

OPTICAL AND INFRARED PHOTOMETRY OF THE NEARBY TYPE Ia SUPERNOVA 2001el

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ABSTRACT

We present well-sampled optical (*UBVRI*) and infrared (*JHK*) light curves of the nearby (≈ 18.0 Mpc) Type Ia supernova SN 2001el, from 11 days before to 142 days after the time of *B*-band maximum. The data represent one of the best sets of optical and infrared photometry ever obtained for a Type Ia supernova (SN). Based on synthetic photometry using optical spectra of SN 2001el and optical and infrared spectra of SN 1999ee, we were able to devise filter corrections for the *BVJHK* photometry of SN 2001el, which to some extent resolve systematic differences between SN 2001el data sets obtained with different telescope/filter/instrument combinations. We also calculated *V*-minus-infrared color curves on the basis of a delayed detonation model and show that the theoretical color curves match the unreddened loci for Type Ia SNe with midrange decline rates to within 0.2 mag. Given the completeness of the light curves and the elimination of filter-oriented systematic errors to some degree, the data presented here will be useful for the construction of photometric templates, especially in the infrared. On the whole the photometric behavior of SN 2001el was quite normal. The second *H*-band maximum being brighter than the first *H*-band maximum is in accord with the prediction of Krisciunas et al. for Type Ia SNe with midrange decline rates. The photometry exhibits non-zero host extinction, with total $A_V = 0.57 \pm 0.05$ mag along the line of sight. NGC 1448, the host of SN 2001el, would be an excellent target for a distance determination using Cepheids.

Key words: supernovae: individual (SN 2001el) — techniques: photometric

On-line material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe) continue to be some of the most important objects of study in extragalactic astronomy. Since the discovery of the luminosity decline rate relation (Phillips 1993; Phillips et al. 1999) and the corresponding relationships between light-curve shapes and luminosities at maximum (Riess, Press, & Kirshner 1996; Riess et al. 1998; Perlmutter et al. 1997), Type Ia SNe have been regarded as standardizable candles to be used for calibrating the distances to the host galaxies.

Until recently, the amount of published infrared data of Type Ia SNe was quite small (Elias et al. 1981, 1985; Meikle 2000, and references therein; Krisciunas et al. 2000, 2001). Beginning in 1999 two of us (M. M. P. and N. B. S.) began a coordinated effort, using telescopes at Las Campanas Observatory (LCO) and Cerro Tololo Inter-American Observatory (CTIO), to obtain well-sampled optical and infrared light curves of Type Ia supernovae. The first of

these, SN 2000bk, was published by Krisciunas et al. (2001), including data from Apache Point Observatory.

Recently, we have published well-sampled light curves of SNe 1999aw (Strolger et al. 2002) and 1999ac (Phillips et al. 2002). In the *H* and *K* bands, in particular, we note that the light curves of Type Ia SNe are quite flat about 10 days after the time of *B*-band maximum, $T(B_{\max})$, allowing us to get an accurate brightness measure of Type Ia SNe in the near-infrared independent of the peculiarities of the light curves around the time of the primary maximum ($t \approx -3$ days) or the time of the secondary maximum ($t \approx +25$ days).⁶

In addition to the data of SN 2001el presented here, we are finishing up the reduction of the light curves of another dozen objects. This will allow us to characterize better than ever before the infrared light curves of Type Ia SNe and correlate the variations observed at infrared wavelengths with those seen at optical wavelengths. Because interstellar extinction at infrared wavelengths is an order of magnitude less than extinction at optical wavelengths, we expect that we will be able to exploit this fact to obtain intrinsic photometry of Type Ia SNe only minimally affected by interstellar extinction. This will lead to an infrared Hubble diagram for Type Ia SNe free of significant systematic errors incurred from imprecise reddening estimates and characterized by small random errors. Only with such a foundation for *nearby* Type Ia SNe can we have confidence in the conclusions drawn from observations of *distant* SNe, such as evidence for a nonzero cosmological constant (Riess et al. 1998; Perlmutter et al. 1999).

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⁶ As is conventional, we shall measure the “age” of a supernova in time before or after $T(B_{\max})$. For this we use the variable t , measured in days.

2. OBSERVATIONS

SN 2001el was discovered by Monard (2001) on 2001 September 17.064 UT (= Julian Date 2,452,169.564) some 22" west and 19" north of the nucleus of the SAd galaxy NGC 1448, which, incidentally, was also the host of the Type II SN 1983S. According to the NASA/IPAC Extragalactic Database, the heliocentric velocity of this galaxy is 1164 km s⁻¹. Based on a spectrum taken with the VLT on 2001 September 21 UT (JD = 2,452,173.5), Sollerman, Leibundgut & Lundquist (2001) showed SN 2001el to be a Type Ia SN well before maximum. On this basis we requested that frequent optical and infrared imagery be made with the Yale-AURA-Lisbon-Ohio (YALO) 1 m telescope at Cerro Tololo. We also obtained optical imagery on six nights with the CTIO 0.9 m telescope. Optical data of Landolt presented here are single-channel photoelectric photometry carried out with the CTIO 1.5 m telescope. Finally, we obtained other infrared imagery with the 1 m Swope telescope at Las Campanas, which was used, along with observations of infrared standards of Persson et al. (1998) to calibrate the *JHK* magnitudes of the field stars near SN 2001el.

Figure 1 is a *V*-band optical image in which we identify the location of SN 2001el and various local field standards.

In Tables 1 and 2 we give optical and infrared photometry of some of these local standards. These were used as secondary standards tied to the optical and infrared standards of Landolt (1992) and Persson et al. (1998), respectively. This allowed us to calibrate the photometry of the SN on photometric as well as nonphotometric nights.

Photometry reduction of the YALO data was carried out using DAOPHOT (Stetson 1987, 1990) and a set of programs written by one of us (N. B. S.). The photometric techniques were described by Suntzeff et al. (1999) and involve using aperture magnitudes and aperture corrections for the brighter stars, while relying on point-spread function (PSF) magnitudes for fainter stars. We used transformation equations of the following form:

$$b = B + ZP_b - 0.079(B - V) + k_b X, \quad (1)$$

$$v = V + ZP_v + 0.018(B - V) + k_v X, \quad (2)$$

$$r = R + ZP_r - 0.030(V - R) + k_r X, \quad (3)$$

$$i = I + ZP_i + 0.045(V - I) + k_i X, \quad (4)$$

$$j = J + ZP_j - 0.034(J - H) + k_j X, \quad (5)$$

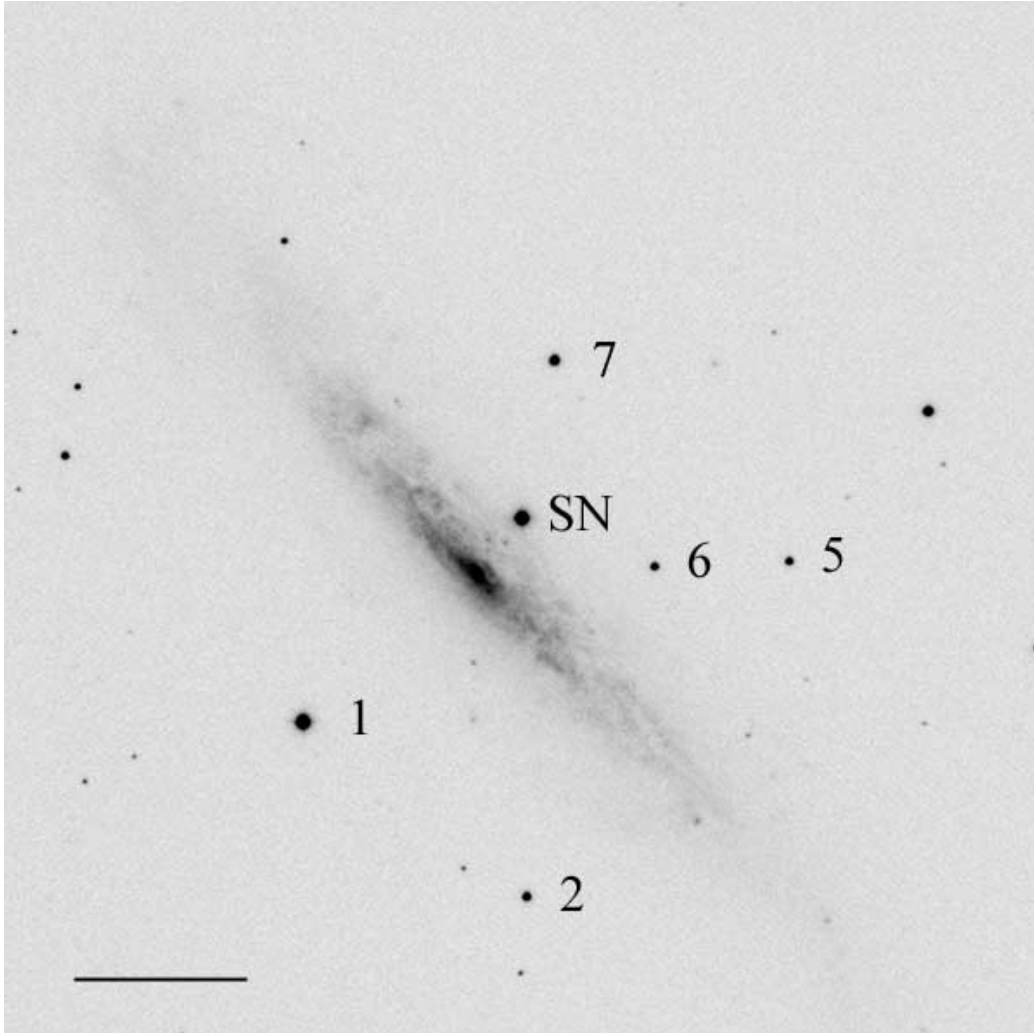


FIG. 1.—*V*-band image of SN 2001el in NGC 1448 obtained with the CTIO 0.9 m telescope on 2001 September 26.4. The exposure time was 25 s. The local photometric standards are shown. The bar corresponds to 1". North is up, and east to the left. The supernova is marked "SN".

TABLE 1
OPTICAL PHOTOMETRIC SEQUENCE NEAR SN 2001el

Star ID	α (J2000.0)	δ (J2000.0)	V	$B-V$	$V-R$	$V-I$
SN	3 44 30.6	-44 38 24	...	...	...	...
1 ^a	3 44 37.7	-44 39 34	12.736 (0.002)	0.621 (0.003)	0.372 (0.002)	0.747 (0.004)
1 ^b .....	...	...	12.739 (0.003)	0.623 (0.006)	0.367 (0.002)	0.738 (0.002)
2 ^a	3 44 30.4	-44 40 36	15.377 (0.002)	1.086 (0.009)	0.666 (0.003)	1.221 (0.005)
5 ^a	3 44 21.8	-44 38 38	15.913 (0.002)	0.965 (0.010)	0.532 (0.004)	0.986 (0.005)
6 ^a	3 44 26.3	-44 38 40	15.756 (0.002)	1.132 (0.013)	0.675 (0.006)	1.236 (0.004)
7 ^a	3 44 29.5	-44 37 29	14.524 (0.002)	0.836 (0.005)	0.487 (0.002)	0.932 (0.005)

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Based on five nights of CCD photometry with YALO.

^b The second set of values is based on seven nights of single-channel photoelectric photometry by Landolt, who also obtained $U-B = +0.049 \pm 0.012$ for this star.

$$h = H + ZP_h + 0.022(J-H) + k_h X, \quad (6)$$

$$k = K + ZP_k - 0.003(J-K) + k_k X. \quad (7)$$

The parameters on the left-hand sides are the instrumental magnitudes. On the right-hand side of each equation we have the standardized magnitude, a photometric zero point, a color term times a standardized color, and an extinction term times the air mass. Given that the color terms are reasonably close to zero, the YALO filters provide a good, but not perfect, match to the filters used by Landolt (1992) and Persson et al. (1998) for the derivation of their standard star networks.

In Table 3 we present *UBVRI* photometry of SN 2001el. A majority of the data are from YALO, calibrated using the secondary standards from Table 1. Landolt's data are tied directly to the Landolt (1992) standards, i.e., without using the secondary standards. The internal errors of the Landolt data are as small as several millimagnitudes. His data were taken when the SN was getting monotonically fainter, and the data bear this out on those four nights when he measured the SN on more than one occasion. For our field star number 1 Landolt obtained mean values of V , $B-V$, $V-R$, and $V-I$, which are $+0.003$, $+0.002$, -0.005 , and -0.009 mag different, respectively, than the values obtained from CCD photometry with YALO. Thus, photometry of stars carried out with the CTIO 1.5 m and YALO telescopes is in excellent agreement.

We note that Landolt's measurements of SN 2001el are aperture photometry using a 14" diameter aperture. His sky readings were taken 15" to the north of supernova. To determine the amount of diffuse light of NGC 1448 that was in his diaphragm while measuring SN 2001el, we used CCD frames of the field taken 2001 October 16 and 2002 January 15. We determined that U -band corrections to Landolt's photoelectric photometry are negligible, 0.002 mag or less.

In B , V , R , and I , however, the data required correction by 0.019 to 0.043, 0.024 to 0.035, 0.034 to 0.048, and 0.058 to 0.078 mag, respectively. (Another way of describing this is that galaxy light is *red*.) The Landolt data in Table 3 include these corrections.

There were four nights when Landolt observed SN 2001el when it was also observed with YALO. In the sense "YALO minus Landolt," the B -band data show a difference of $+0.037$ mag. For other bands, $\Delta V = -0.025$ mag, $\Delta R = -0.009$ mag, and $\Delta I = -0.064$ mag. V -band data obtained with the CTIO 0.9 m telescope by Arenas is up to 0.067 mag fainter at the time of maximum light than corresponding YALO data.

Suntzeff (2000) notes that one observes sizable and repeatable systematic differences for the $B-V$ colors of Type Ia SNe measured with different telescopes. In the cases of SNe 1998bu and 1999ee observed with the YALO and CTIO 0.9 m telescopes, one finds that YALO colors are 0.03 mag redder at maximum and 0.12 mag in the tail of the color curve, as shown in Figure 2. Obviously, if we try to derive a $B-V$ color excess from late-time photometry, we must identify and correct systematic differences in the photometry that are as large as shown in Figure 2.

To account for possible systematic errors in our photometry of SN 2001el, we investigated the method of computing filter corrections described by Stritzinger et al. (2002). In the end these authors chose not to apply their derived filter corrections, describing the whole exercise as "somewhat disappointing."⁷ By contrast, we were quite encouraged by similar efforts for SN 2001el. In particular, our corrections to the B and V magnitudes not only tighten up the light curves in those filters, but they solve the problem of the $B-V$ colors being too red in the tail of the color curve. Also, our JHK light curves are improved. Still, should the reader disagree with our application of the filter corrections, we present the data in this paper in multiple tables: two for uncorrected photometry and two for corrections.

The determination of filter corrections involves at minimum the dot product (i.e., multiplying together) of filter transmission functions, quantum efficiency as a function of wavelength, and an atmospheric transmission profile. The zero points are first fixed with Vega (see Appendix A), then

TABLE 2
INFRARED PHOTOMETRIC SEQUENCE NEAR SN 2001el^a

Star ID ^b	J	H	K
5.....	14.260 (0.042)	13.739 (0.029)	13.727 (0.021)
6.....	13.745 (0.009)	13.163 (0.004)	13.017 (0.026)
7.....	13.302 (0.043)	13.170 (0.146)	13.194 (0.041)

^a Based on five nights of J -band calibration with the LCO 1 m telescope, four nights in H , and two nights in K .

^b The identifications are the same as those in Table 1 and Fig. 1.

⁷ Some of their disappointment stemmed from trying to correct YALO observations taken with a very wide, nonstandard R filter. Our YALO observations were made with a much narrower, more standard R filter.

TABLE 3
UBVRIPHOTOMETRY OF SN 2001el

JD-2,450,000	UT Date ^a	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>	Observer+Telescope
2171.85	Sep 19.35	...	14.075 (0.013)	13.808 (0.009)	13.711 (0.016)	13.742 (0.015)	Espinoza+YALO
2174.81	Sep 22.31	...	13.407 (0.012)	13.258 (0.008)	13.111 (0.015)	13.120 (0.014)	Espinoza+YALO
2177.84	Sep 25.34	...	13.032 (0.015)	12.927 (0.010)	12.768 (0.024)	12.838 (0.016)	Espinoza+YALO
2178.82	Sep 26.32	12.753 (0.045)	12.932 (0.023)	12.899 (0.014)	...	...	Arenas+CTIO 0.9 m
2179.81	Sep 27.31	12.708 (0.043)	12.887 (0.026)	12.868 (0.015)	...	...	Arenas+CTIO 0.9 m
2183.84	Oct 01.34	...	12.871 (0.019)	12.686 (0.010)	12.622 (0.045)	12.885 (0.016)	D. Gonzalez+YALO
2183.86	Oct 01.36	12.765 (0.027)	12.850 (0.013)	12.753 (0.008)	...	...	Arenas+CTIO 0.9 m
2184.88	Oct 02.38	12.824 (0.029)	12.867 (0.013)	12.755 (0.007)	...	...	Arenas+CTIO 0.9 m
2186.80	Oct 04.30	...	12.966 (0.009)	12.724 (0.004)	12.624 (0.009)	12.954 (0.008)	Espinoza+YALO
2189.74	Oct 07.24	13.418 (0.019)	13.157 (0.014)	12.810 (0.013)	12.729 (0.015)	13.115 (0.015)	Landolt+CTIO 1.5 m
2189.76	Oct 07.26	13.392 (0.019)	13.160 (0.014)	12.812 (0.013)	12.730 (0.015)	13.119 (0.015)	Landolt+CTIO 1.5 m
2189.83	Oct 07.33	...	13.193 (0.007)	12.784 (0.004)	12.738 (0.010)	13.073 (0.008)	Espinoza+YALO
2189.85	Oct 07.35	13.428 (0.019)	13.171 (0.014)	12.831 (0.013)	12.736 (0.015)	13.113 (0.015)	Landolt+CTIO 1.5 m
2190.72	Oct 08.22	13.507 (0.019)	13.230 (0.014)	12.834 (0.013)	12.772 (0.015)	13.211 (0.015)	Landolt+CTIO 1.5 m
2190.85	Oct 08.35	13.545 (0.019)	13.266 (0.014)	12.859 (0.013)	12.798 (0.015)	13.207 (0.015)	Landolt+CTIO 1.5 m
2191.72	Oct 09.22	13.643 (0.019)	13.331 (0.014)	12.879 (0.013)	12.835 (0.015)	13.240 (0.015)	Landolt+CTIO 1.5 m
2191.85	Oct 09.35	13.669 (0.019)	13.353 (0.014)	12.901 (0.013)	12.864 (0.015)	13.278 (0.015)	Landolt+CTIO 1.5 m
2192.83	Oct 10.33	...	13.453 (0.016)	12.906 (0.011)	12.909 (0.018)	13.259 (0.016)	D. Gonzalez+YALO
2192.85	Oct 10.35	13.765 (0.019)	13.425 (0.014)	12.924 (0.013)	12.902 (0.015)	13.331 (0.015)	Landolt+CTIO 1.5 m
2193.72	Oct 11.22	13.881 (0.019)	13.542 (0.014)	12.981 (0.013)	12.969 (0.015)	13.368 (0.015)	Landolt+CTIO 1.5 m
2193.85	Oct 11.35	13.913 (0.019)	13.565 (0.014)	13.007 (0.013)	12.988 (0.015)	13.374 (0.015)	Landolt+CTIO 1.5 m
2194.78	Oct 12.28	14.009 (0.019)	13.651 (0.014)	13.056 (0.013)	13.032 (0.015)	13.375 (0.015)	Landolt+CTIO 1.5 m
2195.75	Oct 13.25	...	13.793 (0.027)	13.068 (0.018)	13.040 (0.035)	13.358 (0.027)	D. Gonzalez+YALO
2195.83	Oct 13.33	14.188 (0.019)	13.779 (0.014)	13.130 (0.013)	13.103 (0.015)	13.440 (0.015)	Landolt+CTIO 1.5 m
2197.71	Oct 15.21	14.450 (0.019)	13.989 (0.014)	13.230 (0.013)	13.175 (0.015)	13.462 (0.015)	Landolt+CTIO 1.5 m
2198.71	Oct 16.21	14.544 (0.019)	14.086 (0.014)	13.265 (0.013)	13.156 (0.015)	13.359 (0.015)	Landolt+CTIO 1.5 m
2198.80	Oct 16.30	...	14.155 (0.008)	13.278 (0.005)	13.169 (0.014)	13.322 (0.008)	D. Gonzalez+YALO
2201.81	Oct 19.31	...	14.506 (0.012)	13.453 (0.008)	13.232 (0.014)	13.253 (0.012)	Pizarro+YALO
2204.78	Oct 22.28	...	14.804 (0.016)	13.590 (0.009)	13.303 (0.019)	13.226 (0.024)	Espinoza+YALO
2207.77	Oct 25.27	...	15.090 (0.012)	13.746 (0.007)	13.392 (0.015)	13.224 (0.012)	Pizarro+YALO
2210.82	Oct 28.32	...	15.357 (0.013)	13.924 (0.006)	13.524 (0.011)	13.235 (0.010)	Pizarro+YALO
2213.68	Oct 31.18	...	15.554 (0.015)	14.109 (0.006)	13.697 (0.015)	13.306 (0.009)	Espinoza+YALO
2216.73	Nov 03.23	...	15.727 (0.011)	14.301 (0.005)	13.880 (0.012)	13.486 (0.009)	Espinoza+YALO
2222.75	Nov 09.25	...	15.998 (0.020)	14.606 (0.010)	14.248 (0.018)	13.904 (0.017)	D. Gonzalez+YALO
2225.72	Nov 12.22	...	16.060 (0.012)	14.706 (0.007)	14.331 (0.014)	14.038 (0.012)	D. Gonzalez+YALO
2228.73	Nov 15.23	...	16.149 (0.016)	14.806 (0.009)	14.478 (0.016)	14.171 (0.015)	Espinoza+YALO
2231.71	Nov 18.21	...	16.198 (0.017)	14.865 (0.009)	14.584 (0.016)	14.314 (0.014)	Espinoza+YALO
2234.73	Nov 21.23	...	16.215 (0.016)	14.940 (0.006)	14.675 (0.013)	14.447 (0.012)	D. Gonzalez+YALO
2237.73	Nov 24.23	...	16.265 (0.017)	15.042 (0.008)	14.738 (0.016)	14.560 (0.014)	D. Gonzalez+YALO
2240.73	Nov 27.22	...	16.282 (0.020)	15.121 (0.009)	14.835 (0.019)	14.689 (0.015)	D. Gonzalez+YALO
2243.71	Nov 30.21	...	16.333 (0.021)	15.178 (0.012)	14.917 (0.021)	14.801 (0.019)	Espinoza+YALO
2246.78	Dec 03.28	...	16.383 (0.038)	15.238 (0.009)	15.042 (0.020)	14.922 (0.022)	Espinoza+YALO
2289.64	Jan 15.14	17.695 (0.037)	16.924 (0.013)	16.349 (0.006)	...	...	Candia+CTIO 0.9 m
2324.55	Feb 19.05	18.685 (0.023)	17.500 (0.011)	17.072 (0.013)	17.294 (0.008)	17.401 (0.031)	Candia+CTIO 0.9 m

^a Year is 2001, except for the last two lines for which the year is 2002.

one determines synthetic broadband magnitudes using spectra of spectrophotometric standards (Hamuy et al. 1992, 1994). This allows one to derive color terms based on the synthetic photometry. In order for the synthetic color terms to match the color terms derived from actual broadband photometry within 0.01, we found, as did Stritzinger et al. (2002), that we had to shift the optical filter profiles by as much as 100 Å to match the synthetic color terms with the actual observed ones.⁸ In Appendix B we give the filter shifts used for the optical photometry.

⁸ Shifting the filter profiles in this manner will strike some readers as unsatisfactory. However, the manufacturer of our *R*-band filter gives a particular filter curve but states that, when the filter is used in a liquid nitrogen filled Dewar, the filter curve should be shifted 300 Å to the blue. We find that a shift of 270 Å gives the correct color term, or 30 Å to the red of the expected filter curve. Thus, the use of these wavelength shifts is justified at some level.

We took as our filter references the *BVRI* profiles of Besell (1990), corrected for wavelength (i.e., divided by λ). In Figure 3 we show the derived magnitude corrections for *B*-band photometry of SNe 1999ee and 2001el. In Figure 4 we show the analogous filter corrections for the *V* band. These corrections were obtained using spectra of SN 1999ee from Hamuy et al. (2002), while some spectra of SN 2001el are discussed by Wang et al. (2002).⁹ Six *HST* spectra were also kindly made available to us by P. Nugent (2002, private communication). These range from 2947 to 10238 Å, thus covering the *UBVRI* passbands, and were taken from $29.5 \leq t \leq 65.3$ days.

⁹ The first two of these spectra range from 4179 to 8634 Å, while the last three range from 3327 to 8634 Å. Because the *B* band starts at roughly 3600 Å, we obtain three synthetic *B*-band magnitudes and five synthetic *V*-band magnitudes of SN 2001el. Both are needed to derive filter corrections for *B* and *V* data because of color terms that need to be applied.

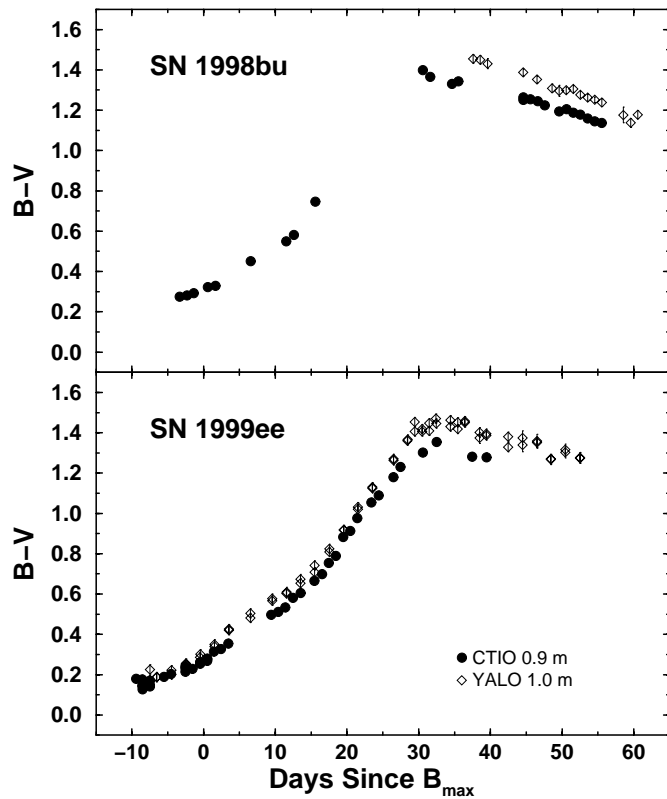


FIG. 2.— $B-V$ colors of SNe 1998bu and 1999ee, as observed with the CTIO 0.9 m and YALO telescopes. As a result of differences in the filter transmission curves, late-time $B-V$ colors derived from YALO data are roughly 0.12 mag redder.

We find that, for the CTIO 1.5 m telescope with the filters used by Landolt, the B -band filter corrections are essentially the same for SNe 1999ee and 2001el. The situation is not too bad for the CTIO 0.9 m telescope, but for YALO the

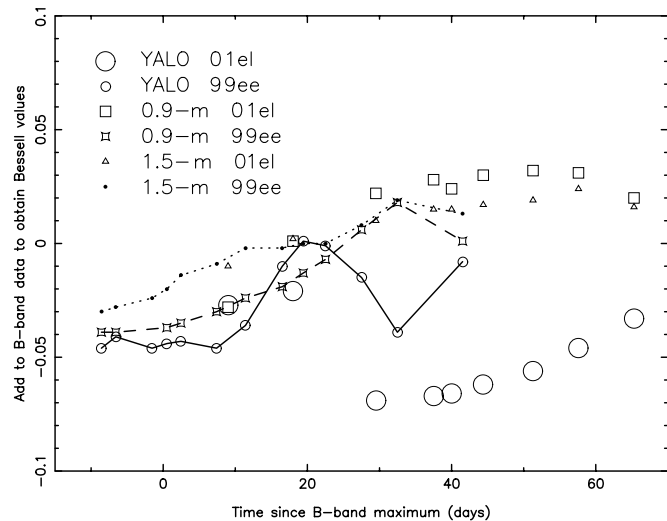


FIG. 3.—Based on synthetic photometry using Bessell (1990), YALO, CTIO 0.9 m, and CTIO 1.5 m filter functions, we show B -band corrections to YALO and CTIO data to place photometry of SNe 1999ee and 2001el on the Bessell system. The time of B -band maximum is JD 2,451,469.1 for SN 1999ee (Stritzinger et al. 2002) and 2,452,182.5 for SN 2001el. We used spectra of SN 1999ee given by Hamuy et al. (2002), and spectra of SN 2001el by Wang et al. (2002) and P. Nugent (2002, private communication). The filter corrections for SN 1999ee are connected by lines, telescope by telescope, to guide the eye.

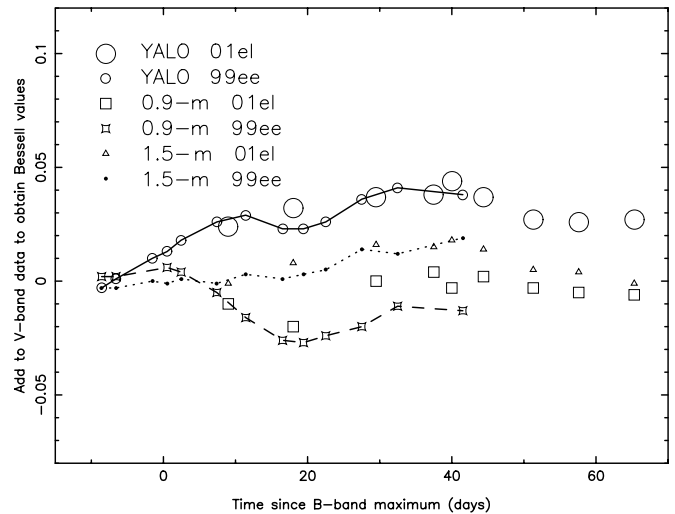


FIG. 4.—Same as Fig. 3, but for the V band. Note that, unlike the B band, these corrections are mostly telescope dependent, not telescope and object dependent after $t = 20$ days.

B -band corrections are not as well behaved, indicating that the filter corrections can be telescope *and* object dependent. For example, features at the blue end of the B band are included more or less with different B filters, and these features are different in the spectra SNe 1999ee and 2001el. As a check on our method, filter corrections based on spectra by Wang et al. (2002) and *HST* (P. Nugent 2002, private communication) give very consistent corrections at $t \approx 40$ days for the YALO B -band filter. In the case of the V band (see Fig. 4) the corrections are better behaved and seem to be telescope dependent, i.e., more independent of the object under study.

In Table 4 we give the B - and V -band corrections to the photometry tabulated in Table 3. These corrections would place the measurements obtained with three different telescopes and filter sets on the Bessell (1990) system. The consistency of the photometry obtained on different telescope is improved. With the corrections, $\Delta B = +0.020$ mag and $\Delta V = -0.002$ mag, with “ Δ ” in the sense “YALO minus Landolt.” As we show below, the late-time YALO $B-V$ colors give an estimate of the reddening, which is in agreement with other estimates of the reddening, but only if we take into account the systematic differences of the filters.

The R -band photometry given in Table 3 (i.e., YALO vs. Landolt) is consistent at the 0.01 mag level, on average. Under the assumption that the spectra of SNe 1999ee and 2001el are the same at $t = 16$ days, the application of R -band filter corrections would make the Landolt and YALO R -band photometry differ by as much as 0.04 mag. We do not have spectra of SN 2001el covering the R and I bands at this epoch, and the photometry is not crying out for corrections to be made.

There is a systematic difference of I -band photometry in Table 3 at the 0.06 mag level. The application of filter corrections based on spectra of SN 1999ee would pull the data further apart by an additional 0.10 mag or more. Thus, while the SN 2001el data in Table 3 motivates us to apply I -band filter corrections, corrections based on spectra of a different object make the systematic differences worse, not better.

In the case of the R and I bands we also suspect some unquantified effect of the YALO dichroic on the photom-

TABLE 4
CORRECTIONS TO *B*- AND *V*-BAND PHOTOMETRY^a

JD -2,450,000	<i>t</i> (days)	ΔB	ΔV	Telescope ^b
2171.85	-10.65	[-0.027]	-0.007	1
2174.81	-7.69	[-0.027]	-0.001	1
2177.84	-4.66	[-0.027]	+0.005	1
2178.82	-3.68	-0.038	+0.004	2
2179.81	-2.69	-0.038	+0.005	2
2183.84	1.34	[-0.027]	+0.018	1
2183.86	1.36	-0.036	+0.005	2
2184.88	2.38	-0.035	+0.004	2
2186.80	4.30	[-0.027]	+0.020	1
2189.78	7.28	-0.012	+0.001	3
2189.83	7.33	[-0.027]	+0.023	1
2190.79	8.29	-0.011	0.000	3
2191.79	9.29	-0.010	-0.001	3
2192.72	10.22	-0.008	0.000	3
2192.83	10.33	-0.026	+0.026	1
2193.78	11.28	-0.007	+0.001	3
2194.78	12.28	-0.006	+0.002	3
2195.75	13.25	-0.024	+0.028	1
2195.84	13.34	-0.004	+0.004	3
2197.71	15.21	-0.002	+0.005	3
2198.71	16.21	0.000	+0.007	3
2198.80	16.30	-0.022	+0.030	1
2201.81	19.31	-0.023	+0.033	1
2204.78	22.28	-0.039	+0.034	1
2207.77	25.27	-0.051	+0.035	1
2210.82	28.32	-0.065	+0.037	1
2213.68	31.18	-0.069	+0.038	1
2216.73	34.23	-0.068	+0.040	1
2222.75	40.25	-0.066	+0.040	1
2225.72	43.22	-0.063	+0.038	1
2228.73	46.23	-0.060	+0.034	1
2231.71	49.21	-0.058	+0.030	1
2234.73	52.23	-0.054	+0.027	1
2237.73	55.23	-0.050	+0.026	1
2240.73	58.23	-0.044	+0.026	1
2243.71	61.21	-0.040	+0.026	1
2246.78	64.28	-0.034	+0.027	1

^a The following corrections are to be *added* to the data in Table 3 to correct them to the filter system of Bessell (1990). Values in square brackets are less certain; we have assumed that the YALO *B*-band filter corrections are represented by a flat function at the start. The value *t* is the number of days since the time of *B*-band maximum, JD 2,452,182.5.

^b YALO=1; CTIO 0.9 m=2; CTIO 1.5 m=3.

etry. While we are satisfied with the *B*- and *V*-band corrections, we feel it unwise to apply corrections to the *R*- and *I*-band data.

Figure 5 shows the *UBVRI* light curves of SN 2001el, with the corrections of Table 4 applied to the *B* and *V* data given in Table 3.

The most interesting result of the application of the filter corrections is that, by *t* = 40 days, we have reproduced a correction (with respect to Bessell filter functions) of ≈ 0.1 mag to the YALO *B*-*V* colors (see Fig. 10), almost exactly what was found for SNe 1998bu and 1999ee using YALO and CTIO 0.9 m photometry.

In Table 5 we give near-infrared photometry of SN 2001el obtained with the YALO and LCO 1 m telescopes. The near-infrared data were calibrated using our “best” IR secondary standard, star 6, which was tied to the system of Persson et al. (1998) from observations on five photometric

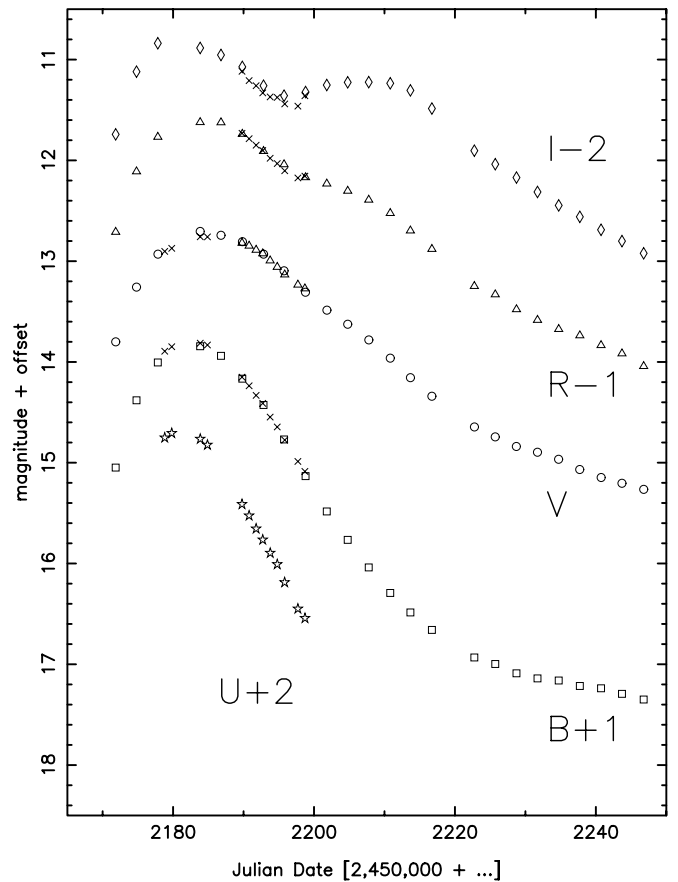


FIG. 5.—Optical photometry of SN 2001el. For *B*, *V*, *R*, and *I* the YALO data are plotted as smaller open symbols, while data from the CTIO 0.9 and 1.5 m telescopes are plotted as crosses. We have corrected the *B*- and *V*-band data to the filter system of Bessell (1990) using the values in Table 4. On the whole the internal errors are smaller than the size of the points. The *U*, *B*, *R*, and *I* data have been offset vertically by +2, +1, -1, and -2 mag, respectively. The Landolt data are plotted as nightly means. Data from two nights are off the right edge of the plot.

nights.¹⁰ We note that the LCO observations and Persson’s system of standards rely on different *J*- and *K*-band filters than the broader band filters used at YALO. At LCO one uses a “*J*_{short}” and “*K*_{short}” filter. These are the very filters and telescope used to establish the system of Persson et al. (1998), and by definition the color terms are zero.

The YALO data are systematically fainter than the LCO 1 m data by roughly 0.1 mag at *t* = 20 days in the *J* and *H* bands, and also by 0.1 mag or more in *J* beyond *t* = 55 days, while there appear to be no significant differences in the *K*-band data. Can synthetic photometry confirm that the YALO data are expected to be different at certain epochs for *J* and *H*, while the *K*-band data need little correction beyond *t* = 20 days? To test this, we constructed effective transmission profiles using the raw filter profiles, an atmospheric transmission profile, quantum efficiency, and multiple applications of reflection and window transmission in the optical paths. Then, using spectra of Vega, Sirius, and

¹⁰ The *K*-band magnitude of star 6 is based on data from only two photometric nights. We note that the optical and infrared colors of this star are entirely consistent with it being a normal K2 III star (Allen & Cox 2000). We do not suspect that it is variable.

TABLE 5
NEAR-INFRARED PHOTOMETRY OF SN 2001el^a

JD -2,450,000	UT Date ^b	<i>J</i>	<i>H</i>	<i>K</i>	Observer+Telescope
2171.84	Sep 19.34	13.607 (0.021)	13.661 (0.036)	13.543 (0.044)	D. Gonzalez+YALO
2174.80	Sep 22.30	13.129 (0.020)	13.161 (0.037)	13.021 (0.045)	Espinoza+YALO
2177.82	Sep 25.33	12.878 (0.022)	13.085 (0.037)	12.831 (0.046)	Espinoza+YALO
2183.83	Oct 01.33	12.986 (0.020)	13.193 (0.036)	12.919 (0.043)	D. Gonzalez+YALO
2186.79	Oct 04.29	13.177 (0.020)	13.253 (0.036)	13.061 (0.043)	Espinoza+YALO
2189.82	Oct 07.33	13.538 (0.020)	13.239 (0.036)	13.116 (0.043)	Espinoza+YALO
2192.82	Oct 10.32	14.139 (0.022)	13.276 (0.042)	13.142 (0.051)	D. Gonzalez+YALO
2195.74	Oct 13.24	14.265 (0.032)	13.245 (0.051)	13.085 (0.063)	D. Gonzalez/Pizarro+YALO
2198.79	Oct 16.29	14.290 (0.068)	13.140 (0.099)	13.036 (0.103)	D. Gonzalez+YALO
2201.81	Oct 19.31	14.380 (0.020)	13.045 (0.036)	12.987 (0.043)	Pizarro/Espinoza+YALO
2202.75	Oct 20.25	14.191 (0.023)	12.978 (0.040)	13.035 (0.036)	S. Gonzalez/Krisciunas+LCO 1 m
2203.74	Oct 21.24	14.167 (0.022)	12.982 (0.019)	12.957 (0.039)	S. Gonzalez+LCO 1 m
2204.70	Oct 22.20	14.174 (0.025)	12.966 (0.026)	12.988 (0.036)	S. Gonzalez+LCO 1 m
2204.77	Oct 22.27	14.263 (0.043)	13.084 (0.071)	12.873 (0.086)	Espinoza+YALO
2207.84	Oct 25.34	14.217 (0.021)	13.061 (0.038)	12.941 (0.045)	Pizarro+YALO
2210.81	Oct 28.31	14.199 (0.025)	13.108 (0.042)	13.045 (0.053)	Pizarro+YALO
2213.67	Oct 31.17	13.997 (0.023)	13.132 (0.041)	13.082 (0.049)	Espinoza+YALO
2216.72	Nov 03.22	14.112 (0.021)	13.259 (0.039)	13.317 (0.043)	Espinoza+YALO
2222.74	Nov 09.24	14.774 (0.025)	13.769 (0.043)	13.867 (0.058)	D. Gonzalez+YALO
2225.71	Nov 12.21	14.917 (0.028)	13.812 (0.048)	13.893 (0.058)	D. Gonzalez+YALO
2228.72	Nov 15.22	15.204 (0.026)	13.991 (0.044)	14.112 (0.053)	Espinoza+YALO
2231.70	Nov 18.20	15.354 (0.027)	14.090 (0.045)	14.305 (0.056)	Espinoza+YALO
2234.72	Nov 21.22	15.544 (0.026)	14.213 (0.044)	14.404 (0.059)	D. Gonzalez+YALO
2237.73	Nov 24.23	15.799 (0.033)	14.349 (0.053)	14.537 (0.065)	D. Gonzalez+YALO
2238.79	Nov 25.29	15.713 (0.020)	14.355 (0.054)	14.711 (0.038)	S. Gonzalez+LCO 1 m
2240.70	Nov 27.20	15.879 (0.020)	14.514 (0.039)	14.690 (0.053)	S. Gonzalez+LCO 1 m
2240.72	Nov 27.22	15.974 (0.034)	14.488 (0.055)	14.711 (0.077)	D. Gonzalez+YALO
2241.69	Nov 28.19	15.964 (0.020)	14.492 (0.016)	14.798 (0.048)	S. Gonzalez+LCO 1 m
2242.69	Nov 29.19	16.030 (0.025)	14.562 (0.022)	14.751 (0.059)	S. Gonzalez+LCO 1 m
2243.68	Nov 30.18	16.069 (0.024)	14.548 (0.080)		S. Gonzalez+LCO 1 m
2243.74	Nov 30.24	16.238 (0.033)	14.576 (0.055)	14.780 (0.075)	Espinoza+YALO
2244.71	Dec 01.21	16.089 (0.046)		14.833 (0.044)	S. Gonzalez+LCO 1 m
2246.77	Dec 03.27	16.420 (0.043)	14.824 (0.067)	14.938 (0.081)	Espinoza+YALO

^a The data are based on differential photometry with respect to star 6 given in Table 2. The YALO data are presented *without* the corrections given in Table 6.

^b Year is 2001.

the Sun (see Appendix A), we found that the synthetic infrared color terms for the YALO telescope match observed ones to better than 0.01. This required no arbitrary shifting of the filter transmission profiles.

In Figure 6 we show the derived photometric corrections to YALO data, based on spectra of SN 1999ee, which would have to be added to YALO data to make them agree with photometry obtained with the LCO 1 m. Under the assumption that these corrections are applicable to SN 2001el, we give in Table 6 a set of corrections to YALO IR photometry. We assume that the *J*- and *H*-band corrections at $t = 43$ days are appropriate until $t = 64$ days. Obviously, the two assumptions just made may be somewhat dubious. But consider the IR light curves of SN 2001el shown in Figure 7. By application of the corrections in Table 6, we find that the *J*- and *H*-band data are in agreement within the internal errors now that corrections up to 0.13 mag have been made. Since the corrections based on spectra of an actual Type Ia SN are about the right size and are to be made in the right direction, we feel confident that an application of these corrections is fully warranted for the IR data. Thus, for the rest of this paper we include these corrections, and all analysis based on IR data uses the corrected YALO data.

One curious thing about the *H*-band light curve is that SN 2001el was brighter at the time of the second maximum

($H = 12.97$ at $t = +22.2$ days) than at the time of the first maximum ($H = 13.08$ at $t = -4.7$ days). This is in agreement with the prediction of Krisciunas et al. (2000, Fig. 13; Table 11) for Type Ia SNe with midrange decline rates.

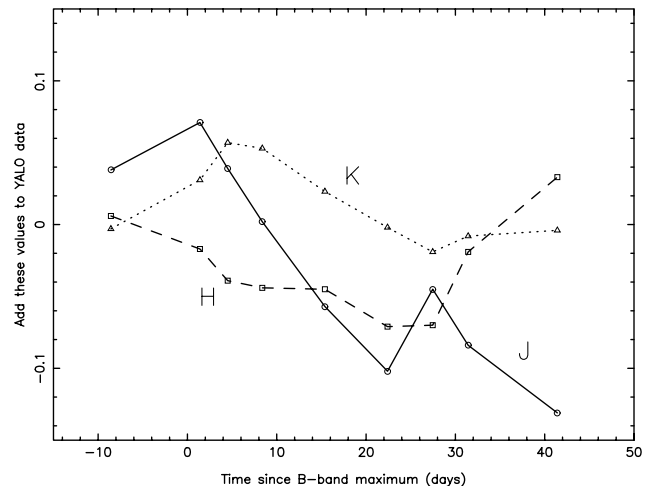


FIG. 6.—Corrections to YALO infrared photometry, based on spectra of SN 1999ee (Hamuy et al. 2002), to place the YALO data on the system of Persson et al. (1998). Solid line: *J*; dashed line: *H*; dotted line: *K*.

TABLE 6
CORRECTIONS TO YALO INFRARED PHOTOMETRY^a

JD -2,450,000	<i>t</i> (days)	ΔJ	ΔH	ΔK
2171.84	-10.66	0.030	0.011	-0.011
2174.80	-7.70	0.042	0.004	0.000
2177.82	-4.68	0.051	-0.003	0.010
2183.83	1.33	0.071	-0.016	0.032
2186.79	4.29	0.041	-0.038	0.056
2189.82	7.32	0.014	-0.042	0.054
2192.82	10.32	-0.013	-0.044	0.044
2195.74	13.24	-0.037	-0.045	0.033
2198.79	16.29	-0.062	-0.049	0.021
2201.81	19.31	-0.080	-0.059	0.010
2204.77	22.27	-0.102	-0.070	-0.001
2207.84	25.34	-0.070	-0.071	-0.012
2210.81	28.31	-0.051	-0.062	-0.016
2213.67	31.17	-0.082	-0.022	-0.009
2216.72	34.22	-0.097	-0.005	-0.007
2222.74	40.24	-0.125	0.030	0.004
2225.71	43.21	-0.131	0.033	0.000
2228.72	46.22	-0.131	0.033	0.000
2231.70	49.20	-0.131	0.033	0.000
2234.72	52.22	-0.131	0.033	0.000
2237.73	55.23	-0.131	0.033	0.000
2240.72	58.22	-0.131	0.033	0.000
2243.74	61.24	-0.131	0.033	0.000
2246.77	64.27	-0.131	0.033	0.000

^a The following corrections are to be *added* to the YALO data in Table 5 to correct them to the photometric system of Persson et al. 1998. The value *t* is the number of days since the time of *B*-band maximum, JD 2,452,182.5.

Table 7 gives the maximum apparent *UBVRJHK* magnitudes and the respective times of maximum for SN 2001el. Note that, within the uncertainties, the time of maximum light in the *I*, *J*, *H*, and *K* bands was the same, about 4.0 days before $T(B_{\max})$. This is apparent visually by an inspection of Figure 8, which also shows how the secondary hump or shoulder in the light curve varies as a function of filter from *V* through *K*.

To compare SN 2001el with other supernovae, we show in Figure 9 a stack of *H*-band light curves ordered by the decline rate parameter $\Delta m_{15}(B)$. Given the number of nights of SN 2001el photometry and the minimal gaps in the data set, it is clear that the data presented here are of high quality. Just as in the *I* band, most Type Ia SNe exhibit a secondary

TABLE 7
MAXIMUM MAGNITUDES OF SN 2001el

Filter	JD -2,450,000	m_{\max}
<i>U</i>	2181.4 (1.0)	12.67 (0.04)
<i>B</i>	2182.5 (0.5)	12.81 (0.02)
<i>V</i>	2184.5 (0.5)	12.73 (0.02)
<i>R</i>	2185.3 (0.5)	12.62 (0.04)
<i>I</i>	2179.1 (1.0)	12.82 (0.04)
<i>J</i>	2178.4 (1.0)	12.90 (0.04)
<i>H</i> ^a	2177.8 (1.0)	13.08 (0.04)
<i>K</i>	2178.8 (1.0)	12.83 (0.04)

^a The second maximum ($H = 12.97$ at JD 2,452,204.7) is actually brighter than the first *H*-band maximum.

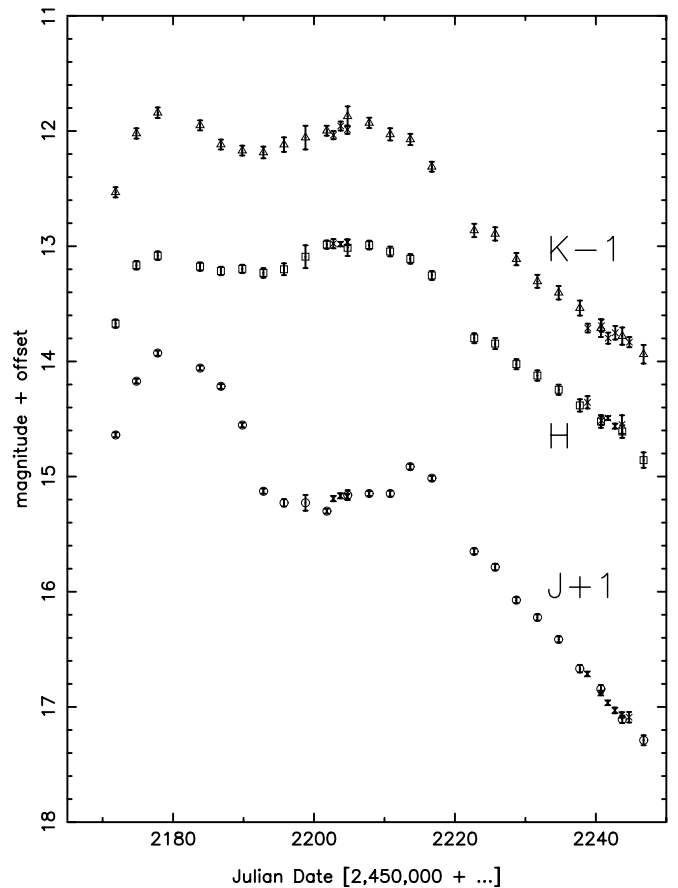


FIG. 7.—*JHK* photometry of SN 2001el. The *J* and *K* data have been offset vertically by +1 and -1 mag, respectively. *Open symbols*: YALO data. *Crosses*: LCO 1 m data. The YALO data include the corrections given in Table 6.

hump in *H*. However, the objects with the lowest values of $\Delta m_{15}(B)$ seem to exhibit rather flat light curves in the *H* band for the first 40 days after $T(B_{\max})$. Unlike *I*-band light curves, however, Type Ia SNe with large *B*-band decline rates (e.g., SN 2000bk) do not monotonically decline after the time of maximum light.

3. DISCUSSION

3.1. Optical Light Curves

The uncertainties given in Table 3 should be considered minimum values of the internal errors (i.e., essentially based on photon statistics and the uncertainties of the zero points and color corrections). A more honest measure of the internal errors can be obtained from higher order polynomial fits to the light curves, filter by filter, under the assumption that the supernova's light varied smoothly with time. On this basis, we believe that the uncertainties of the *U*-band magnitudes in Table 3 are sensible as given. For *B*, *V*, *R*, and *I*, respectively, we estimate that the internal errors are ± 0.016 , 0.025 , 0.029 , and 0.047 mag, where the *B* and *V* data include the filter corrections of Table 4.

According to Phillips et al. (1999) a typical Type Ia SN has a *B*-band decline rate $\Delta m_{15}(B) = 1.1$ mag. This parameter varies roughly from 0.75 (SN 1999aa, Krisciunas et al. 2000) to 1.94 mag (SN 1999da, Krisciunas et al. 2001). SN

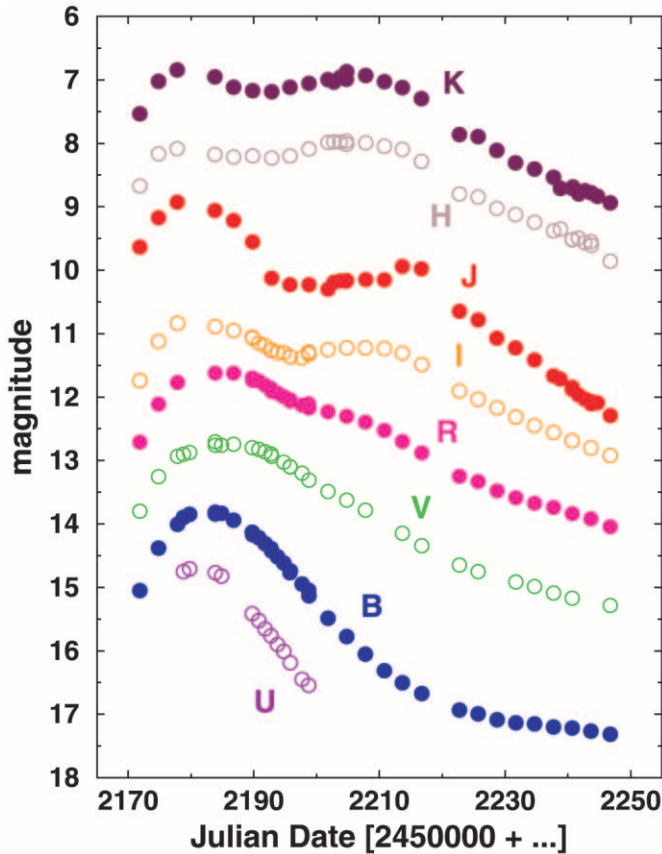


FIG. 8.—*UBVRIJHK* light curve of SN 2001el. The different bands are offset for plotting purposes but show that the red and infrared maxima occurred earlier than for the *UBV* bands.

2001el has $\Delta m_{15}(B) = 1.13 \pm 0.04$ mag and is thus a mid-range decliner.

One of the characteristic features of the light curves of Type Ia SNe is the secondary hump observed in the *IJHK* bands. To a lesser extent this can be seen as a “shoulder” in the *R*-band and sometimes even in the *V*-band light curves. Krisciunas et al. (2001, Fig. 17) took various well-sampled *I*-band light curves, fitted polynomials to the data between 20 and 40 days after $T(B_{\max})$, using the flux at *I*-band maximum as the reference, and showed that an integration of the *I*-band flux over this range correlated quite well with the *B*-band decline rate. If we let $X = \langle I \rangle_{20-40}$, we find that

$$\Delta m_{15}(B) = 0.0035 + 17.475X - 47.838X^2 + 35.618X^3, \quad (8)$$

with a typical rms residual of ± 0.093 mag in $\Delta m_{15}(B)$.

Since the *B*-band decline rate is correlated with the intrinsic luminosity at maximum of Type Ia SNe, therefore this relationship implies that the strength of the *I*-band secondary hump is also correlated with the intrinsic luminosity. We note two exceptions to equation (8). SN 1992bc had a much weaker *I*-band secondary hump than expected on the basis of its *B*-band decline rate, and SN 1994M had a much stronger *I*-band secondary hump.

SN 2001el had a mean flux over the time span $20 < t < 40$ days of 0.594 ± 0.04 with respect to the *I*-band maximum. On the basis of its *B*-band decline rate, we would have predicted $\langle I \rangle_{20-40} = 0.530$. Thus, it has a slightly stronger than

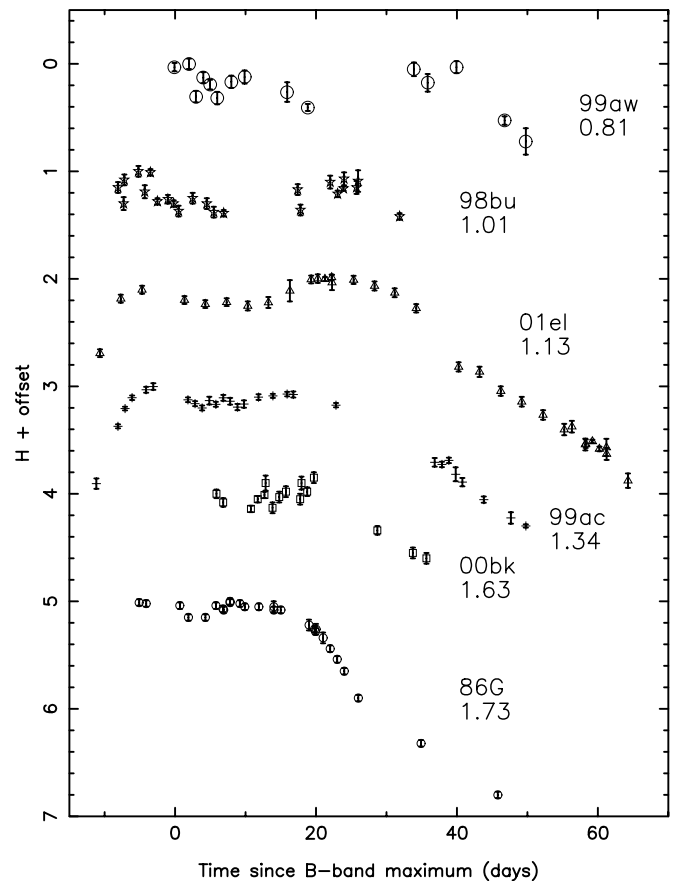


FIG. 9.—*H*-band light curves of a number of Type Ia supernovae. The objects are ordered from top to bottom by the decline rate parameter $\Delta m_{15}(B)$. Sources: SN 1999aw, Strolger et al. (2002); SN 1998bu, Meikle (2000); SN 2001el, this paper; SN 1999ac, Phillips et al. (2002); SN 2000bk, Krisciunas et al. (2001); SN 1986G, Frogel et al. (1987).

“normal” *I*-band secondary hump, but well within the uncertainty of the relationship given above.

3.2. Spectra

Regarding the spectrum of SN 2001el, Sollerman et al. (2001) note that the 612 nm Si II absorption line appeared flat bottomed. Interstellar absorption lines of Ca H and K, and the D lines of Na I were observed at the redshift of NGC 1448. Wang et al. (2001) describe spectropolarimetry of SN 2001el on 2001 September 26 UT (JD = 2,452,178.5; $t = -4.0$ days), finding that SN 2001el had a normal spectrum similar to that of SN 1994D except for a strong double-troughed absorption feature around 800.0 nm. The absorption dips of Si II (635.5, 564.0 nm) and Fe II (492.4, 516.9 nm) all showed velocities of about $10,000 \text{ km s}^{-1}$. Ca II lines (the “infrared triplet”) were present in the spectrum at a velocity comparable to that of the Si II 635.5 nm feature but were much weaker than an absorption feature at 800.0 nm. It is possible that the 800 nm feature was a second component of high-velocity Ca II, as suggested by Hatano et al. (1999) to explain a similar (but much weaker) feature in SN 1994D; if this identification is correct, then this Ca II feature was due to a detached shell/clump with a relative velocity of roughly $23,000 \text{ km s}^{-1}$.

Wang et al. (2002) also obtained spectropolarimetry of SN 2001el on 2001 October 1, 10, 18, and November 9 UT. Their data indicate, among other things, that the value of

$R_V \equiv A_V/E(B-V) = 2.88 \pm 0.15$, somewhat less than the standard Galactic value of 3.10 (Snedden et al. 1978; Rieke & Lebofsky 1985). From their spectra, the interstellar Na I line has an equivalent width of 0.47 Å. From Figure 4 of Barbon et al. (1990), this corresponds to a color excess $E(B-V) \approx 0.12$ mag. However, the uncertainty of this number is greater than or equal to 0.10 mag. We believe that the most accurate estimate of $E(B-V)$ is obtained from a combination of optical and infrared photometry (see below).

The *HST* spectra provided by Nugent for purposes of determining filter corrections and comparing synthetic photometry to our data were obtained on 2001 October 29, November 6, 13, 20, 26, and December 4 UT. These spectra will be discussed in a subsequent paper.

3.3. Reddening and Implied Extinction

From an analysis of SNe 1992A, 1992bc, 1992bo, and 1994D, Lira (1995) found a uniform color evolution for unreddened $B-V$ colors of Type Ia SNe from 30 to 90 days after V -band maximum. Phillips et al. (1999) used Lira's relation to get an estimate of the color excess for the tail of the $B-V$ colors of the SNe they analyzed. A majority of SNe analyzed by Jha (2002, § 4.2.3) show that the Lira relation works very well to describe the late-time $B-V$ color evolution of unreddened Type Ia SNe. In Figure 10 we show the $B-V$ colors of SN 2001el, with and without the filter corrections given in Table 4. Given that the Lira relation was based on observations with the CTIO 0.9 m telescope, we clearly want to correct the YALO data to the CTIO 0.9 m system so as to derive $E(B-V)_{\text{tail}}$ (see below) using the same zero point for the Lira relation.

In Table 8 we give the color excesses for SN 2001el, based on a variety of indices. Following the analysis of Phillips et al. (1999), we give the $B-V$ color excess as implied from the photometry at maximum light, the $V-I$ color excess at maximum, and the $B-V$ color excess from the photometry for $t > 32$ days. The three estimates of A_V that result are in reasonable agreement, but only if we correct the $B-V$ colors for filter differences. A weighted $B-V$ color excess is $E(B-V)_{\text{avg}} = 0.206 \pm 0.046$ mag for the host galaxy red-

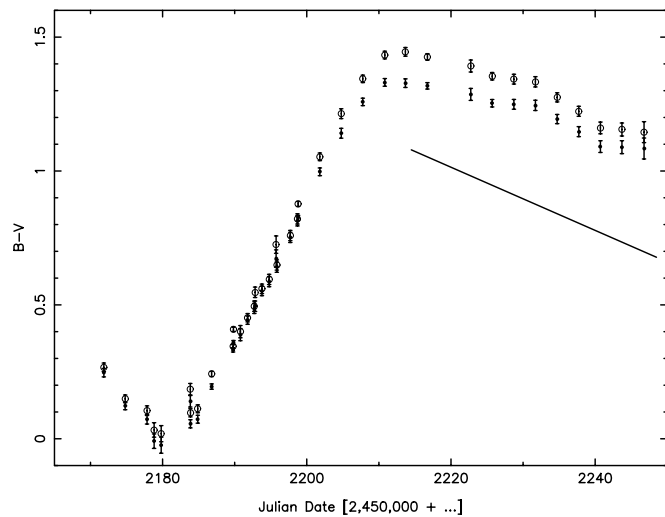


FIG. 10.— $B-V$ colors of SN 2001el vs. Julian Date. The smaller open circles represent the uncorrected data, while the solid dots include the corrections of Table 4. The solid line is the zero reddening line of Lira (1995) adjusted to the time of V -band maximum given in Table 7.

TABLE 8
COLOR EXCESSES AND IMPLIED EXTINCTION^a

Color Index	Color Excess	A_V (host galaxy)	A_V (total)
$(B-V)_{\text{max}}$	0.185 (0.104)	0.53 (0.30)	0.57 (0.30)
$(B-V)_{\text{tail}}$	0.253 (0.063)	0.73 (0.19)	0.77 (0.19)
$(V-I)_{\text{max}}$	0.133 (0.087)	0.31 (0.20)	0.35 (0.20)
$(B-V)_{\text{avg}}$	0.206 (0.046)	0.593 (0.136)	0.636 (0.136)
$V-J$	0.350 (0.077)	0.445 (0.114)	0.488 (0.114)
$V-H$	0.450 (0.071)	0.502 (0.089)	0.545 (0.089)
$V-K$	0.530 (0.054)	0.554 (0.063)	0.597 (0.063)

^a All values are measured in magnitudes. Values in parentheses are 1σ uncertainties. We adopt $R_V \equiv A_V/E(B-V) = 2.88 \pm 0.15$ (Wang et al. 2002) for the host galaxy. We also adopt $E(B-V) = 0.8E(V-I)$.

dening. The small contribution of Galactic dust reddening is $E(B-V) = 0.014$ mag (Schlegel, Finkbeiner, & Davis 1998), indicating a small Galactic contribution to A_V amounting to 0.043 mag. Adopting $R_V = 2.88 \pm 0.15$ from Wang et al. (2002) for the host galaxy, the estimated total extinction based on optical photometry alone is $A_V = 0.64 \pm 0.14$ mag.

As is well known, interstellar extinction in the near-infrared is an order of magnitude lower than in the V band. If there exists a color index such as $V-K$, which is “well behaved” for some range of decline rates of Type Ia SNe, then a $V-K$ color excess, for example, is almost a direct measure of the V -band extinction. We shall adopt Rieke & Lebofsky's (1985) values of $A_\lambda/A_V = 0.282$, 0.175, and 0.112 for the J , H , and K bands, respectively, and assign an uncertainty of 20% to each ratio. It follows that

$$\begin{aligned} A_V &= (1.393 \pm 0.110)E(V-J) \\ &= (1.212 \pm 0.052)E(V-H) \\ &= (1.126 \pm 0.028)E(V-K) . \end{aligned}$$

In other words, if we can estimate a color excess in $V-K$, A_V numerically is only 10% to 15% greater than that color excess.

Krisciunas et al. (2000, 2001) showed that, over a range of decline rates ($0.87 < \Delta m_{15}(B) < 1.28$), Type Ia SNe exhibit uniform V minus near-IR color curves from $-9 \leq t \leq +27$ days. $V-K$ colors were particularly well behaved and were so over the widest range of decline rates. However, on the basis of a small number of data points *per object*, they could not justify fitting the $V-H$ or $V-K$ colors by anything more sophisticated than two straight lines. The $V-J$ colors were fitted with a second-order curve for $-9 \leq t \leq +9.5$ days, while a linear fit was used for $+9.5 \leq t \leq +27$ days.

From the well-sampled V minus near-IR color curves of SNe 1999ac and 2001el, we now know that there is no abrupt change of the color evolution 1 week after $T(B_{\text{max}})$. Thus, we feel justified in fitting a higher order curve to the data of eight midrange decliners studied by Krisciunas et al. (2000) to give more realistic unreddened color loci.

In Figure 11 we show the V minus near-IR colors of SN 2001el, along with loci derived from SNe 1972E, 1980N, 1983R, 1999cp, 1981B, 1981D, 1998bu, and 1999cl, adjusted in the ordinate direction so as to minimize the reduced χ^2 of the fits. The shape of the $V-K$ locus matches the data of SN 2001el very well (with $\chi^2_\nu = 0.76$). The $V-H$ and $V-J$ loci match the data of SN 2001el well only from $+10 \lesssim t \lesssim +20$ days.

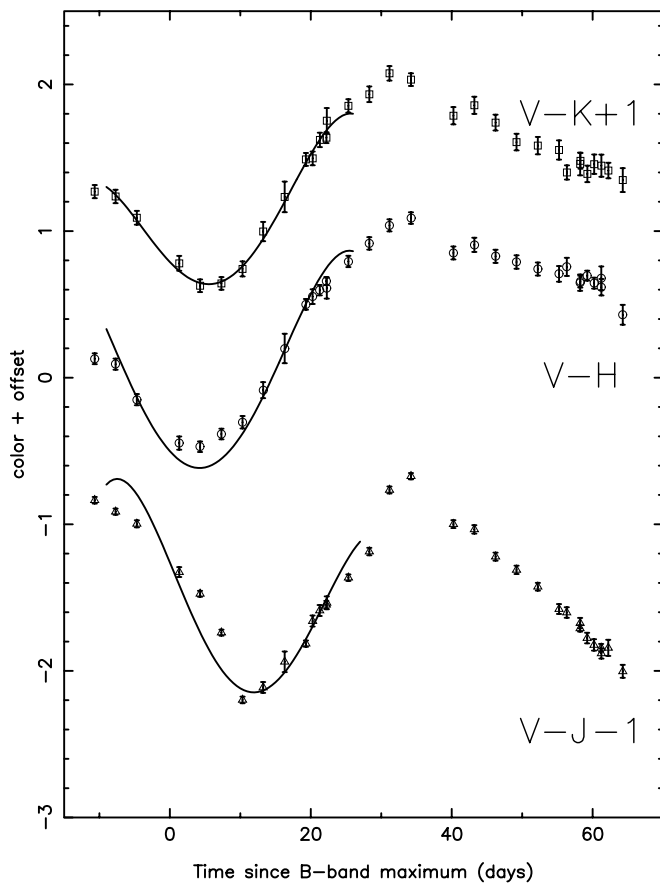


FIG. 11.— V minus near-IR color curves for SN 2001el, using the V -band data of Table 3 corrected by the values in Table 4, and the JHK data in Table 5, with the YALO data corrected according to the values in Table 6. The $V-K$ data have been offset by +1 mag, while the $V-J$ data have been offset by -1 mag. The solid lines are based on the fourth-order polynomial fits to data of eight Type Ia SNe studied by Krisciunas et al. (2000), which have midrange B -band decline rates. The loci are adjusted in the ordinate direction to minimize the reduced χ^2 of the fits.

In Table 8 we also give the color excesses and values of A_V derived from $VJHK$ photometry. Within the errors, these estimates of A_V are in agreement with the value derived from optical photometry alone. The weighted mean from the V minus near-IR colors and $E(B-V)_{\text{avg}}$ is $A_V = 0.57 \pm 0.05$ mag.¹¹ The use of optical and infrared data results in a smaller statistical uncertainty for the extinction. Though the filter corrections adopted for the $BVJHK$ photometry are only approximate (± 0.02 mag), we feel that the consistency of the various estimates of A_V is facilitated by the adoption of the filter corrections. While the calculation of such corrections is time consuming because of its iterative nature, this extra work will likely become a standard part of the production of high-quality SN light curves.

3.4. Theoretical V -IR Color Curves

Model calculations for the explosion, light curves, and spectra of typical Type Ia SNe indicate that there exists a physical basis for well-behaved optical-versus-infrared

color relationships (Höflich 1995; Wheeler et al. 1998). What we see as a supernova event is the light emitted from a rapidly expanding envelope. As a result of the increasing geometrical dilution, deeper layers of the envelope become exposed with time. Until about maximum light the spectra are formed in the regions that have undergone incomplete Si burning. During this period both the fluxes in the V and K bands are mainly determined by the free-free/bound-free opacities and Thomson scattering and the source functions, i.e., the temperature evolution at the photosphere, which is rather insensitive to the total luminosity because of the steep dependence of the opacity on the temperature (Höflich, Müller, & Khokhlov 1993).

Starting a few days before maximum light, the V -band flux reflects the evolution of the luminosity. Around the same time the Fe/Ni core becomes exposed and broad emission features due to iron-group elements occur in the H and K bands (Wheeler et al. 1998), which determine the flux. They are in emission because the IR source functions are close to thermal and the optical depth is large; i.e., they are formed well above the photosphere close to the outer edge of the Fe/Ni core. With time the optical photosphere recedes in mass. Thus, the emission features in the K -band increase in strength while the V -band flux decreases, leading to $V-K$ colors that get redder for some time. Once the SNe enter the nebular stage, there should be a spread in $V-K$ color curves for different objects, even if they have the same decline rate. The $V-K$ color curve should be reasonably model-independent (i.e., whether the explosion is due to deflagration or a delayed detonation should not matter significantly) because, virtually, the entire K band is dominated by the iron feature.

The $V-J$ and $V-H$ color curves would not be as well behaved because the J and H bands cover spectral regions that are affected both by the IR-emission features and the continua. The fractional contribution depends on the Doppler shift of the chemical layers, and, thus, it depends on the details of the nuclear burning. Note that, for very subluminal Type Ia SNe (e.g., SN1999by), the $V-K$ evolution after maximum light is delayed because the Fe/Ni core is exposed only 2 weeks after maximum (Höflich et al. 2002).

In Figure 12 we show the $V-H$ and $V-K$ color curves for a delayed detonation model of a “Branch-normal” Type Ia SN (model 5p028z22.23 of Höflich et al. 2002). To derive synthetic magnitudes we used the V -band filter profile of Bessell (1990) and the H and K_{short} filter profiles of Persson et al. (1998), along with appropriate quantum efficiency and atmospheric transmission functions. The fluxes were normalized to the spectra of Vega given by Castelli & Kurucz (1994) and assumed $V-H$ and $V-K = 0.00$. For comparison, we show the unreddened loci based on the eight SNe studied by Krisciunas et al. (2000). The color indices are well reproduced within the model uncertainties of ≈ 0.2 to 0.3 mag. We note that our delayed detonation model gives $t(V_{\text{max}}) - t(B_{\text{max}}) = 1.1$ days, which is smaller than the nominal value of 1.7 to 2.0 days. A shift of the theoretical V minus infrared color curves by ± 1 days is within the uncertainties. Likewise, from data on any given SN, the time of B -band maximum is rarely known to better than ± 0.5 days, so the observed colors can be shifted in the time direction as well.

The colors have been calculated by our spherical NLTE light-curve code, which uses about 500 depths, 3000 frequency points, and 50 NLTE superlevels. A comparison

¹¹ The various estimates of A_V are only semi-independent, as all rely on the V -band photometry. However, we believe that our V -band photometry suffers from no serious systematic errors.

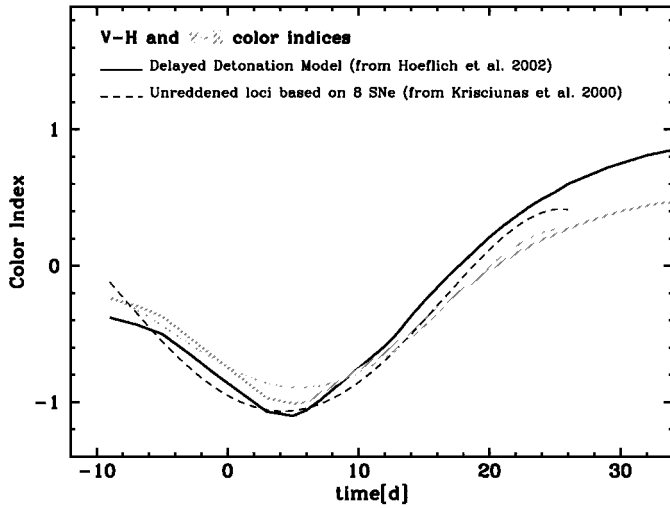


FIG. 12.—Color curves based on a delayed detonation model of a typical Type Ia SN (Höflich et al. 2002). The abscissa is the number of days since B -band maximum. Model uncertainties allow the theoretical curves to be shifted ± 1 day in the x -direction. $V-H$ loci are black lines while $V-K$ loci are gray. Also shown (dashed lines) are the unreddened loci based on eight midrange decliners studied by Krisciunas et al. (2000). Given the 0.2 to 0.3 mag accuracy of the infrared models, the agreement between theory and observation is better than expected.

with detailed NLTE-spectral calculations shows that the reduction of atomic levels and frequencies produces uncertainties of ≈ 0.2 to 0.3 mag in H and K . However, the small number of frequencies is responsible for the failure to properly reproduce $V-J$, especially after the time of B -band maximum when the flux varies strongly within the J band (a factor of ≈ 10 , Wheeler et al. 1998). As a result, we do not show our theoretical $V-J$ curve.

3.5. Distance

NGC 1448, the host of SN 2001el, has not been the target of study for determining its distance via surface brightness fluctuations (SBFs) or Cepheids. Since it is a spiral galaxy inclined to the line of sight, one can derive a Tully-Fisher (TF) distance to it. Mathewson & Ford (1996) give the following parameters: velocity width $V_{20} = 208 \text{ km s}^{-1}$, inclination angle $i = 88^\circ$, integrated extinction-corrected I -band magnitude 9.44. Using the I -band Tully-Fisher calibration of Sakai et al. (2000), $W_{20} = 2V_{20}$, and a slight correction for the inclination angle of the galaxy and its redshift, we find $W_{20}^C = 414.6 \text{ km s}^{-1}$. It follows that the absolute I -band magnitude of NGC 1448 $M_I = -22.21$, and the distance modulus is 31.65 mag. Giovanelli et al. (1997) indicate that the uncertainty of a single TF distance is roughly ± 0.35 mag. The TF distance of NGC 1448 is therefore $21.4^{+3.7}_{-4.2}$ Mpc.

We note that H -band and K -band light curves of many Type Ia SNe are reasonably flat at $t \approx +10$ days. We assume, then, that this is a “well-behaved” part of the light curves. The J -band light curves, by contrast, exhibit rapidly changing flux at this epoch.

In Figure 13 we show the absolute magnitudes at BVI maximum light and absolute H -band magnitudes at $t = +10$ days versus the decline rate parameter $\Delta m_{15}(B)$. Some of the data shown are derived using Cepheid distances

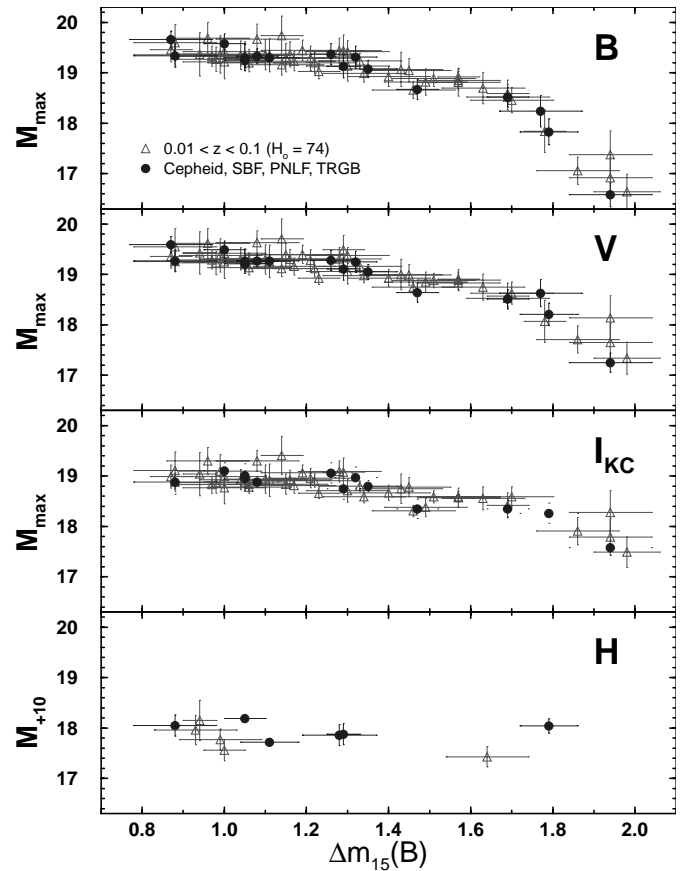


FIG. 13.—Absolute magnitudes of Type Ia SNe vs. decline rate parameter $\Delta m_{15}(B)$. For the H band the absolute magnitudes correspond to 10 days after the time of B_{\max} . The solid points were derived using distances from Cepheids or other direct measures of the distance to the host galaxy, such as surface brightness fluctuations, the planetary nebula luminosity function, or using the “tip of the red giant branch method.” Open triangles correspond to points derived using a Hubble constant of $74 \text{ km s}^{-1} \text{ Mpc}^{-1}$; these objects are sufficiently distant to be in the Hubble flow. The rightmost point in the bottom panel corresponds to SN 1986G, which was highly reddened and whose distance is subject to some uncertainty.

to host galaxies, surface brightness fluctuations, the planetary nebula luminosity function method, or the “tip of the red giant branch” method, assuming the Cepheid distance scale adopted by Freedman et al. (2001). Other data for galaxies in the Hubble flow (i.e., with redshifts greater than 3000 km s^{-1}) are derived assuming $H_0 = 74 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In all four bands the absolute magnitude is reasonably constant for $0.87 < \Delta m_{15}(B) < 1.30$. For nine SNe that satisfy this criterion we find a weighted mean H -band absolute magnitude at $t = +10$ days of $M_H(t = 10) = -17.91 \pm 0.05$.

From an interpolation of the *corrected* YALO data for SN 2001el we estimate that at $t = +10$ days $H = 13.228 \pm 0.04$. Adopting an extinction of $A_H = 0.10$ mag and the absolute magnitude just given, we obtain a distance modulus of 31.04 mag with an uncertainty of ± 0.14 . The corresponding distance is 16.1 ± 1.1 Mpc.

Using the method of Phillips et al. (1999), the BVI optical photometry gives a distance modulus of $m - M = 31.29 \pm 0.08$ mag. This is on the Cepheid distance scale adopted by Freedman et al. (2001). The corresponding distance is 17.9 ± 0.8 Mpc.

With a distance somewhere in the range 16.1 to 21.4 Mpc, NGC 1448 is clearly near enough for a determination of its distance via Cepheids.

4. CONCLUSIONS

Perhaps the most significant finding of this paper is that we were able to calculate corrections to BV and infrared photometry, based on synthetic photometry but using spectra of actual supernovae, that to some extent eliminated systematic differences in the data obtained on different telescopes with different physical detectors and filters. Under the assumption that the infrared spectrum of SN 2001el was like that of SN 1999ee and that it evolved similarly with time, we derived corrections to YALO IR photometry, which had the right size and were to be applied in the right direction to bring the YALO data fully onto the system of Persson et al. (1998) and in agreement with the data taken with the LCO 1 m telescope. Though it is known that the spectrum of a SN is not like that of a star, especially once the SN enters the nebular phase ($t \gtrsim 30$ days), such corrections have been ignored in the past because we simply did not have enough spectra and photometry to confirm to what degree synthetic photometry gives the right results. Clearly, not all optical response functions are well known. Further information (e.g., the effect of the YALO dichroic on the optical transmission) is needed to make analogous corrections to the RI data.

Another significant result of this paper is the excellent agreement between theoretical $V-H$ and $V-K$ color curves with the unreddened loci based on eight SNe studied by Krisciunas et al. (2000). This gives us further confidence that there exist “uniform” color curves for Type Ia SNe with midrange decline rates, which can be used to derive accurate values of the total extinction suffered by the light of such objects. A comparison of theoretical color curves with observational data, covering the full range of decline rates of Type Ia SNe, is beyond the scope of the present paper.

Given the importance of SNe in modern cosmological studies, it is worth our while to investigate the uniformity of behavior of as many nearby SNe as we can. Though the light curves of SN 2001el are quite normal, we note that the observed $B-V$ color 3 to 4 days before $T(B_{\max})$ was slightly negative. Given the extinction along the line of sight, the color excess $E(B-V)$ must be about 0.20 mag. Thus, the dereddened color shortly before $T(B_{\max})$ was $B-V \approx -0.22$, which is extremely blue. The second H -band maximum at $t = +22.2$ days was 0.1 mag brighter than the first H -band maximum at $t = -4.7$ days. This is consistent with a prediction of Krisciunas et al. (2000) based on an analysis of other Type Ia SNe with midrange decline rates, but not all H -band light curves of midrange decliners show this.

On the basis of the optical and IR photometry, we derive $A_V = 0.57 \pm 0.05$ mag. Given the small formal uncertainty in A_V , we can state that the uncertainty in the distance estimate to SN 2001el and its host is *not* due to the extinction along the line of sight. Given the attention we have paid to possible sources of systematic error in the $UBVRIJHK$ photometry and the good coverage of the light curve, we hope that photometry of SN 2001el can serve as a template for studies of other Type Ia SNe.

With a distance in the range 16.1 to 21.4 Mpc, the host galaxy of SN 2001el is close enough for its distance to be determined by means of Cepheids. Given the small number

of nearby galaxies that have hosted SNe and also had their distances determined via Cepheids, we suggest that NGC 1448 be a future target for such observations with *HST*.

It is worth (re)stating that (for the foreseeable future) high-redshift SNe will only be observed in *rest-frame* optical bands, because we do not yet have infrared detectors sensitive enough, even with an 8 m class telescope, to detect these objects in the rest-frame IR bands. This is unfortunate, as it is becoming increasingly clear that a combination of optical and infrared photometry of Type Ia SNe allows us to get a better handle on the host extinction suffered by these objects. Since the advocacy of a nonzero cosmological constant based on supernova studies hinges on the systematic faintness of objects in the redshift range $0.2 < z < 0.8$, we want to minimize as much as possible the effect of systematic errors in distances to these most important cosmological beacons.

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APPENDIX A

SPECTRA FOR SYNTHETIC PHOTOMETRY

The near-infrared photometry required an estimate of the theoretical color terms for the various natural systems. There is no grid of spectrophotometric standards in the near-infrared comparable to what is available in the optical. As a simple guide to color terms, we have chosen to use synthetic photometry based on the Sun, Vega, and Sirius. This color range generally encompasses the photometric standards (Persson et al. 1998) used in our study. All spectrophotometric data were convolved 2 Å and sampled at 1 Å pixel⁻¹. The spectrophotometric models did not include atmospheric absorption. Rather, we added the telluric absorption to the transmissions functions used to calculate the synthetic photometry. The adopted photometry was taken from the discussion in Bessell et al. (1998).

A1. THE SUN

The solar spectrophotometry is a combination of observed solar fluxes and models. We chose the solar model from the Kurucz Web site (see also Fontenla et al. 1999) as (T_{eff} , $\log g$, v_{micro} , mixing length/scale height) = (5777 K, 4.438, 1.5 km s⁻¹, 1.25). The Kurucz model reproduces the Kitt Peak Solar Flux Atlas (Kurucz et al. 1984). In the near-infrared, we have inserted the Livingston & Wallace (1991)

observed spectra, which were scaled to the continuum of the Kurucz model.

A2. VEGA

The Vega spectrophotometry is a combination of empirical data and model data. The fundamental flux calibration in the optical comes from Hayes (1970, 1985), Oke & Schild (1970), and Tüg (1980). We have adopted the model “veg090250000p.asc5” from the Web site of Kurucz. This model corresponds to the physical parameters (T_{eff} , $\log g$, $[M/H]$, v_{micro} , v_{macro}) = (9550 K, 3.950, -0.5 , 2 km s^{-1} , 0 km s^{-1}), which is the model adopted by Bessell et al. (1998). This model was then scaled from the calculated Eddington fluxes corrected to an angular size $3.24 \pm 0.07 \text{ mas}$ (Code et al. 1976).

We then compared this scaled model with the Hayes (1985) fluxes of Vega in the wavelength region 4000–8000 Å and found that the model needed to be scaled to 3.26 mas, in agreement with the conclusions of Bessell et al. (1998). At the extremes of the measured data the models did not fit well. We needed to scale the model by 0.972 at 3300 Å and 1.009 at 10500 Å to fit the Hayes points.

The final semiempirical spectrophotometric model of Vega was created by using the Hayes (1985) points from 3300–10500 Å, the Kurucz model scaled by 0.972 below 3300 Å, and the Kurucz model scaled by 1.009 above 10500 Å. A more complete discussion of the range in models of Vega can be found in Cohen et al. (1999) and Bessell et al. (1998).

A3. SIRIUS

For Sirius we have adopted the model “sir.ascsq5” from the Kurucz Web site, which was run with the physical parameters (T_{eff} , $\log g$, $[M/H]$, v_{micro}) = (9850 K, 4.30, $+0.4$, 0 km s^{-1}). This is very similar to the model used by Cohen et al. (1999). We scaled the model from the Eddington fluxes to observed fluxes assuming an angular diameter of 5.89 mas (Code et al. 1976). It was found, however, that this did not reproduce the observed V mag of Sirius from Ian Glass as quoted in Bessell et al. (1998). The final fluxes were scaled by 1.049 to force $V = -1.43$.

APPENDIX B

FILTER SHIFTS FOR SYNTHETIC PHOTOMETRY

Synthetic photometry uses spectra of spectrophotometric standards, filter, and atmospheric transmission

TABLE 9
WAVELENGTH SHIFTS TO INSTRUMENTAL BANDPASSES^a

Telescope	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>
YALO	25 red	100 blue	30 red	100 blue
CTIO 0.9 m.....	25 red	0	50 blue	50 red
CTIO 1.5 m.....	25 blue	0	0	0

^a All values are measured in angstroms.

curves to derive broadband magnitudes of the standards. These should give photometric color terms that match the color terms derived from actual photometry of stars. However, we find that the filter profiles must be shifted in order to match the synthetic color terms with the observed values. In Table 9 we give the filter shifts adopted to place optical photometry on the Bessell (1990) system.

We found that no shifts needed to be applied for the infrared photometry (YALO vs. LCO 1 m).

We note that the R -band filter used by Stritzinger et al. (2002) for their YALO observations was a very wide non-standard filter. Our observations were made with a much narrower, more standard filter.

We also note that Stritzinger et al. (2002) found a filter shift of only 10 Å for the YALO I -band filter, compared with our value of 100 Å. Their color terms for YALO photometry were based on the photometric sequence of SN 1999ee, rather than Landolt standards, as were ours, and their I -band color term has a size half as large as ours. Our filter shift would be comparable to theirs for identical color terms.

As stated above, since the YALO and Landolt R -band data agree, on average, at the 0.01 mag level, there is no great motivation to apply R -band filter corrections. If we did so, it would produce systematic differences at the 0.04 mag level. We do have a motivation to resolve systematic differences in I -band photometry, but we do not have spectra of SN 2001el at the appropriate epochs to make these corrections directly. Assuming that the spectra of SNe 1999ee and 2001el are the same in the I band would give us filter corrections that would make the photometry nearly 0.20 mag different (YALO vs. Landolt) at $t = 16$ days. We suspect that a significant unknown is the effect of the YALO dichroic on the actual R - and I -band filter functions.

REFERENCES

- Allen, C. W., & Cox, A. N. 2000, *Allen's Astrophysical Quantities* (4th ed.; New York: Springer), 152, 388
- Barbon, R., Benetti, S., Rosino, L., Cappellaro, E., & Turatto, M. 1990, *A&A*, 237, 79
- Bessell, M. S. 1990, *PASP*, 102, 1181
- Bessell, M. S., Castelli, F., & Plez, B. 1998, *A&A*, 333, 231 (erratum 337, 321 [1998])
- Castelli, F., & Kurucz, R. L. 1994, *A&A*, 281, 817
- Code, A. D., Bless, R. C., Davis, J., & Brown, R. H. 1976, *ApJ*, 203, 417
- Cohen, M., Walker, R. G., Carter, B., Hammersley, P., Kidger, M., & Noguchi, K. 1999, *AJ*, 117, 1864
- Elias, J. H., Frogel, J. A., Hackwell, J. A., & Persson, S. E. 1981, *ApJ*, 251, L13
- Elias, J. H., Matthews, G., Neugebauer, G., & Persson, S. E. 1985, *ApJ*, 296, 379
- Fontenla, J., White, O. R., Fox, P. A., Avrett, E. H., & Kurucz, R. L. 1999, *ApJ*, 518, 480
- Freedman, W., et al. 2001, *ApJ*, 553, 47
- Frogel, J. A., Gregory, B., Kawara, K., Laney, D., Phillips, M. M., Terndrup, D., Vrba, F., & Whitford, A. E. 1987, *ApJ*, 315, L129
- Giovanelli, R., Haynes, M. P., Herter, T., Vogt, N. P., da Costa, L. N., Freudling, W., Salzer, J. J., & Wegner, G. 1997, *AJ*, 113, 53
- Hamuy, M., Suntzeff, N. B., Heathcote, S. R., Walker, A. R., Gigoux, P., & Phillips, M. M. 1994, *PASP*, 106, 566
- Hamuy, M., et al. 2002, *AJ*, 124, 417
- Hamuy, M., Walker, A. R., Suntzeff, N. B., Gigoux, P., Heathcote, S. R., & Phillips, M. M. 1992, *PASP*, 104, 533

- Hatano, K., Branch, D., Fisher, A., Baron, E., & Filippenko, A. V. 1999, *ApJ*, 525, 881
- Hayes, D. S. 1970, *ApJ*, 159, 165
- . 1985, in *IAU Symp.* 111, *Calibration of Fundamental Stellar Quantities*, ed. D. S. Hayes et al. (Dordrecht: Reidel), 225
- Höflich, P. 1995, *ApJ*, 443, 89
- Höflich, P., Gerardy, C., Fesen, R., & Sakai, S. 2002, *ApJ*, 568, 791
- Höflich, P., Müller, E., & Khokhlov, A. 1993, *A&A*, 268, 570
- Jha, S. 2002, Ph.D. thesis, Harvard Univ.
- Krisciunas, K., Hastings, N. C., Loomis, K., McMillan, R., Rest, A., Riess, A. G., & Stubbs, C. 2000, *ApJ*, 539, 658
- Krisciunas, K., et al. 2001, *AJ*, 122, 1616
- Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, *Solar Flux Atlas from 296 to 1300 nm* (Sunspot, NM: Natl. Solar Obs.)
- Landolt, A. U. 1992, *AJ*, 104, 340
- Lira, P. 1995, Master's thesis, Univ. Chile
- Livingston, W., & Wallace, L. 1991, *NSO Tech. Rep.* 91-001 (July)
- Mathewson, D. S., & Ford, V. L. 1996, *ApJS*, 107, 97
- Meikle, W. P. S. 2000, *MNRAS*, 314, 782
- Monard, L. A. G. 2001, *IAU Circ.* 7720
- Oke, J. B., & Schild, R. E. 1970, *ApJ*, 161, 1015
- Perlmutter, S., et al. 1997, *ApJ*, 483, 565
- . 1999, *ApJ*, 517, 565
- Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, *AJ*, 116, 2475
- Phillips, M. M. 1993, *ApJ*, 413, L105
- Phillips, M. M., Lira, P., Suntzeff, N. B., Schommer, R. A., Hamuy, M., & Maza, J. 1999, *AJ*, 118, 1766
- Phillips, M. M., et al. 2002, in preparation
- Rieke, G. H., & Lebofsky, M. J. 1985, *ApJ*, 288, 618
- Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, *ApJ*, 473, 88
- Riess, A. G., et al. 1998, *AJ*, 116, 1009
- Sakai, S., et al. 2000, *ApJ*, 529, 698
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Snedden, C., Gehrz, R. D., Hackwell, J. A., York, D. G., & Snow, T. P. 1978, *ApJ*, 223, 168
- Sollerman, J., Leibundgut, B., & Lundqvist, P. 2001, *IAU Circ.* 7723
- Stetson, P. 1987, *PASP*, 99, 191
- . 1990, *PASP*, 102, 932
- Stritzinger, M., et al. 2002, *AJ*, 124, 2100
- Strolger, L.-G., et al. 2002, *AJ*, 124, 2905
- Suntzeff, N. B. 2000, in *AIP Conf. Proc.* 522, *Cosmic Explosions*, ed. S. S. Holt & W. W. Zhang (Melville, NY: AIP), 65
- Suntzeff, N. B., et al. 1999, *AJ*, 117, 1175
- Tüg, H. 1980, *A&A*, 82, 195
- Wang, L., et al. 2001, *IAU Circ.* 7724
- . 2002, in press
- Wheeler, J. C., Höflich, P., Harkness, R. P., & Spyromilio, J. 1998, *ApJ*, 496, 908