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OPTICAL LIGHT CURVE OF THE TYPE Ia SUPERNOVA 1998bu IN M96 AND THE SUPERNOVA CALIBRATION OF THE HUBBLE CONSTANT

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ABSTRACT

We present the $UBV(RI)_{\rm KC}$ light curves of the Type Ia supernova SN 1998bu, which appeared in the nearby galaxy M96 (NGC 3368). M96 is a spiral galaxy in the Leo I group that has a Cepheid-based distance. Our photometry allows us to calculate the absolute magnitude and reddening of this supernova. These data, when combined with measurements of the four other well-observed supernovae with Cepheid-based distances, allow us to calculate the Hubble constant with respect to the Hubble flow defined by the distant Calán/Tololo Type Ia sample. We find a Hubble constant of 63.9 ± 2.2(internal) $\pm$ 3.5(external) km s^{-1} Mpc^{-1}, consistent with most previous estimates based on Type Ia supernovae. We note that the two well-observed Type Ia supernovae in Fornax, if placed at the Cepheid distance to the possible Fornax spiral NGC 1365, are apparently too faint with respect to the Calán/Tololo sample calibrated with the five Type Ia supernovae with Cepheid distances to the host galaxies.

Key words: distance scale — galaxies: individual (NGC 3368) — supernovae: general — supernovae: individual (SN 1998bu)

1. INTRODUCTION

When corrected for reddening and small luminosity differences, the Type Ia supernova peak magnitudes show dispersion from a uniform Hubble flow of only 0.12 mag for nearby supernovae with redshifts of $z \sim 0.05$ (Riess, Press, & Kirshner 1996; Phillips et al. 1999). The distance to a single Type Ia supernova can therefore be measured to roughly 5%, which makes these objects very accurate distance probes for measuring the Hubble constant (Hamuy et al. 1996b; Riess et al. 1996) and the geometry of the universe (Perlmutter et al. 1997; Schmidt et al. 1998). Measuring the geometry of the universe, which can be expressed in dimensionless constants, requires the measurement of the relative magnitudes (corrected for relativistic effects and K-corrections) for nearby and distant objects (Sandage 1961). To measure the Hubble constant (which is not dimensionless) with supernovae, we require a calibration of the intrinsic luminosities of the objects.

If we ignore the "second-order effects" of reddening and the small intrinsic luminosity differences between Type Ia supernovae, the measurement of the Hubble constant requires three sets of observed quantities to be accurately determined: (1) the true distance to a set of Cepheids defining a period-luminosity relationship, often taken as the distance to the LMC Cepheids, (2) the relative distance moduli from the LMC to the galaxies hosting both Cepheids and a Type Ia supernovae, and (3) the zero point of the observed

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Hubble diagram of Type Ia supernovae that are distant enough to be in the undisturbed Hubble flow. The error in (1) is about 0.12 mag (Silbermann et al. 1998); however, the range in values for the distance moduli to the LMC is much larger at 18.3–18.7 (see Walker 1999 for a recent review). The error in (3) is only 0.03 mag (Hamuy et al. 1996b). The error in (2) for the galaxy NGC 1365 studied by Silbermann et al. (1998) is 0.20 mag. This galaxy is more distant than the other calibrators and perhaps a better error estimate is the average error for the five galaxies cited in this paper (see Table 5 below) or 0.15 mag. This error should be combined with the intrinsic dispersion in the peak magnitude for a single Type Ia supernova, which is about 0.12 mag as mentioned above. Thus, the final error in (2) is $\sim 0.2/(n)^{0.5}$ mag, where n is the number of galaxies in the sample.

With only four Type Ia supernovae with both Cepheid distances and reliable light curves (Hamuy et al. 1996b), the dominant source of error in the Hubble constant based on supernovae is not from the zero point of the Hubble diagram of the distant sample, but from the small number of supernovae in host galaxies with Cepheid distances. It is therefore important to follow any supernova that appears in a galaxy with a Cepheid distance. SN 1998bu, which appeared in NGC 3368 (M96), was such a candidate. This galaxy in the Leo I group has a Cepheid distance published by Tanvir et al. (1995).

SN 1998bu was discovered on 1998 May 9.9 (Villi 1998) (all dates given as UT). The coordinates of the supernova are ($10^{\mathrm{h}}46^{\mathrm{m}}46\overset{\mathrm{s}}{.}01$, $+11°50'07\overset{''}{.}5$, J2000.0) (Boschini 1998). Both Ayani, Nakatani, & Yamaoka (1998) and Meikle, Hernandez, & Fassia (1998) classified the supernova as a Type Ia before or near maximum light based on spectra taken around May 13.

Munari et al. (1998) obtained echelle spectra on May 12 that showed a strong Na I D interstellar absorption feature of 350 mÅ (D1) at 744.8 ± 0.3 km s^{-1} at the redshift of the host galaxy, indicating a substantial reddening for the supernova in the host galaxy. They also found an interstellar component from the Galaxy at -6 ± 1.5 km s^{-1} with a Na I (D1) equivalent width of 190 mÅ. Using the Munari & Zwitter (1997) calibration, they estimated the reddening due to the host galaxy and our Galaxy at 0.15 and 0.06 in units of $E(B-V)$. The large interstellar absorption features were confirmed by Centurion et al. (1998), who found two components at the Ca II K with velocities of 743 and 750 km s^{-1} with equivalent widths of 107 and 60 mÅ. They also found a weak Na I component at 722 km s^{-1}. The Galactic component of the Ca II K line was seen at five velocities: -26, -8, $+7$, $+48$, $+53$ km s^{-1} with equivalent widths of 77, 154, 16, 12, 22 mÅ.

Schaefer (1998) used the photometry reported in the IAU Circulars and two photometric data points from the WIYN telescope to estimate the time of B maximum of May 21.0 ± 0.3 with $\Delta m_{15}(B) = 0.95 \pm 0.05$, where $\Delta m_{15}(B)$ is the decline in B magnitude over 15 days from maximum light (Phillips 1993). He also estimated the peak magnitudes of $B = 12.36 \pm 0.05$ and $V = 11.93 \pm 0.04$.

Skiff & Faranda (1998) reported a prediscovery detection of 16.5 ± 0.3 on May 3.14 on an unfiltered CCD image.

In the remaining sections of the paper, we discuss the observations and reduction to the $UBVRI$ photometric system in § 2, and in § 3 we discuss the evaluation of the Hubble constant with the addition of this new distance to a Type Ia supernova.

2. OBSERVATIONS

2.1. *Detector and Filters*

We began observations of SN 1998bu with the facility "Tek2048 No. 3" CCD on the 0.9 m telescope at CTIO on 1998 May 16 and finished on July 14 when the supernova reached the west limit of the telescope at twilight. We obtained data on 30 nights, often through cirrus due to the poor weather associated with the 1998 El Niño weather pattern. We also obtained a small amount of data with other telescopes. We observed one night with the CTIO Curtis Schmidt telescope with the "Tek2048 No. 5" CCD and the facility filters. We observed two nights with the Las Campanas Observatory (LCO) Swope 1.0 m telescope "2 × 3K SITe 3" CCD and facility filters.

The CCD at the 0.9 m telescope is a thinned, antireflection coated front-side illuminated CCD with 0.024 mm ($0\overset{''}{.}40$) pixels. The CCD has very low read noise at 4 e^- through all four amplifiers and also has very high full-well depths of about 150,000 e^-. We observed the supernova with the facility "Tek No. 2" $UBV(RI)_{\mathrm{KC}}$ filters. The filters have the following prescriptions: U, UG1/1 mm + WG295/1 mm + $\mathrm{CuSO_4}$ (5 mm cell with saturated liquid); B, GG385/1 mm + BG1/2 mm + BG39/2 mm; V, GG495/2 mm + BG38/2 mm + BG39/1 mm; R_{KC}, OG570/3 mm + KG3/2 mm; I_{KC}, interference filter with $\lambda_c = 8050$ Å, FWHM = 1500 Å. The filter glasses were chosen from the Schott Glass Technologies catalog and the listed dimensions are the thickness. The CTIO $V(RI)_{\mathrm{KC}}$ sensitivity functions are a good match to the those published by Bessell (1990).[2] The B filter is about 150 Å blue of the Bessell B filter. In the following text we will refer to the filters $(RI)_{\mathrm{KC}}$ as simply RI.

The U sensitivity function is quite different between the CTIO U and the "UX" curve listed by Bessell. The CTIO curve has the same red cutoff, but the blue cutoff is about 200 Å redward of the Bessell UX cutoff due to the rapid falloff of the CTIO CCD quantum efficiency below 3800 Å. Because the CTIO U sensitivity is very low blueward of the Balmer jump, the transformation from the natural to the standard system will be sensitive to gravity and metallicity differences at a fixed $U-B$ between photometric standards. This will appear as extra random scatter in the U transformations. For a nonstellar spectrum of a supernova, a simple transformation from the natural to the standard system cannot be expected to reproduce accurate colors of the SN on the Johnson U system. A correction akin to the "*K*-correction" will need to be applied. We will discuss this effect on U photometry in a future paper.

2.2. *Observations and Reductions to Photometry of the Local Standards*

The data were reduced through flat-fielding using standard techniques. For the CTIO data, we removed the "shutter error," which is the increment in time across the CCD relative to the requested exposure time due the finite open and close time of the iris shutter In this case, the shutter error is about +0.065 s at the center and +0.020 s

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[2] Note that Bessell (1990) defines the sensitivity function as the product of the quantum efficiency of the detector + telescope, the filter transmission curve, the atmospheric extinction, and a linearly increasing function of wavelength.

TABLE 1

AVERAGED PHOTOMETRIC TRANSFORMATION VALUES

Magnitude	Color Term	Mean Error	Color Index	Extinction	Mean Error
CTIO 0.9 m (10 nights)					
U	−0.079	0.011	$U-B$	0.462	0.036
B	0.089	0.007	$B-V$	0.219	0.014
V	−0.018	0.006	$B-V$	0.124	0.010
V	−0.017	0.009	$V-I$	...	...
R	0.012	0.008	$V-R$	0.097	0.009
I	−0.019	0.005	$V-I$	0.045	0.010
Curtis Schmidt (1 night)					
U	−0.064	0.012	$U-B$	...	...
B	0.081	0.006	$B-V$	...	...
V	0.002	0.008	$B-V$	...	...
R	−0.016	0.010	$V-R$	...	...
I	−0.001	0.010	$V-I$	...	...
LCO Swope 1 m (2 nights)					
U	−0.140	0.015	$U-B$	0.406	0.026
B	−0.035	0.007	$B-V$	0.219	0.031
V	0.090	0.005	$B-V$	0.122	0.008
R	0.012	0.008	$V-R$	...	...
I	−0.039	0.006	$V-I$	...	...

at the corners. A two-dimensional "shutter image" was created by comparing long and short exposures of the dome. This image was used to correct the shutter error to better than 0.005 s everywhere on the image. The long and short images were also used to identify bad CCD pixels and low-level traps. These were masked out of the final image before the photometric measurements.

All the CCD frames were processed through the programs DAOPHOT and ALLSTAR of Stetson (1987) and Stetson (1994). These programs output pointspread function (psf) photometry of the stellar images. We also corrected the aperture photometry to a digital aperture diameter of 14″ using the program DAOGROW (Stetson 1990) to correspond to the standard photometer aperture used by Landolt (1972) and Landolt (1992).

On 10 nights we have enough photometric standards to calculate the color terms of the transformation from the natural to the standard *UBVRI* system for the 0.9 m telescope system. We have used the technique suggested by Harris, Fitzgerald, & Reed (1981). They recommend that each night be independently reduced and that the specific color terms be averaged across all the runs. Each night is then rereduced to the final photometry with the averaged color terms. We also use a transformation equation of the form $m = f(M, I, X, T)$ suggested by Harris et al. (1981) where m is the observed magnitude, M is the tabulated magnitude, I is the tabulated color index, X is the air mass, and T is the time during the night. The inclusion of the variable T allows for small and linear changes in the extinction during the night. Wintertime observations at CTIO rarely require this correction, and we found the linear coefficient of this variable consistent with zero for all 10 nights. We dropped this term from the function. We also tried a cross term of the form XI, which is the "second-order" extinction term. The averages for the 10 nights in all colors were consistent with zero and this term was also dropped. Finally, with a linear form of the function f we examined the residuals for evidence of higher order terms. Only in $U-B$ was there evidence of nonlinear residuals. The inclusion of a quadratic term in $U-B$ barely lowered the final dispersion, so we kept only the linear term in $U-B$.

We list the averaged color terms in Table 1. As an example, Table 1 indicates that $v = a_0 + V - 0.018 (B-V) + a_1 X$. The averaged extinctions in Table 1 are also listed for reference purposes: however, we used only the nightly extinctions in the reductions. The photometry used the standards of Landolt (1972) and Landolt (1992). A typical night had four to eight photometric fields with a total of ∼35 standards. The color range was usually (−0.3, 2.0) in $B-V$.

The photometry programs keep track of the total variance from the photon statistics, errors in the psf, and the errors in the tabulated magnitudes of the standard stars. The final residuals in the transformation are compared to the expected errors. For *BVRI* the measured and estimated standard deviations are the same to within 0.01 mag. For U, one must add about 0.035 mag in quadrature to the estimated error to force agreement with the observed dispersion in the residuals. This extra dispersion is another indication that the transformation of the U photometry is uncertain due to the nonstandard transmission function of the U filter/CCD system.

With the color terms fixed, we measured the local standards near NGC 3368 marked in Figure 1 for 11 photometric nights.[3] The averaged colors for the 15 local standards are given in Table 2 and represent aperture photometry with a 14″ digital aperture. The table also lists the number of independent nights of data in each color. Except for the fainter stars, the mean errors are below 0.01 mag. There are more nights of data for the stars near NGC 3368 because roughly half the data were taken with only the

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[3] There was one more photometric night used here than was used for creating the color terms. On this extra night only a few standards of limited color range were observed.

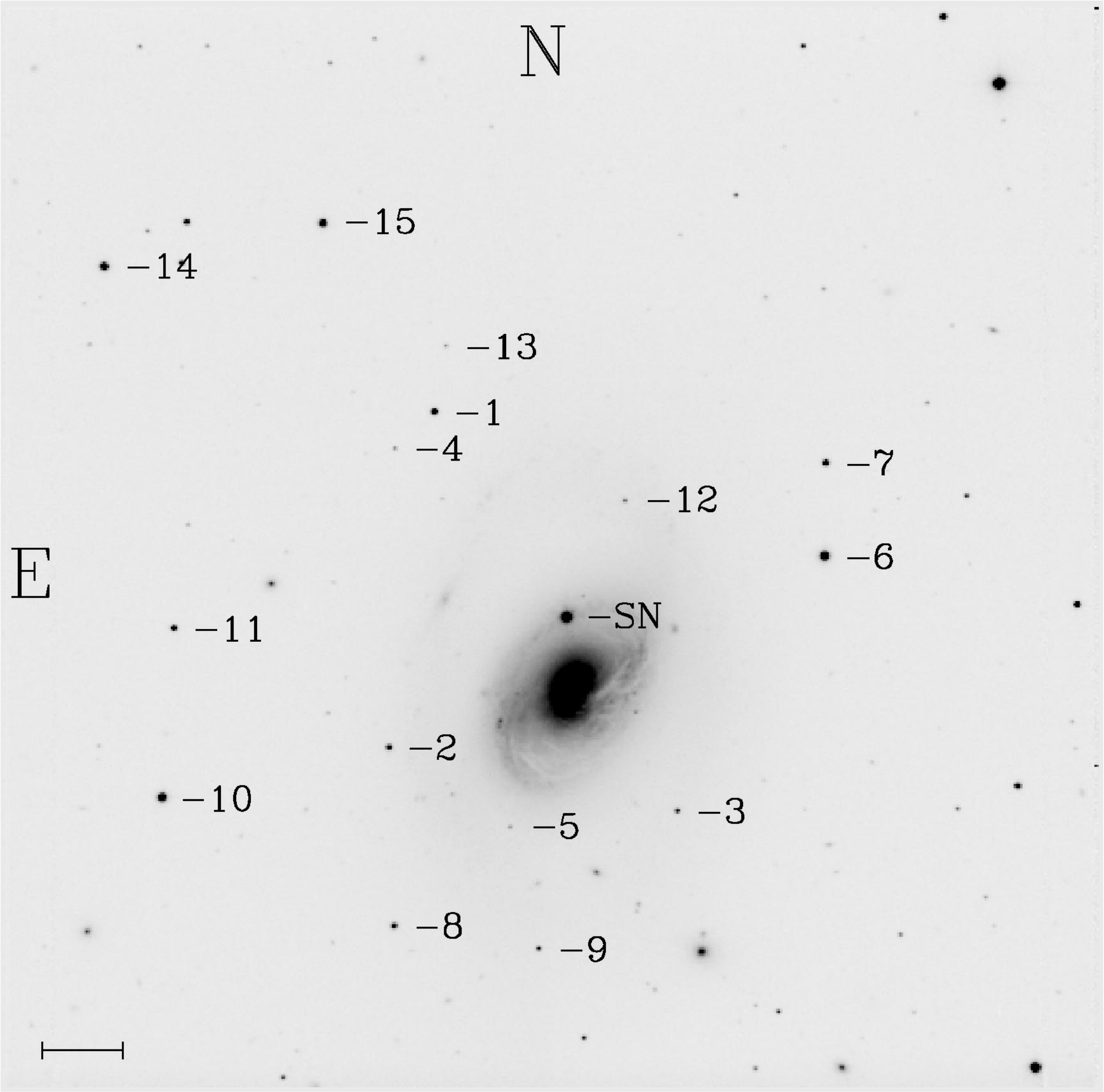

FIG. 1.—SN 1998bu in M96 (NGC 3368). The local standards listed in Table 2 are marked. This is a composite V image taken on 1998 May 17 with the CTIO 0.9 m telescope. The scale bar corresponds to 1′.

central 1024 × 1024 pixels read out. The standards 14 and 15 were added later, and the photometry of these stars was measured relative to the local stars rather from the full nightly photometric solutions. The fainter stars in the table were not used in the subsequent measurements of SN 1998bu.

In Table 1 we list the color terms derived for the Schmidt data based on one photometric night and for the LCO data based on two photometric nights. For the Schmidt data, only a single Landolt field was observed at various air masses, and the color terms should be used with caution. The errors in the color terms for the Schmidt data represent the residuals from a linear fit to the color index and X, whereas the color term errors for the 0.9 m data represent the observed night-to-night variation in the color terms. The color terms for the LCO data are the averages for the two nights.

2.3. *Photometry of SN 1998bu*

With well-determined color terms and local standards, we can now transform the psf photometry to the standard system. The psf magnitudes were fitted over a *radius* equal to the Gaussian FWHM of the stellar images, which varied from frame to frame with the seeing. The sky value for the psf fit was determined in the star subtracted image from the pixel values out to a radius of 8″.8 excluding the central few pixels at the coordinates of the star. Each frame of the supernova field was inspected for the quality of the psf fitting and sky determination around the supernova. We typically used linearly or quadratically varying psf's to achieve the highest quality fits. Each star in the psf was inspected to throw out nonstellar objects from the psf calculation.

The supernova magnitudes can be affected by the galaxy background, especially in the case where the supernova is in a spiral arm. One cannot accurately know the galaxian background until the supernova fades. When the supernova is bright, as is the case with our data, this effect is not usually a problem. The surface brightness of the spiral arm near the supernova is $UBVRI$ = (20.3, 21.8, 21.0, 20.4, 19.7) mag arcsec^{-2}. At this magnitude level, the errors introduced by assuming a uniform galaxian brightness at the

TABLE 2

Photometry of the Local Standards near NGC 3368

Name[a]	V	$B-V$	$U-B$	$V-R$	$V-I$	n				
1	14.906(02)	0.585(04)	−0.025(16)	0.367(03)	0.720(03)	11	10	9	10	10
2	15.797(04)	0.665(05)	−0.035(16)	0.422(03)	0.847(04)	11	10	9	10	10
3	16.545(04)	1.060(06)	0.902(18)	0.660(04)	1.234(04)	11	10	4	10	10
4	18.089(05)	0.466(07)	−0.265(41)	0.330(06)	0.656(05)	11	10	4	10	10
5[b]	18.535(10)	0.395(14)	−0.231(46)	0.315(09)	0.620(12)	10	9	2	9	9
6	13.088(03)	0.497(04)	−0.106(28)	0.295(07)	0.617(04)	4	4	4	3	4
7	15.028(05)	0.508(06)	−0.140(28)	0.318(07)	0.635(07)	4	4	4	4	4
8	15.453(06)	0.827(05)	0.441(24)	0.460(08)	0.885(04)	3	3	2	3	3
9[b]	17.025(11)	0.626(05)	−0.038(08)	0.410(16)	0.845(07)	3	3	2	3	3
10	13.425(03)	0.601(02)	−0.043(33)	0.373(08)	0.757(04)	5	4	3	4	4
11	15.443(04)	0.904(02)	0.591(41)	0.502(09)	0.986(08)	5	4	3	4	4
12[b]	17.762(06)	1.440(17)	...	1.031(08)	2.180(08)	10	9	0	9	9
13[b]	18.420(08)	1.050(24)	...	0.685(10)	1.250(16)	5	4	0	5	5
14[c]	13.900(03)	0.507(05)	−0.172(06)	0.331(05)	0.674(06)	14	14	14	14	14
15[c]	14.088(02)	0.598(03)	0.016(06)	0.363(04)	0.715(04)	14	14	14	14	14

[a] The mean errors are listed in units of 0.001 mag; n is the number of independent nights of (V, $B-V$, $U-B$, $V-R$, $V-I$) data.

[b] These stars were not used as local standards.

[c] These standards were calibrated relative to the other local standards.

TABLE 3

Photometry of Supernova 1998bu in NGC 3368

Day[a]	U	B	V	R	I
947.59[b]	12.000(05)	12.434(05)	12.183(05)	11.862(06)	11.696(07)
948.56[b]	11.940(07)	12.353(08)	12.092(04)	11.807(05)	11.662(05)
949.55	11.947(19)	12.299(10)	12.024(05)	11.774(07)	11.667(07)
950.58	11.916(18)	12.241(07)	11.960(03)	11.747(07)	11.667(10)
951.55	11.908(22)	12.218(04)	11.926(03)	11.735(07)	11.689(06)
951.53[c]	11.913(07)	12.207(04)	11.921(03)	11.729(05)	11.686(04)
953.48	11.973(16)	12.202(06)	11.880(04)	11.701(06)	11.718(06)
954.53	12.034(48)	12.232(19)	11.903(08)	11.716(29)	11.747(45)
957.52	...	...	...	...	11.815(15)
959.47	12.444(46)	12.450(16)	11.998(09)	11.855(17)	11.982(19)
960.46	12.542(30)	...	12.075(06)	11.959(15)	12.087(07)
964.45	12.950(24)	12.872(09)	12.323(06)	12.279(07)	12.349(17)
965.50	13.066(25)	12.972(11)	12.390(06)	12.346(08)	12.380(09)
968.46	13.509(27)	13.316(12)	12.570(09)	12.432(13)	12.341(15)
971.46	...	...	12.711(07)	12.453(08)	12.286(08)
972.50	...	...	12.751(04)	12.450(06)	12.242(07)
975.48	...	...	12.919(04)	12.487(06)	12.181(05)
978.49	...	...	13.071(05)	12.551(07)	12.124(07)
983.47	15.212(25)	14.825(11)	13.426(09)	12.861(24)	12.298(09)
984.48	15.292(25)	14.869(11)	13.505(07)	12.938(07)	12.374(08)
987.52	15.355(47)	15.010(19)	13.679(10)	13.153(19)	12.562(18)
988.45	15.473(26)	15.069(08)	13.725(04)	13.208(07)	12.696(06)
997.48	15.673(47)	15.291(15)	14.041(06)	13.608(08)	13.214(10)
997.50	15.645(48)	15.315(15)	14.051(06)	13.612(07)	13.214(07)
998.46	15.677(44)	15.326(07)	14.071(04)	13.637(04)	13.263(06)
999.48	15.698(29)	15.346(07)	14.102(04)	13.684(05)	13.320(06)
1000.48	15.678(50)	15.345(14)	14.121(07)	13.713(09)	13.356(09)
1002.47	15.790(51)	15.383(14)	14.189(07)	13.785(08)	13.461(08)
1003.50	15.813(54)	15.404(15)	14.200(07)	13.810(09)	13.521(08)
1004.46	15.780(49)	15.410(14)	14.222(08)	13.839(10)	13.562(09)
1005.45	15.802(51)	15.436(14)	14.257(08)	13.884(10)	13.607(10)
1006.46	15.833(29)	15.444(14)	14.285(07)	13.910(09)	13.654(08)
1007.45	15.828(46)	15.467(13)	14.321(06)	13.953(08)	13.700(07)
1008.45	15.864(47)	15.486(13)	14.349(07)	13.984(07)	13.762(11)

[a] Date given as JD −2,450,000. Mean error listed in units of 0.001 mag.

[b] LCO Swope data.

[c] Curtis Schmidt data.

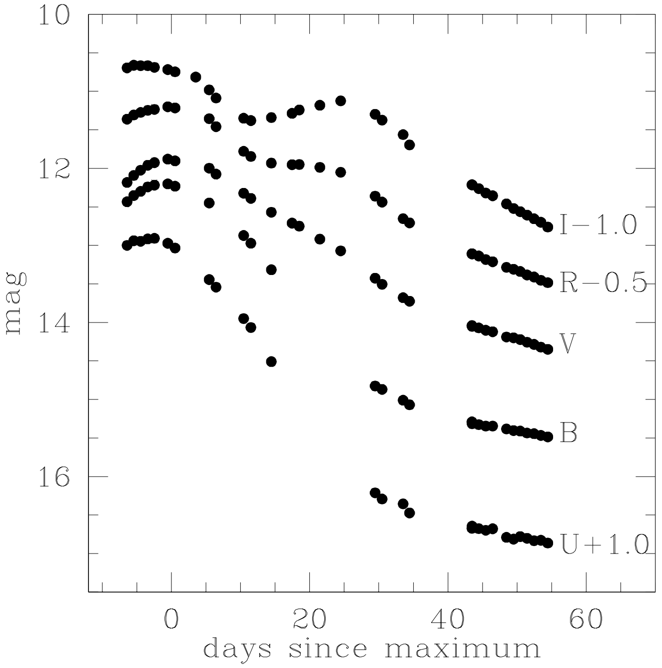

FIG. 2.—*UBVRI* light curves for SN 1998bu from Table 3. The magnitude scales for *URI* have been shifted by the amount shown in the figure. The first two points are from data taken at LCO.

position of the supernova are small. For instance, if the supernova happens to be in a region of twice the galaxian brightness inside an aperture of diameter 3″.2, the faintest magnitudes in Table 3 will decrease by (0.13, 0.03, 0.02, 0.02, 0.03) magnitudes.

The final *UBVRI* photometry of SN 1998bu is given in Table 3. The light curves are plotted in Figure 2 and the color curves in Figure 3. The errors in Table 3 combine the errors in the psf fits, the errors in the color terms, and mean error of the photometric zero point in each frame. In many cases these errors are less than 0.01 mag. We note that while the mean error of the photometric zero point is typically less than 0.01 mag, the typical scatter of the standards around the mean is more like 0.01–0.015 mag. The zero point is more accurate because we have 4–10 standards per field. We regard this typical scatter of 0.01 mag as a more realistic minimum error of a single observation of the supernova.

Finally, we caution the readers that *the U photometry should be considered uncertain due to the nonstandard U filter + CCD transmission. Systematic errors of a few 0.1 mag could be present especially in the late-time data.* Such a systematic error due to a nonstandard bandpass was seen in the photometry of SN 1987A (Suntzeff et al. 1988; Menzies 1989; Hamuy et al. 1990), where differences of 0.3 mag were seen in *I*.

3. DISCUSSION AND CONCLUSIONS

From Figure 2 we see that the supernova was caught before maximum. Peak magnitudes in *UBVRI* were measured directly via low-order polynomial fits to the photometry near maximum. These fits are summarized in the first three columns of Table 4. As seen in other well-observed type Ia supernovae (SNe Ia), maximum light in *U* was reached ∼1–2 days before *B* maximum, which, in turn, occurred ∼1–2 days before the *V* and *R* maxima. Maximum light in *I* clearly took place *before U* maximum; our observations seem to have started just before *I* maximum.

To measure the initial decline rate of the *B* light curve, we employ the parameter $\Delta m_{15}(B)$, defined by Phillips (1993) as the amount in magnitudes that the *B* light curve decays in

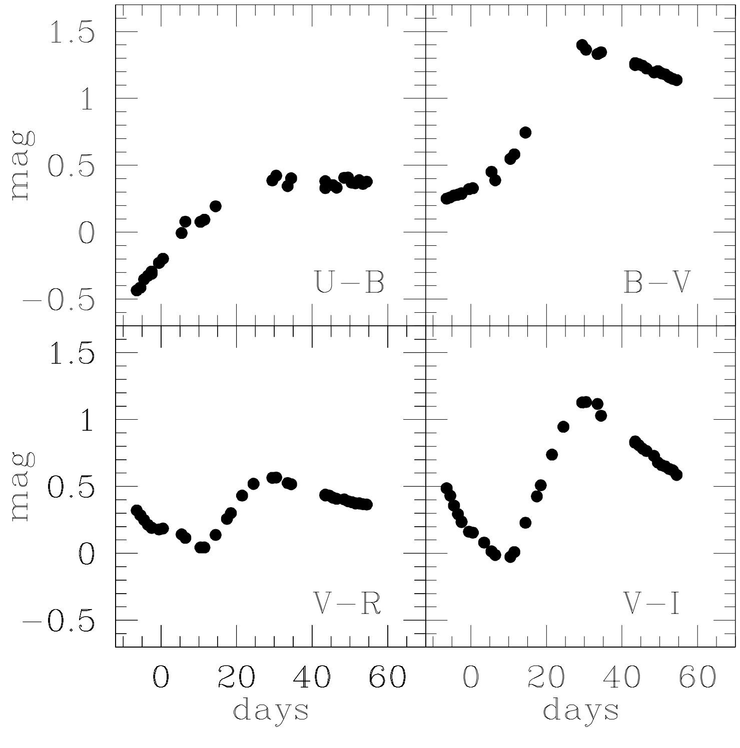

FIG. 3.—Color curves for SN 1998bu from Table 3. The red colors at maximum light for a supernova with a normal $\Delta m_{15}(B)$ indicate a substantial reddening for this object.

TABLE 4

PEAK PHOTOMETRIC MAGNITUDES OF SUPERNOVA 1998bu

Filter	$T_{\max}$ [a]	m(obs) [b]	m(corr) [c]	M(corr) [d]
U......	951.1(0.5)	11.91(03)	10.21(14)	−20.16(22)
B......	952.9(0.5)	12.20(03)	10.70(13)	−19.67(20)
V......	954.1(0.5)	11.88(03)	10.74(10)	−19.63(19)
R......	953.5(0.5)	11.70(03)	10.78(08)	−19.59(18)
I.......	949.5(1.0)	11.67(05)	11.01(07)	−19.36(18)

[a] Date of maximum light given as JD −2,450,000. Mean error listed in units of days.

[b] Apparent magnitude. Mean error listed in units of 0.01 mag.

[c] Apparent magnitude corrected for Galactic and host galaxy reddening. Mean error listed in units of 0.01 mag.

[d] Absolute magnitude corrected for Galactic and host galaxy reddening. Mean error listed in units of 0.01 mag.

the first 15 days after maximum light. For well-observed events such as SN 1998bu, $\Delta m_{15}(B)$ can be measured directly from a polynomial fit to the photometry. We find $\Delta m_{15}(B) = 1.01 \pm 0.05$, close to the preliminary estimates of Schaefer (1998).

The red color ($B-V \sim 0.3$) of SN 1998bu at maximum is indicative of significant dust reddening, consistent with the strong Na I D and Ca II interstellar absorption lines observed by Munari et al. (1998) and Centurion et al. (1998). From the dust maps of Schlegel, Finkbeiner, & Davis (1998), the Galactic reddening is estimated to be $E(B-V) = 0.025 \pm 0.003$. Hence, the majority of the reddening must have been produced in the host galaxy of SN 1998bu, NGC 3368. Using the methodology of Phillips et al. (1999), which is based on the $B-V$ and $V-I$ color evolution of the SN, and assuming a Galactic reddening equal to the Schlegel et al. value, we derive a host galaxy reddening of $E(B-V) = 0.34 \pm 0.03$. We note that this value is more than twice the amount estimated by Munari et al. (1998) from the equivalent widths of the Na I D lines. The Munari & Zwitter (1997) empirical calibration assumes a single-line component to the Na I D equivalent width. Multiple components have the effect of desaturating the line, which means that reddening based on a given equivalent width for the single-line component analysis should be an *upper limit*. This is inconsistent with the reddening measured from the supernova colors. We await the publication of the interstellar line data to explore this matter further.

In the fourth column of Table 4, the reddening-corrected peak magnitudes of SN 1998bu are given assuming a standard Galactic reddening law. The distance to NGC 3368 (M96) has been measured by Tanvir et al. (1995) from Cepheid variables discovered and observed with the *Hubble Space Telescope* (*HST*). These authors derived a *true* distance modulus of $(m-M)_0 = 30.32 \pm 0.16$ mag. To this value, an offset of +0.05 mag should be added to correct for the "long" versus "short" exposure zero point (see Silbermann et al. 1998 and references therein). Combining this distance with our reddening-corrected peak magnitudes for SN 1998bu gives the absolute magnitudes listed in the final column of Table 4.

In Table 5, which is an updated version of Table 2 from Hamuy et al. (1996b), we summarize the data for the four other well-observed SNe Ia with *HST* Cepheid-derived host galaxy distances, as well as for three SNe whose host galaxies are members of a group or cluster for which at least one *HST* Cepheid distance is available. By "well-observed," we mean those SNe for which the photometry are sufficiently precise to allow derivation of a reliable value of the decline rate parameter $\Delta m_{15}(B)$. For completeness, the data for SN 1998bu are repeated in Table 5, which has the following format:

Column (*1*).— SN name.

Column (*2*).— the name of the host galaxy.

Column (*3*).— the true distance modulus of the host galaxy, or for the group/cluster to which the host galaxy belongs.

Column (*4*).— references to the distance moduli given in column (3).

Columns (*5*), (*6*), *and* (*7*).— the apparent BVI peak magnitudes of the SN as determined from the light curves.

Column (*8*).— the observed value of the decline rate parameter $\Delta m_{15}(B)$.

Column (*9*).— references to the SN photometry.

Column (*10*).— the Galactic reddening $E(B-V)$ derived from the dust maps of Schlegel et al. (1998).

Column (*11*).— the host galaxy reddening $E(B-V)$ as given by Phillips et al. (1999).

Columns (*12*), (*13*), *and* (*14*).— the absolute BVI peak magnitudes of the SN as calculated from the apparent magnitudes, the distance modulus of the host galaxy, and the Galactic and host galaxy reddenings.

There is now abundant evidence (see Hamuy et al. 1996a and references therein) that the absolute luminosities of SNe Ia are a function of the decline rate parameter $\Delta m_{15}(B)$. Hence, to derive the Hubble constant, H_0, from SN 1998bu and the other SNe listed in Table 5 we must use Hubble relations corrected for this effect. We assume the reddening-corrected fits given by Phillips et al. (1999), which leads to the following expressions for H_0 in BVI:

$$\begin{aligned}\log H_0(B) &= 0.2\{M_{\max}^B - 0.720[\Delta m_{15}(B) - 1.1] \\ &\quad - 1.010[\Delta m_{15}(B) - 1.1]^2 + 28.653\}\ , \\ \log H_0(V) &= 0.2\{M_{\max}^V - 0.672[\Delta m_{15}(B) - 1.1] \\ &\quad - 0.633[\Delta m_{15}(B) - 1.1]^2 + 28.590\}\ , \\ \log H_0(I) &= 0.2\{M_{\max}^I - 0.853[\Delta m_{15}(B) - 1.1] + 28.219\}\ .\end{aligned}$$

It should be noted that the observed decline rate of a SN Ia is a weak function of the dust extinction that affects the light curves (Leibundgut 1988), and so the values of $\Delta m_{15}(B)$ used in the above equations should be corrected for this effect. We use the following approximate relation given by Phillips et al. (1999):

$$\Delta m_{15}(B)_{\rm true} \simeq \Delta m_{15}(B)_{\rm obs} - 0.1{\rm E}(B-V)\ .$$

Table 6 lists the resulting values of H_0 for each of the SNe with a Cepheid distance. Note that the errors in this table are internal—i.e., they include the error contributions due to the apparent magnitude measurements, reddening estimates, distance modulus, absolute magnitude versus decline rate relation, Hubble diagram zero point, and the dispersion in the Hubble diagram only. To these must be added the external uncertainty in the zero point of the Cepheid calibration, which we take to be ±0.12 mag (±3.5 km s^{-1} Mpc^{-1} in terms of H_0).

Table 6 shows that the five SNe with *HST* Cepheid distances give results that are in excellent agreement, yielding a weighted average value of $H_0 = 63.9 \pm 2.2$ km s^{-1} Mpc^{-1}, with an unweighted dispersion of only 2.0 km s^{-1} Mpc^{-1}.

TABLE 5

TYPE Ia SUPERNOVAE WITH *HST* CEPHEID DISTANCES

SN (1)	Host (2)	$(m-M)_0$ [a] (3)	References (4)	$B_{\rm max}$ [b] (5)	$V_{\rm max}$ [b] (6)	$I_{\rm max}$ [b] (7)	$\Delta m_{15}(B)$[b] (8)	References (9)	$E(B-V)_{\rm Gal}$ [c] (10)	$E(B-V)_{\rm Host}$ [b] (11)	$M^B_{\rm max}$ [b] (12)	$M^V_{\rm max}$ [b] (13)	$M^I_{\rm max}$ [b] (14)
Cepheid Distance to Host													
1937C…….	IC 4182	28.31(11)	1	8.80(09)	8.82(11)	…	0.87(10)	8	0.014(001)	0.03(02)	−19.69(17)	−19.63(17)	…
1972E…….	NGC 5253	27.92(08)	2	8.49(14)	8.49(15)	8.80(19)	0.87(10)	8	0.056(006)	0.01(02)	−19.69(18)	−19.63(18)	−19.24(21)
1981B…….	NGC 4536	31.10(13)	3	12.03(03)	11.93(03)	…	1.10(07)	8	0.018(002)	0.12(02)	−19.63(17)	−19.59(15)	…
1990N ……	NGC 4639	32.03(23)	4	12.76(03)	12.70(02)	12.94(02)	1.07(05)	9	0.026(003)	0.09(02)	−19.76(25)	−19.70(24)	−19.30(23)
1998bu……	NGC 3368	30.37(16)	5	12.20(03)	11.88(03)	11.67(05)	1.01(05)	10	0.025(003)	0.34(03)	−19.67(20)	−19.63(19)	−19.36(18)
Cepheid Distance to Group/Cluster													
1980N ……	NGC 1316	31.34(20)	6	12.49(03)	12.44(03)	12.70(04)	1.28(04)	8	0.021(002)	0.05(02)	−19.15(22)	−19.12(21)	−18.77(21)
1989B…….	NGC 3627	30.22(25)	5, 7	12.34(05)	11.99(05)	11.75(05)	1.31(07)	11	0.032(003)	0.37(03)	−19.55(28)	−19.50(27)	−19.21(26)
1992A…….	NGC 1380	31.34(20)	6	12.57(03)	12.58(03)	12.85(03)	1.47(05)	8	0.017(002)	0.00(01)	−18.84(21)	−18.81(20)	−18.52(20)

[a] Corrected to "long" exposure zero point.

[b] Mean error listed in units of 0.01 mag.

[c] Mean error listed in units of 0.001 mag.

REFERENCES.—(1) Saha et al. 1994; (2) Saha et al. 1995; (3) Saha et al. 1996; (4) Saha et al. 1997; (5) Tanvir et al. 1995; (6) Silbermann et al. 1998; (7) Graham et al. 1997; (8) Hamuy et al. 1996b and references therein; (9) Lira et al. 1998; (10) this paper; (11) Wells et al. 1994.

TABLE 6

VALUES OF H_0

SN	$H_0(B)$	$H_0(V)$	$H_0(I)$	H_0(avg)
Cepheid Distance to Host				
1937C	65.4(8.0)	65.7(7.8)	...	65.5(5.6)
1972E	65.3(8.1)	65.6(8.0)	68.7(9.1)	66.3(4.8)
1981B	64.0(7.0)	63.2(6.6)	...	63.6(4.8)
1990N	60.9(8.4)	60.7(8.1)	61.7(8.3)	61.1(4.8)
1998bu	64.7(8.0)	64.2(7.6)	62.0(7.2)	63.6(4.4)
Cepheid Distance to Group/Cluster				
1980N	74.2(9.8)	73.5(9.3)	72.5(9.1)	73.3(5.4)
1989B	61.6(9.7)	61.9(9.4)	59.3(8.7)	60.9(5.3)
1992A	76.2(12.1)	77.3(11.4)	75.3(9.7)	76.2(6.3)

The three SNe with Cepheid group/cluster show more scatter, yielding a somewhat higher weighted average of 69.4 ± 3.3 km s^{-1} Mpc^{-1}. A weighted average of all eight SNe gives $H_0 = 65.6 \pm 1.8$ km s^{-1} Mpc^{-1}. These values are very similar to most other recent estimates of H_0 based on SNe Ia (e.g., Hamuy et al. 1995; Riess et al. 1995; Hamuy et al. 1996a; Riess et al. 1996; Phillips et al. 1999).

Interestingly, the two most discrepant objects correspond to the Fornax cluster SNe, 1980N and 1992A, suggesting that the barred spiral galaxy NGC 1365 whose distance modulus we have taken to be that of the cluster may actually be foreground by ∼0.3 mag. This discrepancy is illustrated graphically in Figure 4, where we plot the absolute magnitudes given in Table 5 as a function of the decline rate parameter $\Delta m_{15}(B)$. Also plotted as dotted crosses in Figure 4 are the reddening-corrected absolute magnitudes for 35 SNe Ia in the Hubble flow ($0.01 \leq z \leq 0.1$) for which distances were calculated from the observed radial velocities (corrected to the cosmic microwave background reference frame) and an assumed Hubble constant of $H_0 = 65$ km s^{-1} Mpc^{-1}. The dashed lines show the fits derived by Phillips et al. (1999) to the latter data. Note that both Fornax cluster SNe lie systematically lower than these fits by ∼0.3 mag in all three colors.

According to Silbermann et al. (1998), the *HST* Key Project on the Extragalactic Distance Scale collaboration has recently observed two other spiral galaxies considered to be members of the Fornax cluster, NGC 1425 and NGC 1326A. It will be very interesting to see if the Cepheid variables discovered in these galaxies give true distance moduli closer to 31.6–31.7 as suggested by the SNe data. We also await with interest the results of the *HST* observations announced by Saha et al. (1997) of the host galaxy of SN 1989B, NGC 3627, which should yield a direct measurement of the distance to this SN. Not only should these new distances provide more precise estimates of the Hubble constant, but, as shown in Figure 4, they will be extremely useful for confirming the shape of the absolute magnitude versus $\Delta m_{15}(B)$ relation over a wide range of decline rates.

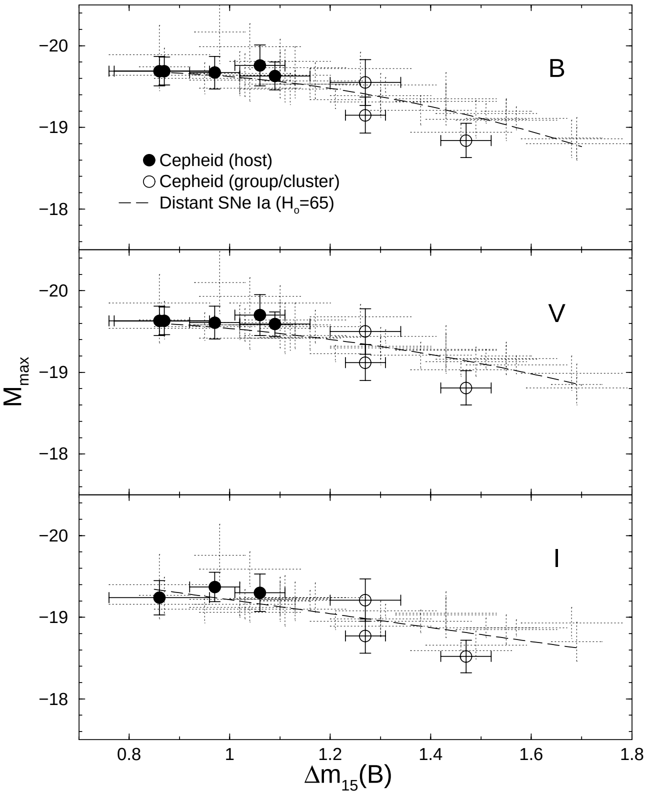

FIG. 4.—Absolute magnitudes in *BVI* for Type Ia supernovae as a function of the Phillips (1993) parameter $\Delta m_{15}(B)$. The filled circles correspond to the five SNe that occurred in host galaxies with *HST* Cepheid distances. The open circles are SNe, which are members of groups or clusters for which at least one *HST* Cepheid distance is available. The dotted crosses are 35 SNe Ia in the Hubble flow whose distances were derived from their radial velocities and an assumed Hubble constant of $H_0 = 65$ km s^{-1} Mpc^{-1}, and the dashed lines are fits to these data from Phillips et al. (1999).

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