivalently, in a measurement of $\Omega_{\rm M}$ or Ω_Λ alone under the assumption of a flat universe). This means that systematic effects do not currently seriously hamper the cosmological measurements from supernovae where they have the greatest weight, nor do they significantly diminish the direct evidence from supernovae for the presence of dark energy. However, they do limit the ability of supernovae to measure the spatial curvature ("geometry") of the Universe. (Note that the semi-major axis is not precisely in the direction of $\Omega_{\rm M}+\Omega_\Lambda$, nor is the semi-minor axis precisely aligned with $\Omega_{\rm M} - \Omega_\Lambda$, but since these are useful constraints we will quantify the systematic uncertainties along these two directions.)

Systematic effects on flat-universe limits on w are relatively mild. To estimate the size of the effect, in the following subsections we also study how much each identified and quantified systematic effects the 3-σ upper limit on w when combined with the Bennett *et al.* (2003) value of $\Omega_{\rm M} = 0.27 \pm 0.04$(see § 4.3). ☑

5.1. Fit Method

There are multiple reasonable choices for lightcurve fitting methods which yield slightly different results for the lightcurve parameters. For the supernovae in P99, the R-band data on high-redshift supernovae provided much stronger limits on the stretch (the shape of the lightcurve) than did more sparse I-band lightcurves. For consistency, the stretch values for the low redshift supernovae were therefore mea-

Fig. 7.— Joint confidence limits on $\Omega_{\rm M}$ and w assuming $\Omega_{\rm M} + \Omega_X = 1$. Confidence limits plotted are 68%, 90%, 95%, and 99%. The left column shows fits to Subset 2, where host-galaxy extinction corrections have not been applied. The right panel shows fits where $E(B\text{-}V)$ corrections have been applied. The upper panels show the joint limits on $\Omega_{\rm M}$ and w from the supernova data alone, under the assumption of a flat universe. The lower panels show the limits under the assumption both of a flat universe and the constraint that $\Omega_{\rm M} = 0.27 \pm 0.04$ from CMB and large scale structure measurements (Bennett *et al.* 2003).

Table 9: Upper Limits on w

$\Omega_{\rm M}$ Constraint	$\Omega_{\rm M}$ Source	w limit Fit 3[a]	w limit Fit 6[b]	$\Omega_{\rm M}$ Reference
0.27 ± 0.04	Multiple[c]	$w < -0.70$	$w < -0.45$	Bennett *et al.* (2003)
0.29 ± 0.07	WMAP	$w < -0.67$	$w < -0.44$	Spergel *et al.* (2003)
$0.19^{+0.08}_{-0.07}$	SDSS	$w < -0.56$	$w < -0.38$	Bahcall *et al.* (2003)
$0.30^{+0.04}_{-0.03}$	Chandra	$w < -0.77$	$w < -0.48$	Allen, Schmidt, & Fabian (2002)

a: Without host-galaxy extinction corrections; 3-σ upper limit.

b: With unbiased host-galaxy extinction corrections; 3-σ upper limit.

c: See Text

Fig. 8.— The effects of identified systematic errors on the cosmological parameters. The left column shows fits to $\Omega_{\rm M}$ and Ω_Λ, and the right column to $\Omega_{\rm M}$ and the dark energy equation of state parameter w. Rows (a)–(c) show our standard fit (Fit 3) in filled contours. (a) The dotted contours show the results of a fit to Subset 3, only those supernovae with the most secure spectral identifications as Type Ia SNe. (b) The dotted contours show the fit to Subset 1, with host-galaxy extinctions applied. (c) The dotted contorus show a fit to Subset 2, where K-corrections have been applied using a template spectum with an intrinsic value of U-B=-0.5 at the epoch of B-maximum. (d) The filled contours is Fit 6, our standard fit with host-galaxy extinction corrections applied; the dotted contours show a fit to the same Subset, but using a template spectrum with an intrinsic value of U-B=-0.5 for estimating both K-corrections and color excesses.

sured using only the B-band lightcurves in P99.

In this paper, there are high-quality photometric measurements from WFPC2 in both R and I bands. Thus, data in both colors contributes significantly to the constraints on stretch. Additionally, the low background of the HST images, combined with the need to have previously subtracted the host galaxy background in order to combine HST and ground-based data, indicate that it is more appropriate to fit these supernovae with fixed rather than floating lightcurve zero offsets. As this is the most appropriate fit method for the HST data, the low redshift supernovae should be treated consistently. These procedures which are most appropriate for the HST supernovae were used for all new fits performed in this paper and listed in Tables 3 through 5.

To estimate the size of the effect due to these differences in fitting method, cosmological confidence intervals were generated from the "Case C" subset of P99 using the new fits presented in this paper and compared to the results quoted in P99. The value of Ω_M under the assumption of a flat universe changes by 0.03 given the difference in the methods; the minimum-χ^2 value of $\Omega_M + \Omega_\Lambda$ changes by 0.8. (This is still well less than the major-axis extent of the statistical confidence ellipse in this direction.) We use these values as "fit-method" systematic uncertainties.

I DO NOT HAVE THE LIMITS ON W IN THIS CASE!! THAT NEEDS TO BE DONE BY ME. I EXPECT IT TO BE ☑DINKY.

5.2. Supernova Type Contamination

All subsets of supernoave used for cosmological fits in this paper omit supernovae for which there is not a spectral confirmation of the supernova type. Nonetheless, it is possible in some cases where that confirmation is weak that we may have contimation from non-Type Ia supernovae. To estimate the effects of this, we performed fits using only those supernovae which have a firm indentification as Type Ia; this is Subset 3 from § 2.4. The comparison between our primary fit (Fit 3) and this fit with a more stringent type cut is shown in row (a) of Figure 5. This fit has a value of Ω_M in a flat universe which is 0.01 higher than that of Fit 3. The minimum χ^2 value of $\Omega_M + \Omega_\Lambda$ is 0.28 magnitudes lower than that of Fit 3. We adopt these values as our "type contamination" systematic error.

The affect of changing our supernova subset on w is shown in the right panel of Figure 5a. Combined with the CMB and large scale structure mass measurement, the upper limit on w increases by 0.05; we adopt this as our type contamination systematic error on w.

5.3. Host-Galaxy Extinction

Figure 5b shows a direct comparison between the fits with and without extinction corrections applied. The filled contours do not have extinction corrections applied; they represent Fit 3, shown in Figure 4 and the left panel of Figure 7. The dotted contours do have extinction corrections applied; they represent Fit 6, shown in the lower right panel of Figure 5 and the right panel of Figure 7. Although the size of the confidence region obviously swells when $E(B\text{-}V)$ uncertainties are fully propogated into the cosmology, it is plain that the results with and without these corrections are consistent. The flat-universe values for these two fits are listed in Table 8, and differ by 0.03. The maximum likelihood value of $\Omega_{\rm M} + \Omega_\Lambda$ differs by 0.44. We adopt these values as the host-galaxy extinction systematic error for those fits where extinction corrections are not included as a part of the statistical error.

For Fit 1, we omitted supernovae which had both $E(B\text{-}V) > 3\sigma$, where σ represents just the measurement error, and $E(B\text{-}V) > 0.1$, to account for any intrinsic dispersion in $E(B\text{-}V)$. If, as mentioned in Section 3, our intrinsic $B\text{-}V$ is ~ 0.02 magnitudes too blue, then three additional supernovae would have been omitted from our fits: at low redshift, SN 1992bh and SN 1993ag, and from the set of HST-observed high-redshift SNe, SN 1998as. Omitting these supernovae and repeating a fit without E(B-V) corrections lowers the flat-unverse value of $\Omega_{\rm M}$ by 0.03, and lowers the minimum-chi^2 value of $\Omega_{\rm M} + \Omega_\Lambda$ by 0.18. As these values are equivalent to or lower than the host-galaxy extinction systematic errors derived from directly applying unbiased extinction corrections, we use the larger extinction systematic limits above for those fits where host-galaxy extinction is not directly treated as a statistical error.

The first line of Table 9 shows the differences in w with and without host galaxy extinctions applied. Note that in this case, the primary effect is the great increase in the *systematic* error bars, and hence the confidence regions on the $\Omega_{\rm M}/w$ plane. Nonetheless, we adopt the difference in the upper limit on w of 0.25 as our host galaxy extinction systematic.

5.4. K-corrections and Supernova Colors

The generation of the spectral template used for calculating K-corrections is described in § 2.3. The degree to which uncertainties in the K-correction introduce systematic uncertainties into the cosmological parameters depends on whether or not extinction corrections are being individually applied to supernovae. In particular, our K-corrections are most uncertain in the rest-frame U-band range of the supernova spectrum, due to limited published spectrophotmetry. As discussed in § 2.2, our primary fits use a spectral template which has a color $U\text{-}B{=}-0.4$ at the epoch of B-maximum. We have investigated the effects on our cosmology of replacing the spectral templated used both for K-corrections and for determining color excesses with a template that has $U\text{-}B{=}-0.5$ at the epoch of maximum B light.

Figure 5c shows affect on the fitted cosmology caused by using the different template for calculating K-corrections when individual host-galaxy extinction corrections are not applied. These effects are very mild, indicating that our K-corrections are robust with respect to the intrinsic $U\text{-}B$ color of a supernova. Based on the comparison of these fits, we adopt a K-correcton systematic uncertainty of 0.01 on $\Omega_{\rm M}$ in a flat universe, and 0.13 on $\Omega_{\rm M} + \Omega_\Lambda$.

The differnet K-corrections only change the upper limit on w by 0.01 when the supernova data are combined with CMB and large scale structure data; we adopt this as our intrinsic *U*-*B* systematic uncertainty on w when host-galaxy extinction corrections are not applied.

Although the effects of a different intrinsic *U*-*B* color on the *K*-corrections are mild, the effects on calculated color excesses are much greater. Figure 5d shows the difference between Fit 6, where host-galaxy extinction corrections have been applied using our standard color-excess values, and a fit where color-excess values have been determined assuming the intrinsic *U*-*B* color of a supernova is -0.5 at maximum light. As with all other systematics, the primary effect is to move the confidence intervals along their major axis. In this case, the large shift in $\Omega_{\rm M} + \Omega_\Lambda$ is mainly due to the fact that with this bluer assumption amout *U*-*B*, we would believe that all of our $z > 0.7$ supernovae are suffering from a significant about of host-galaxy extinction, and as such all need to be dereddened. Given that the more distant supernovae are dimmer and thus closer to our detection limits than the moderate redshift supernovae, this scenario is implausible. If anything, one would expect the higher redshift supernovae to be *less* subject to host-galaxy extinction due to selection effects. Nonetheless, a value of *U*-*B*$=-0.5$ at the epoch of *B*-band maximum is currently plausible given the *U*-band information available. Only for those fits where extinction corrections are applied, we have an additional intrinsic *U*-*B* systematic error of 0.06 on the flat-universe value of $\Omega_{\rm M}$, and a systematic error of 2.5 on $\Omega_{\rm M}+\Omega_\Lambda$. That it is implausible that our highest redshift supernovae are the most extinguished makes it likely that this is an overestimate of this systematic.

The systematic effect of changing the assumed intrinsic color is not as significant on the flat-universe value of w as it is on the $w = 0$ value of $\Omega_{\rm M} + \Omega_\Lambda$. When combined with the CMB/large scale structure mass measurement, the upper limit on w with this fit is only 0.07 higher than the value obtained with our standard intrinsic *U*-*B* (which is $w < -0.45$; see line 1 of Tabler̃eftab:wlimit). We adopt this difference as our systematic uncertainty on w when host-galaxy extinction corrections are applied.

5.5. Malmquist Bias

As most of our supernovae are from flux-limited samples, they will suffer Malmquist bias Malmquist (1924, 1936). This effect was discussed extensively in P99, and here we update that discussion to include our new HST SNe Ia. For the measurement of the cosmological parameters, it is the difference between the Malmquist bias of the low-redshift and high-redshift samples which matters. In particular, the probability of $\Omega_\Lambda > 0$ is enhanced only if the the low-redshift SNe suffer more Malmquist bias than the high-redshift SNe, as this makes the high-redshift SNe Ia seem fainter.

The P99 high-redshift dataset was estimated to have little Malmquist bias (0.01 mag) because the SN discovery magnitudes were decorrelated with the measured peak magnitudes. However, for the new HST sample, nine of the eleven SNe Ia selected from full search samples were found almost exactly at maximum light. This may reflect a spectroscopic flux limit superimposed on the original search flux limit since only spectroscopically confirmed SNe Ia were considered, and of those, generally the higher redshift SNe Ia from a given search were chosen, for HST for follow-up. In particular, the SNe Ia selected for follow-up from the fall 1997 search were all found at maximum light, while all but SN 1998aw from the spring 1998 search were found at maximum light. SN 2000fr was found well before maximum. Thus, the new dataset is likely to suffer more Malmquist bias than the P99 dataset. Further complicating the interpretation for the high-redshift SNe is the fact that our new HST SNe are spread over a wide range in redshift, such that a single brightness correction for Malmquist bias causes a more complicated change in the fitted cosmological parameters. This is unlike the situation in P99 in which most SNe were at $z \sim 0.5$. Following the calculation in P99 for a high-redshift flux-limited SN sample we estimate that the maximum Malmquist bias for the ensemble of HST SNe is ~ 0.03 mag. However, we caution that it is SNe near the flux-limit which are most strongly biased, and therefore, that a subsample comprised of the highest redshift members drawn from a larger flux-limited sample will be more biased. When combined with the P99 high-redshift SNe, the bias is likely to be ~ 0.02 mag since both samples have roughly the same statistical weight.

As for the low-redshift SNe Ia, in P99 we established that since most of the SNe Ia from the H96 flux-limited search were found near maximum, that sample suffered about 0.04 mag of Malmquist bias. On the other hand, the R99 SNe Ia were discovered using a galaxy-targeted technique, which therefore is not limited by the SN flux, and may be more akin to a volume-limited sample Li, Filippenko, & Riess (2001). Thus, the addition of the R99 SNe Ia could slightly reduce the overall Malmquist bias of the low-redshift sample. If we were to assume no Malmquist bias for the R99 SNe Ia, and allowing for the fact that they contribute only $\sim 1/3$ the statistical weight of the H96 SNe, we estimate that the Malmquist bias in the current low-redshift sample is roughly 0.03 mag.

Since Malmquist bias results in the selection of overly-bright SNe at the limits of a flux-limit survey, and since the flux-limit can be strongly correlated with redshift[26], this bias can result in an apparent distortion of the shape of the Hubble diagram. This may affect estimates of the dark energy equation of state. The selection effects for the current high-redshift SNe are not sufficiently well-defined, nor are the constraints on the dark energy equation of state sufficiently strong, to warrant modeling of this effect with the current datasets. However, for future work, much better control of the selection criteria for SNe Ia at both low- and high-redshift will be required in order to properly estimate the impact of this small, but nearly inescapable, bias.

In the mean time, we simply note that since the *differences* in the Malmquist biases of the high- and low-redshift subsets of SN are likely to be *smaller* in this work than in P99, we are less likely to be affected by Malmquist bias than that work.

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[26] they are 100% correlated for a single field, but this correlation can be diluted by combining fields of different depths

Given that the new HST high-redshift SNe sample suffers more Malmquist bias than the P99 sample, and that the enlarged low-redshift sample is likely to have less Malmquist bias than the low-redshift sample used in P99, the overall bias towards apparently fainter SNe Ia at high-redshift should be less than in P99. In particular, the sign of the bias is working to artificially decrease the statistically infered $P(\Omega_\Lambda > 0)$. Thus, if anything, the Malmquist bias in the present sample works to enhance confidence in the confirmation of an accelerating Universe presented in this paper. In addition, since the intrinsic dispersion decreases from ~ 0.17 mag to ~ 0.10 mag after extinction correction, the Malmquist bias in the extinction corrected fits is almost halved.

5.6. Dust Evolution

Possible evolution in the extinction properties of host-galaxy dust is a source of systematic error in our measurement. To examine the size of the effect, we consider an extreme situation where dust in $z < 0.3$ spiral galaxies have a Cardelli, Clayton, & Mathas (1989) $R_V = 3.1$ law whereas higher-redshift galaxy dust have $R_V = 1.505$. We use the Monte Carlo described in Kim *et al.* (2003) to study the bias induced when an $R_V = 3.1$ extinction correction is unappropriately applied to all supernovae. We incorperate the redshift and $E(B\text{-}V)$ distributions of the supernovae considered in this paper and an $E(B\text{-}V) < 0.1$ cut is applied. For an input cosmology of $\Omega_{\mathrm{M}} = 0.3$ and $\Omega_\Lambda = 0.7$, we find a modest shift in the cosmological parameters to $\Omega_{\mathrm{M}} = 0.34$ and $\Omega_\Lambda = 0.67$ without assuming a flat universe.

This bias moves almost exactly along the line $\Omega_M + \Omega_\Lambda = 1$, increasing uncertainty along the thin axis of the error contour, and hence also in the deceleration parameter. However, the extreme difference in dust properties considered in the Monte Carlo contributes a shift in the cosmological parameters that is less than 1 σ of our quoted statistical error bars. We adopt 0.04 as the dust evolution systematic uncertainty on Ω_{M} in a flat universe for those fits where host galaxy exctinction corrections are applied, with the understanding that this is from the extreme case noted above; this sytematic is insignificant along the major axis of the confidence ellipses.

WHAT ABOUT W? ☑

5.7. Gravitational Lensing

Gravitational lensing decreases the modal brightness and causes increased dispersion in the Hubble diagram for high redshift SNe. These effects have been discussed in some detail in the literature (Wambsganss *et al.* 1997; Frieman, J. A. 1997; Holz 1998; Kantowski 1998; Seljak & Holz 1999; Metcalf & Silk 1999; Metcalf 1999; Holz 2001; Wang, Holz, & Munshi 2002; Minty, Heavens, & Hawkins 2002; Ammanullah, Mörtsell & Goobar 2003; Dalal, Holz, Chen, & Frieman 2003; Oguri, Suto, & Turner 2003), especially in relation to the R98 and P99 SN datasets. A very conservative assumption of an "empty beam" model in a universe filled with compact objects allowed P99 to demonstrate that gravitational lensing does not alter the the case for dark energy. Gravitation lensing may result in a biased determination of the cosmological parameter determination, as discussed in (Ammanullah, Mörtsell & Goobar 2003). The size of the effect depends on the fraction of compact objects of the total mass density of the universe, $\Omega_{\rm M}$.

The potential bias increases with the redshift of the SNe in the sample. E.g. for the most distant known Type Ia SN, SN1997ff at z=1.7, there is evidence for significant magnification, $\Delta m \sim -0.3$ (Lewis & Ibata 2001; Mörtsell, Gunnarsson & Goobar 2001; Benitez et al. 2002).

As the SN sample considered in this paper does not reach as far, the (de)magnification distortions are expected to be small, in general below 0.05 mag. To estimate the systematic uncertainties in the cosmological parameters we have used the SNOC package (Goobar et al 2001) to simulate 100 realizations of our data sets assuming a 20 % universal fraction of Ω_M in compact objects, i.e. of the same order as the halo fraction deduced for the Milky Way from microlensing along the line of sight to the Large Magellanic Cloud (Alcock et al. 2000). The light beams are otherwise assumed to travel through space randomly filled with galaxy halos with mass density with equaly divided into SIS and NFW profiles, as described in (Bergström et al 2000). According to our simulations we find that (for a flat universe), on average, the fitted value of Ω_M is systematically shifted as $\delta =< \Omega_M^{\rm true} - \Omega_M^{\rm fit} >= 0.01$, with a statistical dispersion $\sigma_\delta = 0.01$. We adpot 0.01 as our gravitational lensing systematic error in the flat-universe value of $\Omega_{\rm M}$. ARIEL, DO YOU HAVE A NUMBER FOR $\Omega_{\rm M} + \Omega_\Lambda$ HOW ☑ABOUT W IN A FLAT UNIVERSE?

5.8. Supernova Population Drift

In P99 we discussed in detail whether the high-redshift SNe Ia could have systematically different properties than low-redshift SNe Ia, and in particular, whether intrinsic differences might remain after correction for stretch. One might imagine this to occur if the range of the physical parameters controlling SN Ia brightnesses have little overlap between low- and high-redshift such that corrections applied to low-redshift are inappropriate or incomplete for high-redshift SNe Ia. Since P99, considerable additional work as been done to address this issue, which we now discuss.

First, several tests performed directly with the P99 sample of high-redshift SNe Ia (in addition to the comparisons of stretch range, and spectral (Perlmutter *et al.* 1998) and lightcurve (Goldhaber *et al.* 2001) features already discussed in P99) have shown excellent consistancy with expectations from low-redshift SNe Ia. Most recently, Sullivan *et al.* (2003) have presented results on the Hubble diagram of distant Type Ia supernovae from P99 which have been morphologically-typed with HST. They find no difference in the cosmological results from their morphologically-segragated subsamples. In particular, E/S0 galaxies — for which one expects the tightest possible correlation between progenitor mass and redshift — not only agree with the cosmological fits using only spiral galaxies, but by themselves confirm the results of P99. This is strong evidence that, while age or metallicity could in priciple affect the brightnesses of SNe Ia, stretch correction eliminates these differences. Likewise, the lightcurve rise-time — suggested as an indicator of the energetics of the SN explosion (see Nugent *et al.* (1995); Hoflich, Wheeler, & Thielemann (1998) — while initially claimed to be different between high- and low-redshift SNe Ia (Riess, Filippenko, Li, & Schmidt 1999), has demonstrated very good agreement (within ±1.2 days; Aldering, Knop, & Nugent (2000)). On the theoretical side, the SN formation models of Kobayashi et al. (1998); Nomoto, Nakamura, & Kobayashi (1999) suggest that the progenitor binary system must have $[\mathrm{Fe/H}] > -1$ in order to produce a SN Ia. This would impose a lower limit to the metallicities of all SNe Ia, and thus limit the extent of any metallicity-induced brightness differences between high- and low-redshift SNe Ia. At low-redshift, several studies have presented data suggesting that SNe Ia intrinsic luminosities (i.e., those prior to stretch correction) may correlate with host-galaxy environment (Hamuy *et al.* 1996b; Branch, Romanishin, & Baron 1996; Wang, Hoeflich, & Wheeler 1997; Hamuy *et al.* 2000; Ivanov, Hamuy, & Pinto 2000; Howell 2001; Wang *et al.* 2003, R99). These findings are actually encouraging, since unlike stretch itself, there is some hope that host-galaxy environment variations can be translated into the types of physical parameters such as age and metallicity which can help in relating any drifts in the SNe Ia population to galaxy evolution. Indeed, the lack of a gradient in the intrinsic luminosities of SNe Ia with galactocentric distance, coupled with the fact that metallicity gradients are common in spiral galaxies (Henry & Worthey 1999), lead Ivanov, Hamuy, & Pinto (2000) to suggest that metallicity is not a key parameter in controlling SNe Ia brightnesses at optical wavelengths. In addition, Hamuy *et al.* (2000); Hamuy et al. (2001) find that lightcurve width is not dependent on host-galaxy metallicity. More importantly for cosmology, R99 used their sample of 22 local SNe Ia to demonstrate that any brightness variations between SNe Ia in different host-galaxy environments disappear after correction for lightcurve width. In particular, based on the R99 data, we find that after lightcurve-width correction there can be less than a 0.0X magoffset between ☑ SNe Ia in local spirals and ellipticals. This indicates that lightcurve width is able to correct for age or other differences. Finally, Wang *et al.* (2003) demonstrate a new method, *CMAGIC*, which is able to standard the vast majority of local SNe Ia to within 0.08 mag (in contrast to ~ 0.11 mag which lightcurve width corrections can attain (Phillips *et al.* 1999)). This imposes even more severe limits on the fraction of SNe Ia generated by any alternate progenitor scenario, or requires that variations in the progenitor properties have little effect on whether the resulting SN can be standardized. Therefore, if the local supernova represent SNe Ia of all ages and metallicity, then these studies based on nearby SNe Ia of strongly limit the effects of supernova evolution.

The data from the new SNe Ia presented here do offer one new test for consistancy between low- and high-redshift SNe Ia. The quality of our HST data provides measurements of the SN peak magnitudes and lightcurve widths rivaling those for nearby SNe Ia. This allows a direct comparison between the stretch-luminosity relations at low- and high-redshifts. This comparison is shown in Figure 9. This plot shows graphically that the HST high-redshift supernovae are found at similar stretches as the low-redshift SNe, and are consistent with the same stretch/luminosity relationship.

5.9. Total Identified Systematic Uncertainty

The identified systematic errors are summarized in Table 10. Adding together these errors in quadrature, we obtain a total systematic error of 0.05 on the flat-universe value of $\Omega_{\rm M}$ (along approximately the minor axis of the confidence ellipses shown in $\Omega_{\rm M}$ vs. Ω_Λ plots), and of 0.96 on $\Omega_{\rm M} + \Omega_\Lambda$ (along approximately the major axis of the confidence ellipses). When host-galaxy extinction corrections are applied, we have to consider the additional systematic effect of an uncertainty in the intrinsic value of *U*-*B* on determined color excesses. In this case, we have a total systematic error of 0.08 on the flat-universe value of $\Omega_{\rm M}$ or Ω_Λ, and a total systematic error of 2.6 on $\Omega_{\rm M} + \Omega_\Lambda$; as discussed in § 5.4, this is likely to be an overestimate of the true systematic error.

For the dark energy equation of state parameter, the total systematic error on ☑ the upper limit on w is 0.26in the positive direction when host galaxy extinction corrections are not appolied. When those corrections are directly applied, and included in the statistical error, our systematic uncertainty on the w upper limit is only 0.09.

The predominant effect of systematic errors is to move the confidence ellipses along their major axis; in some cases, these effects can be large. Therefore, any conclusions drawn from the positions of supernova confidence ellipses along this direction should be approached with caution. For example, any of these systematic errors could begin to move the confidence ellipses up and away from the flat-universe line of $\Omega_{\rm M} + \Omega_\Lambda = 1$. Given these systematics, it would be premature to interpret this as a suggestion that supernovae may be inconsistent with a flat universe cosmology.

6. Comparisons with Other Measurements

As is clear from Figure 4, the SN Ia results are more sensitive to a combination close to $\Omega_{\rm M} - \Omega_\Lambda$ than to either variable independently. This nicely complements the CMB measurements, which are more sensitive to $\Omega_{\rm M} + \Omega_\Lambda$, and the measurements of massive clusters which are sensitive primarily to $\Omega_{\rm M}$ (although that is coupled with sensitivity to σ_8). These three measurements of two parameters provide a consistency check; their convergence provides convincing evidence that a $\sim 75\%$ of the energy density of the Universe must not be normal matter, i.e. it must instead by a cosmological constant or some other form of dark energy.

A number of independent measurements of $\Omega_{\rm M}$ have been identified, and were used together with the supernova data to set limits on w in § 4.3. The values of $\Omega_{\rm M}$ used, found in Table 9, are generally consistent with our best-fit flat-universe value of $\Omega_{\rm M}$. The value of $\Omega_{\rm M} = 0.30^{+0.04}-0.03$ from Allen, Schmidt, & Fabian (2002), based on the Chandra observations X-ray gas fraction of clusters (and thus not sensitive to σ_8), is the one most disparate from our best ☑ fit value of $\Omega_{\rm M} = 0.21^{0.06}_{0.05}$. However, even these two measurements are only 1.3-σ different, and thus should not be viewed as

Table 10: Identified Systematic Errors

Systematic	Flat-Universe Ω_M(or Ω_Λ)	$\Omega_M + \Omega_\Lambda$	w^a	Notes
Fit method	0.03	0.80		
Type contamination	0.01	0.28	0.05	
Host-Galaxy Extinction	0.03	0.44	0.25	*b*
Intrinsic U-B: *K*-corrections	0.01	0.13	0.01	*b*
Intrinsic U-B: color excess	0.06	2.50	0.07	*c*
Dust Evolution	0.04	—	?	*c*
Gravitational Lensing	0.01	—	?	

a: Assuming a flat universe, this is the systematic change in the upper limit on w when the supernova data is combined with the mass resulting from a number of other cosmological measurements, assembled by Bennett *et al.* (2003).

b: Only used where host-galaxy extinction corrections are not applied; when $E(B\text{-}V)$ corrections are applied, host-galaxy extinction is a statistical error.

c: Only used where host-galaxy extinction corrections are applied.

inconsistent. Every recent cosmological measurement has been consistent with a low-mass ($\Omega_M \sim 0.2$–0.3), flat universe dominated by vacuum energy or some other form of dark energy.

7. Summary and Conclusions

1. We present a new, independent set of 11 high-redshift supernovae ($z = 0.36$–0.86). These supernovae have very high-quality photometry measured with WPFC2 on the HST. The higher quality lightcurve measurements have small enough errors on each $E(B\text{-}V)$ measurement to allow an unbiased correction host-galaxy reddening.

2. We have performed improved color and K-corrections, necessary to combine WPFC2 photometric filters with ground-based photometric filters. A reanalysis of the P99 supernova lightcurve data with these new corrections shows that the cosmological conclusions of P99 are robust, although there is a small adjustment in the best-fit values of the parameters Ω_M and Ω_Λ.

3. The cosmological fits to Ω_M and Ω_Λ are consistent with the SCP's previous results (P99), providing strong evidence for a cosmological constant. This is a significant confirmation of the results of P99 and Riess (1998), and represents a complete new set of high-redshift supernovae yielding the same results as the earlier work.

4. Under the assumption of a flat universe, we find a value of $\Omega_M = 0.21^{+0.06}_{-0.05}$ (where host-galaxy extinction is handled by omitting severely reddened supernovae) or $\Omega_M = 0.18^{+0.11}_{-0.10}$ (where extinction corrections are applied individually to each SN without any assumptions

Fig. 10.— Primary confidence intervals on Ω_{M} and Ω_{Λ} resulting from this paper. Both sets of contours include all low-z data used in this paper, plus all of the current SCP high-redshift

about the intrinsic $E(B\text{-}V)$ distribution). Our best joint limits on $\Omega_{\rm M}$ and Ω_Λ, including all the high-redshift supernovae, are shown in Figure 10.

5. Most identified systematic errors affect the cosmological results primarily by moving them along the direction where they are most uncertain, that is, along the major axis of the confidence ellipses. This corresponds to a greater error on $\Omega_{\rm M} + \Omega_\Lambda$ than on $\Omega_{\rm M} - \Omega_\Lambda$ (or, equivalently, on $\Omega_{\rm M}$ or Ω_Λ alone under the flat-universe assumption that $\Omega_{\rm M} + \Omega_\Lambda = 1$). Our total identified systematic error for the low-extinction sample analysis is 0.05 on the flat-universe value of $\Omega_{\rm M}$ or Ω_Λ, and 0.96 on $\Omega_{\rm M} + \Omega_\Lambda$. When host-galaxy extinction corrections *are* applied, a conservative estimate of the total identified systematic error is 0.08 on the flat-universe value of $\Omega_{\rm M}$ or Ω_Λ and 2.6 on $\Omega_{\rm M} + \Omega_\Lambda$.

6. The data provide a 3-σ upper confidence limit on w, the equation of state of the dark energy, of $w < -0.70$, under the assumption of a constant w (not varying in time) and a flat universe, and using the additional constraint that $\Omega_{\rm M} = 0.27 \pm 0.04$ (Bennett *et al.* 2003). The supernova data are completely consistent with a low-mass Universe ($\Omega_{\rm M} \sim 0.2$–0.3) dominated by vacuum energy ($w = -1$).

Fig. 2.— A plot of $E(B\text{-}V)$ as a function of redshift for the 11 HST-observed SNe of this paper shows that there is no trend of host-galaxy extinction with redshift. The only supernova with a

Fig. 4.— Old (P99) and new sets of high-redshift supernovae yield consistent measurements of $\Omega_{\rm M}$ and Ω_Λ. Contours indicate the 68% and 90% confidence intervals for each fit. The dotted

Fig. 6.— $\Omega_{\rm M}$ and Ω_Λ 68%, 90%, 95%, and 99% confidence limits which combine the high-redshift data of the SCP (this paper, P99) and the High-Z Team (Riess 1998). The fit includes Subset 2 supernovae

Fig. 9.— Stretch/Luminosity relationship for low-redshift SNe (open circles) and high-redshift HST SNe (filled circles). Each point is the measured m_B for that supernova, minus $\mathcal{D}_{\mathcal{L}}$, the "Hubble-constant-free luminosity di

A. Lightcurve Data

Tabulated below is lightcurve data for the 11 HST SNe presented in this paper. For each event, there are two lightcurves, one for R-band and one for I-band. All photometry has been color corrected to the standard Bessel filters as described in § 3, using color corrections which assume the lightcurve parameters in Table 3. Note that there are correlated errors between the data points. For the ground-based data, there is a covariance because the same final reference images were subtracted from all other ground-based points. Similarly, the HST data include a covariance due to a single background model having been used for all points (see § 2.1). In addition to this, the relative photometric zeropoint magnitudes were determined separately for the ground-based and HST photometry; in the former case, standard stars from Landolt (1992) were used to measure magnitudes of secondary standard stars in the supernova field of view. In the latter case, zeropoints from Dolphin (2000) were used. These covariance matrices are not listed below, but will be available from the SCP website.[27]

Because uncertainties are flux uncertainties rather than magnitude uncertainties, each lightcurve is presented in arbitrary flux units. For each lightcurve, the zeropoint necessary to convert these to magnitudes is given. The magnitude may be calculated using the standard formula:

$$m = -2.5 \log f + m_{zp} \tag{A1}$$

where m_{zp} is the quoted zeropoint and f is the flux value from the table.

The telescope used for each data point is indicated. BTC = the Big Throughput Camera on the CTIO 4m telescope. CTIO = the prime focus imager on the CTIO 4m telescope. WIYN = the Naysmith 2k×2k imager on the WIYN 3.5m telescope at Kitt Peak observatory. INT = the WFC (wide-field camera) on the INT 2.5m telescope at La Palma. JKT = the WFC (wide-field camera) on the JKT 1.0m telescope at La Palma. KECK = the LRIS imager on the Keck 10m telescope. NTT = the SUSI-2 imager on the NTT 3.6m telescope at ESO. CFHT = the CFHT12K multi-chip imager on the 3.6m CFHT telescope on Mauna Kea in Hawaii. Finally, HSTPC indicates data obtained from the Planetary Camera chip on WFPC2.

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[27] http://www.supernova.lbl.gov/

Table 11: SN 1997ek-R

Julian Day -2,400,000	Flux[a]	Telescope
50780.63	0.24 ± 1.27	BTC
50780.69	0.57 ± 0.93	BTC
50781.61	-0.28 ± 1.05	BTC
50781.66	1.22 ± 0.89	BTC
50781.67	0.29 ± 0.89	BTC
50781.72	0.16 ± 1.01	BTC
50810.58	2.71 ± 1.28	BTC
50810.59	4.63 ± 1.29	BTC
50810.60	5.25 ± 1.24	BTC
50810.67	4.86 ± 1.32	BTC
50810.68	5.05 ± 1.24	BTC
50810.69	5.71 ± 1.28	BTC
50811.66	4.35 ± 1.10	BTC
50811.68	4.53 ± 1.07	BTC
50811.69	3.55 ± 1.22	BTC
50817.67	4.92 ± 0.91	BTC
50817.68	5.09 ± 0.84	BTC
50817.69	3.17 ± 0.83	BTC
50817.70	2.65 ± 0.84	BTC
50817.71	3.71 ± 0.85	BTC
50817.72	3.34 ± 1.02	BTC
50817.73	4.45 ± 1.06	BTC
50817.73	4.77 ± 1.04	BTC
50817.74	3.10 ± 1.04	BTC
50818.92	3.82 ± 0.25	HSTPC
50824.77	3.36 ± 0.23	HSTPC
50835.67	2.50 ± 0.87	BTC
50835.68	3.20 ± 0.90	BTC
50835.69	2.56 ± 1.00	BTC
50835.70	3.01 ± 1.05	BTC
50835.70	3.26 ± 1.12	BTC
51165.71	-0.05 ± 0.60	BTC
51165.71	-0.67 ± 0.61	BTC
51165.74	-0.55 ± 0.71	BTC
51166.63	0.44 ± 2.12	BTC
51166.65	1.20 ± 1.28	BTC
51166.66	-0.67 ± 1.49	BTC
51193.59	0.47 ± 0.77	BTC
51193.60	-0.86 ± 0.79	BTC
51193.61	0.76 ± 0.70	BTC
51193.62	0.18 ± 0.73	BTC
51194.65	0.46 ± 0.64	BTC

a: Zeropoint: 25.678

Table 12: SN 1997ek-I

Julian Day -2,400,000	Flux[a]	Telescope
50816.60	5.62 ± 1.45	BTC
50817.56	3.22 ± 1.30	BTC
50817.57	4.27 ± 1.35	BTC
50817.58	4.70 ± 1.40	BTC
50817.58	5.41 ± 1.43	BTC
50817.59	5.82 ± 1.36	BTC
50817.60	4.47 ± 1.66	BTC
50817.61	5.16 ± 1.52	BTC
50817.63	3.68 ± 1.52	BTC
50817.64	4.48 ± 1.48	BTC
50817.64	3.31 ± 1.59	BTC
50817.65	5.89 ± 1.23	BTC
50817.66	4.38 ± 1.44	BTC
50818.93	3.52 ± 0.16	HSTPC
50819.74	2.02 ± 1.70	WIYN
50819.76	3.05 ± 1.65	WIYN
50819.78	4.18 ± 1.90	WIYN
50819.79	1.71 ± 1.60	WIYN
50819.81	4.31 ± 1.58	WIYN
50819.82	3.84 ± 2.09	WIYN
50824.78	3.69 ± 0.16	HSTPC
50835.72	2.72 ± 1.96	BTC
50835.73	3.06 ± 2.05	BTC
50846.74	1.43 ± 0.09	HSTPC
50858.84	0.67 ± 0.07	HSTPC
50871.95	0.44 ± 0.06	HSTPC
51072.07	0.50 ± 0.57	KECK
51072.07	0.35 ± 0.58	KECK
51072.07	0.69 ± 0.58	KECK
51072.11	0.31 ± 0.55	KECK
51072.11	0.94 ± 0.58	KECK
51072.12	−0.23 ± 0.57	KECK
51101.99	−0.37 ± 0.54	KECK
51102.00	0.51 ± 0.58	KECK
51102.00	0.58 ± 0.59	KECK
51102.05	1.20 ± 0.75	KECK
51102.06	1.53 ± 0.90	KECK
51126.93	0.01 ± 0.06	HSTPC
51134.26	0.08 ± 0.05	HSTPC
51165.70	−0.66 ± 1.15	BTC
51165.72	0.21 ± 1.06	BTC
51165.73	−0.44 ± 1.12	BTC
51193.64	0.01 ± 1.12	BTC
51193.65	−0.28 ± 1.13	BTC
51193.67	−0.46 ± 1.50	BTC
51194.59	0.99 ± 1.17	BTC
51194.60	1.34 ± 1.30	BTC
51194.60	0.73 ± 1.15	BTC

a: Zeropoint: 24.801

Table 13: SN 1997eq-R

Julian Day -2,400,000	Flux[a]	Telescope
50780.60	0.01 ± 0.12	BTC
50780.66	0.21 ± 0.12	BTC
50781.60	-0.08 ± 0.10	BTC
50781.63	0.19 ± 0.10	BTC
50781.68	0.09 ± 0.10	BTC
50781.72	0.14 ± 0.11	BTC
50810.61	1.76 ± 0.12	BTC
50810.62	1.80 ± 0.12	BTC
50810.63	1.88 ± 0.13	BTC
50810.64	1.87 ± 0.11	BTC
50810.70	1.91 ± 0.12	BTC
50810.71	1.82 ± 0.11	BTC
50811.70	1.78 ± 0.10	BTC
50818.34	2.23 ± 0.28	INT
50818.36	1.98 ± 0.24	INT
50819.85	1.54 ± 0.06	HSTPC
50821.66	2.14 ± 0.54	WIYN
50821.67	1.79 ± 0.39	WIYN
50835.41	0.85 ± 0.13	JKT
50835.42	0.87 ± 0.18	JKT
50835.43	0.85 ± 0.34	JKT
50843.68	0.37 ± 0.18	WIYN
50843.70	0.02 ± 0.40	WIYN
50846.81	0.29 ± 0.02	HSTPC
50855.82	0.17 ± 0.02	HSTPC
50863.82	0.12 ± 0.02	HSTPC
51165.56	0.01 ± 0.12	BTC
51165.61	0.01 ± 0.41	BTC
51165.62	-0.61 ± 0.67	BTC
51165.64	0.00 ± 0.12	BTC
51193.58	-0.03 ± 0.10	BTC
51193.63	0.02 ± 0.09	BTC

a: Zeropoint: 23.284

Table 14: SN 1997eq-I

Julian Day -2,400,000	Flux[a]	Telescope
50818.37	1.15 ± 0.50	INT
50818.38	1.05 ± 0.32	INT
50818.39	1.20 ± 0.32	INT
50818.41	0.94 ± 0.49	INT
50818.43	1.20 ± 0.48	INT
50818.46	1.05 ± 0.25	INT
50819.87	0.83 ± 0.03	HSTPC
50821.68	0.93 ± 0.35	WIYN
50821.69	0.83 ± 0.41	WIYN
50821.70	0.65 ± 0.38	WIYN
50824.90	0.78 ± 0.02	HSTPC
50835.54	0.59 ± 0.27	JKT
50835.56	0.13 ± 0.29	JKT
50835.58	-0.11 ± 0.50	JKT
50846.82	0.34 ± 0.02	HSTPC
50855.83	0.25 ± 0.02	HSTPC
50863.83	0.20 ± 0.01	HSTPC
51165.57	0.03 ± 0.29	BTC
51165.60	0.06 ± 0.34	BTC
51165.63	0.07 ± 0.20	BTC
51165.65	0.06 ± 0.17	BTC
51193.58	-0.10 ± 0.17	BTC

a: Zeropoint: 22.388

Table 15: SN 1997ez-R

Julian Day -2,400,000	Flux[a]	Telescope
50780.75	-0.41 ± 1.15	BTC
50780.82	-0.88 ± 0.96	BTC
50781.74	-1.46 ± 1.01	BTC
50781.79	0.29 ± 1.18	BTC
50781.79	1.09 ± 0.96	BTC
50811.77	6.05 ± 1.05	BTC
50811.77	3.90 ± 1.89	WIYN
50811.77	5.82 ± 1.03	BTC
50811.78	5.62 ± 1.02	BTC
50811.78	5.82 ± 2.22	WIYN
50811.79	3.97 ± 4.73	WIYN
50811.81	5.97 ± 1.04	BTC
50811.81	4.83 ± 1.16	BTC
50817.84	5.51 ± 1.22	BTC
50817.85	7.73 ± 1.63	BTC
50817.86	4.58 ± 2.15	BTC
50818.70	4.93 ± 1.13	INT
50818.72	5.04 ± 1.09	INT
50819.06	4.56 ± 0.30	HSTPC
50824.97	3.28 ± 0.25	HSTPC
50835.66	4.69 ± 1.49	JKT
50835.67	2.88 ± 1.68	JKT
50835.81	1.82 ± 1.49	BTC
50835.82	-0.07 ± 1.66	BTC
50835.83	0.52 ± 1.70	BTC
51193.75	-0.14 ± 0.74	BTC
51193.76	0.37 ± 0.69	BTC
51193.76	0.00 ± 1.08	BTC
51193.77	-1.23 ± 0.85	BTC
51193.78	-0.20 ± 0.83	BTC
51193.79	-0.21 ± 0.78	BTC
51193.80	-1.80 ± 1.63	WIYN
51195.73	-1.37 ± 1.26	WIYN
51195.75	-0.21 ± 1.40	WIYN
51195.77	-0.58 ± 1.18	WIYN
51195.78	-0.92 ± 1.36	WIYN

[a] Zeropoint: 25.688

Table 16: SN 1997ez-I

Julian Day -2,400,000	Flux[a]	Telescope
50816.74	2.05 ± 1.90	BTC
50816.76	4.82 ± 2.03	BTC
50816.77	4.63 ± 1.89	BTC
50816.78	6.11 ± 1.90	BTC
50816.78	5.02 ± 2.02	BTC
50816.85	6.83 ± 2.14	BTC
50818.63	4.19 ± 2.23	INT
50818.65	4.24 ± 1.55	INT
50818.66	4.12 ± 1.54	INT
50818.68	4.30 ± 1.54	INT
50819.07	4.80 ± 0.17	HSTPC
50820.79	4.43 ± 1.56	WIYN
50820.81	5.70 ± 1.50	WIYN
50820.83	3.92 ± 1.46	WIYN
50820.84	4.23 ± 1.42	WIYN
50820.86	6.09 ± 1.67	WIYN
50820.87	3.26 ± 1.71	WIYN
50824.99	3.82 ± 0.17	HSTPC
50835.60	5.27 ± 1.77	JKT
50835.61	0.53 ± 2.03	JKT
50835.63	5.55 ± 1.94	JKT
50835.64	5.62 ± 2.52	JKT
50835.84	3.39 ± 2.13	BTC
50835.85	1.78 ± 2.23	BTC
50835.86	−0.47 ± 2.56	BTC
50846.55	1.66 ± 0.09	HSTPC
50858.98	0.92 ± 0.08	HSTPC
50871.89	0.39 ± 0.04	HSTPC
51189.97	0.80 ± 1.13	WIYN
51189.98	−0.74 ± 1.22	WIYN
51190.00	−0.20 ± 1.35	WIYN
51191.90	−0.54 ± 1.34	WIYN
51191.92	−1.64 ± 1.16	WIYN
51191.93	0.15 ± 1.28	WIYN
51194.70	−3.19 ± 2.44	BTC
51194.71	−1.06 ± 2.73	BTC
51194.72	−0.60 ± 2.43	BTC
51194.73	−0.52 ± 2.81	BTC
51194.74	−1.26 ± 2.28	BTC
51194.75	−0.84 ± 2.49	BTC
51194.76	−0.27 ± 1.90	BTC
51194.77	−2.00 ± 2.19	BTC
51194.78	−1.89 ± 2.02	BTC
51194.78	−1.58 ± 2.61	BTC
51194.79	−0.68 ± 2.38	BTC

a: Zeropoint: 24.954

Table 17: SN 1998as-R

Julian Day -2,400,000	Flux^a	Telescope
50872.63	-0.10 ± 0.10	BTC
50872.66	-0.07 ± 0.09	BTC
50872.67	0.06 ± 0.09	BTC
50872.72	-0.07 ± 0.10	BTC
50872.73	-0.06 ± 0.11	BTC
50873.57	0.06 ± 0.11	BTC
50873.58	0.03 ± 0.10	BTC
50895.58	2.33 ± 0.12	BTC
50895.62	2.47 ± 0.15	BTC
50896.58	2.65 ± 0.12	BTC
50899.70	2.24 ± 0.12	BTC
50904.68	2.15 ± 0.11	BTC
50904.69	2.05 ± 0.10	BTC
50904.70	2.20 ± 0.10	BTC
50904.71	1.95 ± 0.11	BTC
50904.72	2.00 ± 0.10	BTC
50912.29	1.30 ± 0.05	HSTPC
50935.01	0.33 ± 0.02	HSTPC
50948.52	0.26 ± 0.02	HSTPC
50963.17	0.17 ± 0.02	HSTPC
51193.83	0.06 ± 0.08	BTC
51193.84	-0.07 ± 0.08	BTC
51193.86	0.04 ± 0.08	BTC
51196.03	0.21 ± 0.13	WIYN
51196.04	-0.19 ± 0.12	WIYN
51196.05	-0.11 ± 0.16	WIYN

a: Zeropoint: 23.139

Table 18: SN 1998as-I

Julian Day -2,400,000	Flux[a]	Telescope
50912.31	8.49 ± 0.21	HSTPC
50924.07	6.83 ± 0.20	HSTPC
50932.65	1.95 ± 1.56	WIYN
50935.02	4.58 ± 0.18	HSTPC
50948.53	2.50 ± 0.15	HSTPC
50963.19	1.78 ± 0.13	HSTPC
51194.86	-1.02 ± 0.98	BTC
51194.87	0.60 ± 1.12	BTC
51196.93	-0.55 ± 1.23	WIYN
51196.94	0.73 ± 1.12	WIYN
51196.96	-1.44 ± 1.28	WIYN
51280.50	0.53 ± 1.60	BTC
51280.51	-2.08 ± 1.50	BTC
51280.51	0.67 ± 1.50	BTC
51280.52	0.60 ± 1.33	BTC
51280.53	1.32 ± 1.45	BTC
51280.54	0.72 ± 1.46	BTC

[a] Zeropoint: 24.788

Table 19: SN 1998aw-R

Julian Day -2,400,000	Flux[a]	Telescope
50513.71	0.08 ± 0.14	BTC
50513.73	-0.08 ± 0.16	BTC
50513.75	0.06 ± 0.13	BTC
50514.71	0.08 ± 0.14	BTC
50517.74	-0.19 ± 0.14	BTC
50517.76	0.04 ± 0.16	BTC
50518.79	0.31 ± 0.17	BTC
50518.81	-0.02 ± 0.17	BTC
50872.56	-0.03 ± 0.21	BTC
50872.59	-0.03 ± 0.22	BTC
50873.73	-0.03 ± 0.18	BTC
50873.74	-0.09 ± 0.15	BTC
50895.60	0.02 ± 0.16	BTC
50895.64	0.55 ± 0.16	BTC
50896.58	0.67 ± 0.15	BTC
50896.60	0.39 ± 0.16	BTC
50899.69	0.89 ± 0.15	BTC
50904.63	1.87 ± 0.14	BTC
50904.64	1.66 ± 0.14	BTC
50904.65	1.75 ± 0.13	BTC
50904.66	1.82 ± 0.14	BTC
50904.67	1.82 ± 0.14	BTC
50912.03	2.33 ± 0.07	HSTPC
50922.11	1.93 ± 0.06	HSTPC
50927.56	2.05 ± 0.38	BTC
50927.57	1.80 ± 0.34	BTC
50927.60	1.69 ± 0.36	BTC
50927.61	0.96 ± 0.41	BTC
50929.64	1.48 ± 0.28	WIYN
50929.65	1.06 ± 0.33	WIYN
50929.67	1.90 ± 0.31	WIYN
50933.07	1.21 ± 0.04	HSTPC
50947.71	0.53 ± 0.03	HSTPC
50961.83	0.27 ± 0.03	HSTPC
51192.96	-0.19 ± 0.26	WIYN
51192.98	-0.14 ± 0.39	WIYN
51193.00	0.18 ± 0.28	WIYN
51193.02	-0.14 ± 0.24	WIYN
51193.03	-0.29 ± 0.28	WIYN
51279.60	0.01 ± 0.13	BTC
51279.61	0.04 ± 0.14	BTC
51279.63	-0.04 ± 0.12	BTC
51279.66	0.01 ± 0.13	BTC
51280.56	0.14 ± 0.16	BTC
51280.57	0.17 ± 0.15	BTC

a: Zeropoint: 23.536

Table 20: SN 1998aw-I

Julian Day -2,400,000	Flux[a]	Telescope
50513.76	-0.33 ± 0.25	BTC
50514.74	-0.10 ± 0.22	BTC
50514.76	-0.12 ± 0.21	BTC
50514.78	0.06 ± 0.23	BTC
50518.73	0.18 ± 0.42	BTC
50518.75	-0.08 ± 0.34	BTC
50912.04	1.64 ± 0.05	HSTPC
50922.12	1.57 ± 0.05	HSTPC
50929.70	1.51 ± 0.49	WIYN
50930.71	1.80 ± 0.47	WIYN
50933.08	1.11 ± 0.03	HSTPC
50947.73	0.73 ± 0.03	HSTPC
50961.84	0.49 ± 0.03	HSTPC
51194.03	-0.07 ± 0.32	WIYN
51194.05	-0.26 ± 0.51	WIYN
51195.97	-0.21 ± 0.32	WIYN
51195.98	0.13 ± 0.27	WIYN
51196.00	0.10 ± 0.29	WIYN
51196.02	0.05 ± 0.27	WIYN
51279.59	-0.03 ± 0.21	BTC
51279.62	-0.06 ± 0.25	BTC
51279.64	0.15 ± 0.21	BTC
51279.65	0.01 ± 0.23	BTC
51279.66	0.19 ± 0.25	BTC
51280.55	0.14 ± 0.31	BTC
51280.57	-0.02 ± 0.28	BTC
51280.59	-0.30 ± 0.29	BTC
51280.60	0.09 ± 0.29	BTC

a: Zeropoint: 22.874

Table 21: SN 1998ax-R

Julian Day -2,400,000	Flux[a]	Telescope
50138.65	-0.03 ± 0.09	CTIO
50138.67	-0.09 ± 0.10	CTIO
50159.64	-0.09 ± 0.08	CTIO
50159.66	0.03 ± 0.07	CTIO
50160.67	0.01 ± 0.07	CTIO
50160.68	0.02 ± 0.06	CTIO
50168.59	-0.03 ± 0.07	CTIO
50168.65	0.14 ± 0.06	CTIO
50169.64	0.13 ± 0.15	CTIO
50169.67	-0.01 ± 0.08	CTIO
50432.83	-0.06 ± 0.06	CTIO
50453.84	-0.01 ± 0.08	CTIO
50454.77	0.01 ± 0.06	CTIO
50459.82	-0.02 ± 0.04	CTIO
50459.83	-0.02 ± 0.05	CTIO
50459.84	0.02 ± 0.05	CTIO
50490.79	0.01 ± 0.06	BTC
50490.79	0.07 ± 0.06	BTC
50490.80	-0.04 ± 0.06	BTC
50490.80	-0.04 ± 0.06	BTC
50513.71	-0.03 ± 0.06	BTC
50514.72	-0.06 ± 0.06	BTC
50872.54	0.72 ± 0.12	BTC
50872.57	0.58 ± 0.12	BTC
50873.53	0.84 ± 0.17	BTC
50873.55	0.95 ± 0.10	BTC
50895.52	1.42 ± 0.09	BTC
50895.55	1.06 ± 0.19	BTC
50895.71	1.24 ± 0.07	BTC
50896.53	1.14 ± 0.10	BTC
50900.70	1.14 ± 0.07	BTC
50900.71	1.04 ± 0.07	BTC
50904.59	0.91 ± 0.06	BTC
50904.60	0.84 ± 0.06	BTC
50904.61	0.81 ± 0.06	BTC
50904.62	0.84 ± 0.06	BTC
50904.63	0.89 ± 0.06	BTC
50911.96	0.55 ± 0.03	HSTPC
50922.04	0.27 ± 0.02	HSTPC
50933.00	0.15 ± 0.02	HSTPC
50947.65	0.09 ± 0.01	HSTPC
50961.23	0.09 ± 0.01	HSTPC
51193.80	-0.00 ± 0.05	BTC
51193.81	-0.00 ± 0.05	BTC
51193.82	-0.01 ± 0.06	BTC
51279.52	-0.01 ± 0.08	BTC
51279.57	0.11 ± 0.08	BTC
51280.61	0.06 ± 0.06	BTC

a: Zeropoint: 22.922

Table 22: SN 1998ax-I

Julian Day -2,400,000	Flux[a]	Telescope
50911.97	1.77 ± 0.10	HSTPC
50922.05	1.47 ± 0.10	HSTPC
50933.01	1.09 ± 0.06	HSTPC
50947.66	0.69 ± 0.05	HSTPC
50961.24	0.42 ± 0.04	HSTPC

a: Zeropoint: 23.688

Table 23: SN 1998ay-R

Julian Day -2,400,000	Flux[a]	Telescope
50521.85	0.02 ± 0.50	WIYN
50521.86	0.17 ± 0.56	WIYN
50872.54	2.12 ± 1.08	BTC
50872.57	1.28 ± 0.97	BTC
50873.53	0.58 ± 1.81	BTC
50873.55	-0.70 ± 1.04	BTC
50895.52	5.68 ± 0.90	BTC
50895.55	6.68 ± 1.90	BTC
50895.71	6.08 ± 0.78	BTC
50896.53	6.69 ± 1.24	BTC
50900.70	5.74 ± 0.75	BTC
50900.71	6.73 ± 0.91	BTC
50904.59	5.49 ± 0.78	BTC
50904.60	5.66 ± 0.76	BTC
50904.61	5.63 ± 0.78	BTC
50904.62	5.78 ± 0.82	BTC
50904.63	5.92 ± 0.79	BTC
50912.16	2.83 ± 0.20	HSTPC
50923.99	1.46 ± 0.16	HSTPC
51193.80	-0.09 ± 0.60	BTC
51193.81	0.61 ± 0.48	BTC
51193.82	0.53 ± 0.64	BTC

a: Zeropoint: 25.093

Table 24: SN 1998ay-I

Julian Day -2,400,000	Flux[a]	Telescope
50912.17	1.44 ± 0.07	HSTPC
50924.00	0.89 ± 0.06	HSTPC
50934.68	0.56 ± 0.04	HSTPC
50948.59	0.37 ± 0.04	HSTPC
50967.81	0.23 ± 0.03	HSTPC

a: Zeropoint: 23.688

Table 25: SN 1998ba-R

Julian Day -2,400,000	Flux[a]	Telescope
50873.79	0.03 ± 0.09	BTC
50873.80	0.09 ± 0.09	BTC
50873.81	0.01 ± 0.09	BTC
50873.82	0.03 ± 0.09	BTC
50873.83	0.01 ± 0.08	BTC
50873.84	-0.03 ± 0.09	BTC
50895.78	1.50 ± 0.14	BTC
50895.85	1.65 ± 0.15	BTC
50899.75	1.53 ± 0.11	BTC
50899.84	1.43 ± 0.14	BTC
50899.90	1.20 ± 0.21	BTC
50900.74	1.54 ± 0.10	BTC
50900.75	1.32 ± 0.10	BTC
50904.77	1.36 ± 0.11	BTC
50904.78	1.20 ± 0.11	BTC
50904.79	1.42 ± 0.13	BTC
50904.80	1.30 ± 0.09	BTC
50904.81	1.34 ± 0.11	BTC
50912.10	0.72 ± 0.03	HSTPC
50923.12	0.39 ± 0.02	HSTPC
50933.21	0.21 ± 0.02	HSTPC
50947.12	0.11 ± 0.01	HSTPC
50961.90	0.11 ± 0.01	HSTPC
51258.01	-0.15 ± 0.11	WIYN
51279.82	0.07 ± 0.08	BTC
51279.85	-0.05 ± 0.10	BTC
51280.69	-0.02 ± 0.07	BTC
51280.70	0.03 ± 0.06	BTC

[a]: Zeropoint: 22.779

Table 26: SN 1998ba-I

Julian Day -2,400,000	Flux[a]	Telescope
50907.82	3.19 ± 1.99	WIYN
50907.83	3.97 ± 1.75	WIYN
50907.84	6.81 ± 1.82	WIYN
50907.85	6.05 ± 2.36	WIYN
50912.11	5.38 ± 0.22	HSTPC
50923.13	3.70 ± 0.21	HSTPC
50933.22	2.60 ± 0.13	HSTPC
50947.13	1.44 ± 0.10	HSTPC
50961.92	1.34 ± 0.10	HSTPC
51279.83	-1.51 ± 1.00	BTC
51279.84	0.88 ± 1.09	BTC
51280.69	-1.04 ± 0.83	BTC
51280.71	0.66 ± 0.72	BTC
51280.72	-0.06 ± 0.68	BTC
51280.73	0.13 ± 0.68	BTC

a: Zeropoint: 24.477

Table 27: SN 1998be-R

Julian Day -2,400,000	Flux[a]	Telescope
50490.86	0.49 ± 0.55	BTC
50490.87	−0.39 ± 0.54	BTC
50513.83	−0.02 ± 0.52	BTC
50513.84	0.15 ± 0.54	BTC
50514.83	0.53 ± 0.60	BTC
50514.86	−0.51 ± 0.53	BTC
50517.88	0.33 ± 0.70	BTC
50517.90	−0.26 ± 0.71	BTC
50517.90	0.69 ± 0.81	BTC
50518.86	0.22 ± 0.62	BTC
50518.87	0.57 ± 0.66	BTC
50872.74	−0.75 ± 0.91	BTC
50872.89	1.36 ± 0.93	BTC
50873.87	0.63 ± 0.53	BTC
50895.78	4.22 ± 0.69	BTC
50895.84	5.34 ± 0.88	BTC
50899.75	7.13 ± 0.79	BTC
50899.82	6.98 ± 0.91	BTC
50900.76	4.64 ± 0.65	BTC
50904.73	6.58 ± 0.65	BTC
50904.74	6.90 ± 0.67	BTC
50904.75	6.31 ± 0.72	BTC
50904.75	7.32 ± 0.73	BTC
50904.76	8.30 ± 0.76	BTC
50904.86	7.95 ± 0.89	BTC
50912.23	5.28 ± 0.28	HSTPC
50923.19	1.94 ± 0.18	HSTPC
50932.74	2.04 ± 0.89	WIYN
50932.77	1.38 ± 0.93	WIYN
50934.08	0.62 ± 0.12	HSTPC
50949.00	0.69 ± 0.13	HSTPC
50962.17	0.15 ± 0.12	HSTPC
51279.68	−0.16 ± 0.67	BTC
51279.71	0.31 ± 0.68	BTC
51279.75	0.21 ± 0.73	BTC
51279.77	−0.30 ± 0.79	BTC

a: Zeropoint: 25.350

Table 28: SN 1998be-I

Julian Day -2,400,000	Flux[a]	Telescope
50514.85	-0.21 ± 0.83	BTC
50514.87	-1.02 ± 0.78	BTC
50518.84	2.00 ± 0.90	BTC
50518.85	1.47 ± 0.86	BTC
50518.85	0.31 ± 0.82	BTC
50912.25	3.35 ± 0.18	HSTPC
50923.20	1.96 ± 0.16	HSTPC
50932.80	2.35 ± 1.09	WIYN
50932.85	2.25 ± 0.91	WIYN
50934.09	1.07 ± 0.09	HSTPC
50949.01	0.76 ± 0.08	HSTPC
50962.19	0.38 ± 0.07	HSTPC
51279.69	0.81 ± 0.89	BTC
51279.70	0.49 ± 0.87	BTC
51279.72	1.51 ± 0.73	BTC
51279.73	-0.02 ± 0.71	BTC
51279.76	0.62 ± 0.83	BTC
51279.77	0.58 ± 0.85	BTC
51280.64	-0.87 ± 0.82	BTC
51280.64	0.36 ± 0.84	BTC
51280.65	0.12 ± 0.73	BTC
51280.66	-0.13 ± 0.78	BTC
51280.67	1.24 ± 0.76	BTC
51280.68	-0.62 ± 0.76	BTC

[a]: Zeropoint: 24.384

Table 29: SN 1998bi-R

Julian Day -2,400,000	Flux[a]	Telescope
50138.79	-1.04 ± 0.91	CTIO
50138.82	0.85 ± 0.86	CTIO
50168.80	-0.68 ± 0.66	CTIO
50490.86	0.40 ± 0.49	BTC
50490.87	-0.09 ± 0.48	BTC
50513.83	0.26 ± 0.51	BTC
50513.84	-0.10 ± 0.53	BTC
50514.83	-1.06 ± 0.58	BTC
50514.86	-0.05 ± 0.50	BTC
50517.88	0.13 ± 0.65	BTC
50517.89	-0.11 ± 0.60	BTC
50517.89	0.93 ± 0.60	BTC
50517.90	-0.29 ± 0.68	BTC
50517.90	-0.35 ± 0.74	BTC
50872.74	0.22 ± 0.86	BTC
50872.89	0.52 ± 0.81	BTC
50873.87	0.60 ± 0.51	BTC
50895.78	3.14 ± 0.63	BTC
50895.84	3.11 ± 0.78	BTC
50899.75	4.93 ± 0.65	BTC
50899.82	4.27 ± 0.70	BTC
50900.76	4.44 ± 0.55	BTC
50904.73	6.10 ± 0.61	BTC
50904.74	4.89 ± 0.61	BTC
50904.75	5.30 ± 0.61	BTC
50904.75	5.37 ± 0.64	BTC
50904.76	6.21 ± 0.66	BTC
50904.86	5.26 ± 0.77	BTC
50910.15	4.89 ± 0.25	HSTPC
50922.18	3.53 ± 0.22	HSTPC
51279.68	1.54 ± 0.68	BTC
51279.71	2.18 ± 0.67	BTC
51279.71	0.94 ± 0.73	BTC
51279.74	0.63 ± 0.67	BTC
51279.75	-1.14 ± 0.68	BTC
51279.77	0.47 ± 0.76	BTC

a: Zeropoint: 25.213

Table 30: SN 1998bi-I

Julian Day -2,400,000	Flux[a]	Telescope
50168.80	-0.51 ± 0.76	CTIO
50168.81	0.10 ± 0.83	CTIO
50514.85	-0.86 ± 0.85	BTC
50514.87	-0.23 ± 0.73	BTC
50518.84	1.10 ± 0.81	BTC
50518.85	-1.31 ± 0.80	BTC
50518.85	0.05 ± 0.80	BTC
50910.16	3.65 ± 0.11	HSTPC
50922.20	3.23 ± 0.11	HSTPC
50931.99	2.24 ± 0.07	HSTPC
50946.38	0.97 ± 0.06	HSTPC
50966.88	0.36 ± 0.04	HSTPC
51279.69	0.52 ± 0.89	BTC
51279.70	-0.46 ± 0.79	BTC
51279.72	0.81 ± 0.69	BTC
51279.73	-0.16 ± 0.68	BTC
51279.76	-0.07 ± 0.76	BTC
51279.77	0.86 ± 0.78	BTC
51280.64	-0.04 ± 0.78	BTC
51280.64	0.70 ± 0.75	BTC
51280.65	0.32 ± 0.67	BTC
51280.66	-0.60 ± 0.70	BTC
51280.67	-0.39 ± 0.72	BTC
51280.68	0.30 ± 0.72	BTC

[a]: Zeropoint: 24.381

Table 31: SN 2000fr-R

Julian Day -2,400,000	Flux[a]	Telescope
51671.77	1.02 ± 0.07	KECK
51671.77	1.05 ± 0.07	KECK
51671.78	1.06 ± 0.07	KECK
51671.78	0.99 ± 0.07	KECK
51679.98	1.54 ± 0.05	HSTPC
51692.91	1.30 ± 0.05	HSTPC
51706.26	0.67 ± 0.03	HSTPC
51718.04	0.35 ± 0.01	HSTPC
51733.86	0.15 ± 0.01	HSTPC
52014.72	-0.01 ± 0.07	NTT
52014.73	-0.08 ± 0.07	NTT
52014.74	0.04 ± 0.08	NTT
52014.75	-0.04 ± 0.06	NTT
52014.76	-0.04 ± 0.07	NTT
52014.77	-0.08 ± 0.10	NTT
52014.78	-0.07 ± 0.09	NTT
52014.79	-0.04 ± 0.10	NTT
52014.80	-0.16 ± 0.14	NTT
52376.98	0.01 ± 0.04	CFHT
52376.99	-0.00 ± 0.03	CFHT
52377.04	0.01 ± 0.04	CFHT
52377.05	-0.02 ± 0.04	CFHT
52382.01	0.03 ± 0.05	CFHT
52384.98	-0.00 ± 0.09	CFHT
52386.85	-0.14 ± 0.10	CFHT

[a]: Zeropoint: 22.998

Table 32: SN 2000fr-I

Julian Day -2,400,000	Flux[a]	Telescope
51641.99	0.03 ± 0.04	CFHT
51664.95	0.40 ± 0.05	CFHT
51664.99	0.40 ± 0.06	CFHT
51672.86	1.03 ± 0.02	HSTPC
51679.97	1.49 ± 0.03	HSTPC
51692.91	1.30 ± 0.03	HSTPC
51706.20	0.93 ± 0.03	HSTPC
51717.98	0.61 ± 0.02	HSTPC
51733.79	0.36 ± 0.02	HSTPC
51997.93	0.05 ± 0.06	CFHT
51997.94	0.01 ± 0.06	CFHT
51997.99	0.19 ± 0.05	CFHT
51998.00	0.03 ± 0.06	CFHT
51998.01	0.08 ± 0.06	CFHT
52376.96	0.04 ± 0.06	CFHT
52376.97	-0.06 ± 0.06	CFHT
52377.00	0.13 ± 0.06	CFHT
52377.00	-0.09 ± 0.06	CFHT
52377.01	-0.01 ± 0.06	CFHT
52377.03	0.01 ± 0.07	CFHT

a: Zeropoint: 22.805

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