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THE HUBBLE DIAGRAM FOR SUPERNOVAE OF TYPE Ia. II. THE EFFECT ON THE HUBBLE CONSTANT OF A CORRELATION BETWEEN ABSOLUTE MAGNITUDE AND LIGHT DECAY RATE

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ABSTRACT

New Hubble diagrams in B and V are derived for supernovae of type I based on light curves from the archive literature plus 13 new light curves with superior modern photometry observed in the Cerro Tololo/University of Chile program (Hamuy et al. 1995). The sample is restricted to SNe Ia whose light curves are defined by photometry beginning 5 days or less after maximum light and with $(B-V)_{\max} < 0.5$ mag. Supernovae of known type Ib or Ic are also excluded.

The resulting Hubble diagrams, extending to redshifts of 30,000 km s^{-1}, have dispersions in absolute magnitude of 0.34 mag in B and 0.33 mag in V, confirming that spectroscopically "normal" (Branch et al. 1993) SNe Ia are among the best standard candles known.

A solution for the slope of the Hubble diagram gives $n(B) = 0.977 \pm 0.025$ and $n(V) = 1.020 \pm 0.024$ for the exponent in $v \sim D^n$, proving linearity of the expansion field to a high level.

The residuals in magnitude from the ridge line of the Hubble diagram are compared with the light decay rate during the first 15 days to test the correlation between the two suggested by Pskovskii and by Phillips. The strongest possible correlation using the extant data has a slope 3 times smaller than that derived by Phillips, and 2 times smaller than suggested by Hamuy et al., leading to a decrease of less than 10% in the distance scale based on the present (1995) SNe Ia calibration by means of three supernovae whose distances are known from Cepheids in their parent galaxies.

Applying the maximum possible correction to M(max) for a Pskovskii-Phillips effect would give Hubble constants of

$$H_0(B) \leqslant 54 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1} ,$$

and

$$H_0(V) \leqslant 59 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1} ,$$

where the errors are internal. It is argued that the absence of measurable bias effects in the Hubble diagrams shows that the three local (nearest) SNe Ia presently calibrated via Cepheid distances cannot all be overluminous relative to the average of more distant SNe. If they are *underluminous*, which must be the case by the statistics of the Malmquist effect if the large dispersion in M(max) for SNe Ia claimed by Hamuy et al. applies to the calibrators, then the value of $H_0 = 52$ km s^{-1} Mpc^{-1} given by Saha et al. is an *upper* limit to the Hubble constant.

Subject headings: cosmology: observations — distance scale — supernovae: general

1. INTRODUCTION

The purpose of this paper is to continue the analysis of Hubble diagrams in B and V of supernovae of type Ia (SNe Ia) begun in Paper I (Sandage & Tammann 1993). The Hubble diagrams are needed for the *Hubble Space Telescope* (*HST*) experiments whose aim is to determine the Hubble constant via a calibration of M(max) for supernovae relative to Cepheids.

Criticisms of the method have been made on two levels. Van den Bergh & Pazder (1992) and van den Bergh (1993) argue that the dispersion of M(max) for SNe Ia is so large that the method of photometric parallaxes using SNe Ia is not useful for the distance-scale problem at all. A more moderate but still critical position is taken by Phillips (1993) and by Hamuy et al. (1995). They reintroduce the proposition that the absolute magnitude at maximum for SNe Ia is a nonnegligible function of the decay rate of the light curve, updating the original suggestion by Pskovskii (1977, 1984).

The correlation suggested by Phillips between absolute magnitude and the Δm_{15} decline rate in magnitudes at 15 days after maximum is based on relative absolute magnitudes of nine supernovae determined by applying the Tully-Fisher (TF) and the surface brightness fluctuation (SBF) methods to the parent galaxies to determine their distance ratios. Three of the nine (SN 1986G, 1991T, and 1991bg) used by Phillips are not prototypical type Ia SNe according to the criteria of Branch, Fisher, & Nugent (1993), hereafter called "Branch-normal." The peculiarities of these three SNe have been discussed elsewhere (Branch & Tammann 1992; Sandage & Tammann 1993; Leibundgut et al. 1993).

Their nonnormality excluded them from the analysis made in the first two *HST* experiments (Sandage et al. 1992, 1994; Saha et al. 1994, 1995). Such remaining normal SNe form the core of the Phillips correlation diagram (his Fig. 1). This core is sharply constrained in (relative) absolute magnitude, and it is this sample that the *HST* experiment are designed to calibrate, all "non–Branch-normal" SNe Ia being excluded.

Nevertheless, as more has been learned of the SN Ia phenomenon, a consensus is growing that there may in fact be a continuum in the properties of SNe Ia, including a variation of the decay rate and a concomitant variation in absolute magnitude even among Branch-normal SNe Ia. Branch & Khokhlov (1994) write, "Observations indicate that Type Ia supernovae can be arranged in a sequence ranging from peculiar powerful explosions like SN 1991T through the nearly homogeneous normal ones like 1981B and 1989B to peculiar weak events like 1991bg. The powerful SNe Ia are observationally and intrinsically uncommon, the normal ones are observationally and intrinsically common, and weak events are observationally uncommon but intrinsically common." Although we do not know about the normality (in the sense of Branch et al. 1993) of all the SNe that we have used in the Hubble diagrams in Paper I and now here, it is nevertheless clear that they are "intrinsically common." Contamination of the distant sample by "abnormal" events can be only by some "powerful" (and uncommon) SNe. But in that case the resulting value of H_0 we derive can only be too high (also discussed later in § 3). Hence, the criticisms of van den Bergh (1993), and to a lesser degree of Phillips (1993), are moot concerning our first two *HST* experiments that have calibrated three very *local* SNe Ia.

The absolute magnitude-decay-rate slope obtained by Phillips (his Fig. 1) is $dM_B/d\Delta m_{15} = 2.7$ for *B*-band magnitudes and 1.95 for *V*-band magnitudes. This very strong dependence was used by Pierce & Jacoby (1994, 1995) to argue that the HST calibration of SN 1937C (Sandage et al. 1992; Saha et al. 1994), when combined with their reanalysis of the light curve of SN 1937C using only highly selected data, gave back their (Jacoby et al. 1992) short distance scale with $H_0 = 74 \pm 6$. They gave no countenance to the totality of the available data for 1937C other than their own reconstruction of Baade's photometry near maximum, nor did they use the data from the second *HST* supernovae experiment for SN 1895B and 1972E (Sandage et al. 1994, 1995) that would have countered their conclusion.

Hamuy et al. (1995) added 13 newly observed SN light curves to the data used by Phillips (1993) and derived again a correlation between absolute magnitude and decay rate, but with half the original slope. Their analysis is based on deviations in magnitude from the Hubble (*m*, log *v*) diagram made with their newly discovered SNe, combined with the nine SNe with distances adopted by Phillips using the TF and the SBF methods.

Our concerns about Figure 1 of Phillips are based on (1) his inclusion of non–branch-normal SNe Ia, and (2) his adopted distances based on the TF and surface brightness fluctuation photometric methods, each of which we believe contains the same photometric bias errors when the distance-limited calibrating samples are applied to flux-limited catalogs. This relative distance scale is distorted by distance-dependent observational selection bias effects (Sandage 1988a, b, 1994a, b; Kraan-Korteweg, Cameron, & Tammann 1988; Federspiel, Sandage, & Tammann 1994). Said differently, the nearby galaxies are common. These that enter the catalogs that probe more distant regions are uncommonly bright on average, otherwise they would not have entered the lists, and the larger the distance, the greater the brightness, and the larger the error in distance if all luminosities are assumed to be the same.

On the other hand, *relative* distances determined from redshifts are free of such selection effects. It is our proposition that *redshift* distance ratios are more accurate than *photometric* distance ratios because the local velocity field is astonishingly quiet (Sandage 1986; Jerjen & Tammann 1993). This is even more true in our sample that is restricted to SNe in parent galaxies with $v > 1100$ km s^{-1} as corrected for Virgocentric infall.

If a continuum of SNe Ia properties does indeed exist, even among the Branch-normal SNe that are observationally and intrinsically common, four questions must be addressed. (1) Does a variation of decay rate in fact exist among SNe Ia, (2) if so, is there a correlation of *M*(max) with that rate, (3) if yes, what is its slope, and (4) what is its effect on the value of the Hubble constant using the results of the three extant *HST* experiments? The purpose of this paper is to address these four questions.

2. THE HUBBLE DIAGRAM FOR TYPE Ia SUPERNOVAE

2.1. *The Sample*

The new photometric data, especially those by Hamuy et al. (1995), are now becoming sufficient that we can restrict the sample to those SNe I events (excluding only Ib and Ic) observed within 5 days of (inferred) maximum *B* light, and also with $v_{220} > 1100$ km s^{-1}. With these restrictions, plus the additional restriction that the color at maximum, if known, be bluer than $(B-V) = 0.5$ mag (Vaughan et al. 1995; Hamuy et al. 1995 for similar restrictions; see below), we have used the sample in Table 1 to define the Hubble diagram in *B* and *V*.

Our present sample is more selective than that used in Paper I because of the 5 day restriction on the light curve. The availability of photometry so close to maximum makes the determination of *B*(max) and *V*(max) nearly independent of any adopted template light curve. Furthermore, although a template fit is still necessary in some cases to interpolate the data at 15 days after maximum to determine Δm_{15}, that determination is more dependent on the time of maximum than on the shape of the template (see below). Furthermore, the actual photometric data at 15 days after maximum can often be used directly, provided that the epoch of maximum is accurately known, dispensing even with the need for a template to determine Δm_{15}.

The criteria for the sample selection in Table 1 are as follows:

1. In addition to all SNe of type I with $v_{220} > 1100$ km s^{-1} (Kraan-Korteweg 1986), those in Virgo cluster galaxies are also included. For them, we adopt the single value of v_{220}(cosmic) = 1179 km s^{-1} (Jerjen & Tammann 1993), neglecting any depth effect of the cluster. The catalogs and literature references from which the list is compiled are Tammann & Leibundgut (1990), Sandage & Tammann (1993), Barbon, Cappellaro, & Turatto (1989),[1] Phillips (1993), Maza et al. (1994), and Hamuy et al. (1995).

[1] For the seven SNe from this source, no epochs of the individual observations are available. The condition "within 5 days of *B* maximum" is therefore waived.

TABLE 1

SUPERNOVAE OF TYPE Ia IN THE VIRGO CLUSTER AND BEYOND OBSERVED NOT LATER THAN FIVE DAYS AFTER MAXIMUM[a]

SN (1)	Galaxy (2)	Type (3)	log v_{220} (4)	m_B(max) (5)	m_V(max) (6)	Δm_{15} (7)	Reference (8)
1939A.......	NGC 4636	E/S0	3.072*	...	12.2:	...	1
1954B.......	NGC 5668	Sc	3.273	(12.9:)	...	...	1
1956A.......	NGC 3992	Sb	3.161	(12.7:)	12.5	...	1
1959C.......	UGC 8263	Sc	3.512	13.7	13.8	...	1
1960F.......	NGC 4496	Sc	3.072*	...	11.8	...	1
1960R.......	NGC 4382	S0 pec	3.072*	...	11.7:	...	1
1961D	M + 05 − 30 − 101	E/S0	3.894	(16.5:)	16.7	...	1
1962A.......	M + 05 − 31 − 132	E/S0	3.804	(15.6:)	15.7	...	1
1962E.......	M + 04 − 27 − 10	E	4.154	(17.4:)	17.5:	...	1
1963D	NGC 4146	Sa	3.825	(16.1:)	...	...	1
1963P.......	NGC 1084	Sc	3.150	14.0	...	...	1
1964E.......	NGC 6983	Sc pec	3.178	12.6	12.1:	...	1
1965I........	NGC 4753	S0 pec	3.211	12.5:	12.7:	...	1
1966K	NGC 3074	S0	3.992	(17.0:)	17.0:	...	1
1967C.......	NGC 3389	Sc	3.185	13.3	13.3	...	1
1969C.......	NGC 3811	Sc	3.538	14.15	14.1	...	1
1970J	NGC 7619	E	3.589	14.35	14.6	(1.3)	1
1971G	NGC 4165	Sb	3.337	14.2	14.2	...	1
1971L.......	NGC 6384	Sb	3.284	13.1	12.6	...	1
1972J	NGC 7634	E	3.512	14.35	14.6	...	1
1973N	NGC 7495	Sc	3.698	15.4	15.1	...	1
1974J	NGC 7343	Sc	3.882	15.65	15.9	...	1
1975N	NGC 7723	Sb	3.270	13.65	13.45	(1.1)	1
1976J	NGC 977	S	3.650	15.05	15.15	(0.9)	1
1979B.......	NGC 3913	Sc	3.127	12.7	12.4	...	1
1980N	NGC 1316	Sa pec	3.158	12.49	12.44	1.28	2
1981B.......	NGC 4536	Sbc	3.072*	12.00	11.96	1.10	3
1981D	NGC 1316	Sa pec	3.158	12.59	12.40	1.28	2
1982W......	NGC 5485	S0 pec	3.382	14.5:	...	...	4
1983G	NGC 4753	S0 pec	3.211	13.1	12.8	...	1
1983R.......	IC 1731	Sc	3.572	14.4:	...	...	4
1984A.......	NGC 4419	Sa	3.072*	12.3	12.2	(1.2)	1
1986A.......	NGC 3367	Sc	3.511	14.4:	...	...	4
1987D	UGC 7370	Sbc	3.312	13.7:	...	...	4
1990N	NGC 4639	Sb	3.072*	12.70	12.61	1.01	5
1990af	Anon	S0	4.176	17.86	17.81	1.56	6
1991T.......	NGC 4527	Sb	3.072*	11.64	11.48	0.94	7, 8
1991ag	IC 4919	Sb	3.621	14.72	14.62	0.94	6
1992A.......	NGC 1380	S0/a	3.158	12.60	12.55	1.33	7
1992P.......	IC 3690	Sa	3.879	16.11	16.13	1.17	6
1992ae	Anon	...	4.351	18.50	18.42	1.18	6
1992aq	Anon	...	4.485	19.34	19.25	1.32	6
1992bc	ESO 300-G9	Sab	3.781	15.17	15.24	0.82	6
1992bo......	ESO 352-G97	E/S0	3.753	15.86	15.85	1.72	6

[a] Excluding supernovae with $(B-V)_{\rm max} > 0.3$.

REFERENCES.—(1) Leibundgut et al. 1991b; (2) Hamuy et al. 1991; (3) Buta & Turner 1983; (4) Barbon et al. 1989; (5) Leibundgut et al. 1991a; (6) Hamuy et al. 1995; (7) Phillips 1993; (8) Ford et al. 1993.

2. The published light curves have been reexamined. Those that were judged to be too uncertain are SNe 1955B, 1962J, 1963J, and 1983U.

3. The SNe Ia 1991M and 1992G have not been included because Ford et al. (1993) have determined an absorption of $A_V > 0.5$ mag for them.

4. SNe with $(B-V)_{\rm max} > 0.5$ mag at B(max) are excluded so as to guard against intrinsic absorption and/or blatant intrinsic peculiarity. All but two in the sample have $(B-V)_{\rm max} < 0.3$. The colors of the two redder ones with $(B-V) = 0.5$ are in fact uncertain. However, their position in the Hubble diagrams (Fig. 1 here) belie absorption problems.

Note also that many of the SNe in the sample that remain have no $(B-V)_{\rm max}$ values. The sample in Table 1 may therefore still be "contaminated" by red objects. An obvious candidate is 1963P.

Finally, we have not used any spectroscopic information in the definition of the sample (beyond the restriction in color). Therefore, our sample contains SN 1991T, which was very peculiar in its early phases based on its spectra (see Branch & Tammann 1992; Branch & Khokhlov 1994). The exclusion of SNe known to be "Branch-*abnormal*" would have eliminated this intrinsically bright SN from the sample for spectroscopic reasons.

Column (4) of Table 1 lists the log redshift reduced to the kinematic system of the Virgo Cluster (Kraan-Korteweg 1986). This is the appropriate kinematic system for all but five of the most distant SNe because the "local bubble" for $v < 6000$ km s^{-1} is, to first approximation, in bulk motion toward the microwave background (Tammann & Sandage 1985; Federspiel et al. 1994). No corrections beyond $\sim$6000 km s^{-1} are justified because the details are unknown as to how the bulk motion peters out into the undisturbed Hubble flow (Federspiel et al. 1994), and because the galaxies at these distances presumably partake in the peculiar motion of other bubbles. If the peculiar motions of galaxies over large scales amount to $\sim$450 km s^{-1}, they affect the observed redshifts by less than 8%. This introduces a scatter in absolute magnitude of less than 0.16 mag, which is negligible here.

The seven Virgo Cluster galaxies in Table 1 are identified by asterisks in column (4).

Columns (5) and (6) show the adopted B and V magnitudes at maximum. Parentheses denote data transformed from the old m_{pg} international system to B. Colons denote less certain data caused by less complete photometry. K-corrections for the effects of redshift on the observed magnitudes have been applied to the three SNe with log $v > 4.0$ using the tables of Hamuy et al. (1993).

Column (7) is the decay rate, Δm_{15}, from Phillips (1993) and Hamuy et al. (1995). We have added four tentative values in parentheses. The sources for the photometry are in column (8).

It is, of course, a crucial question whether the variations in Δm_{15} that are listed here are significant. Based on the relatively sparse earlier photographic and photoelectric photometry of SNe Ia, it was reasonable to reserve judgment on the reality of putative variations from a universal template light curve. The early evidence was excellent that such a standard template exists, and that it fitted most of the extant data (Pskovskii 1967; Barbon, Ciatti, & Rosino 1973; Cadonau, Sandage, & Tammann, 1985; Cadonau 1987). However, this precept has changed with the advent of CCD SNe photometry. Deviations from a template light curve appear now to be real, although the photometric data must be exquisite to determine Δm_{15} with the necessary accuracy to remove all doubt.

The restriction to light curves defined within 5 days of maximum give data of the highest weight. As said earlier, the accuracy of the Δm_{15} value depends on the adopted time of maximum and on the shape of the light curve once the concept of a universal template is abandoned. The maximum magnitude itself, if extrapolated by more than $\sim$5 days, is uncertain at the 0.1–0.2 mag level by these effects, affecting Δm_{15} by the same amount. In addition, the uncertainty in the epoch of maximum is particularly severe for the accuracy of Δm_{15}. If that epoch is uncertain by several days, so then is the epoch of m_{15} itself. The B light curve is very steep at 15 days after maximum, declining at a rate of $dB/dt \sim 0.06$ mag day^{-1}. Hence, an error in the maximum epoch of only 3 days falsifies m_{15} and hence Δm_{15} by almost 0.2 mag.

These two effects show that errors of $\sim$0.3 mag are to be expected in Δm_{15} for all but the most exquisite data.

Only five of the nine SNe used by Phillips (1993) are listed in Table 1. SN 1986G and 1991bg are eliminated because their colors are too red; SN 1971I and SN 1989B are in galaxies whose redshifts are smaller than 1100 km s^{-1}. As for our entire sample, we have used *kinematic* distance ratios for the remaining five SNe rather than the photometric ratios given by the TF and SBF methods used by Phillips (1993) and Hamuy et al. (1995), for which we question their absolute calibration because of uncorrected selection effects resulting from bias (Sandage 1988a, b, 1994a, b; Federspiel et al. 1994).

A most important point to stress is that the SNe Ia with Cepheid distances, from the three extant *HST* experiments (Saha et al. 1994, 1995), used in § 3 to find H_0, fulfill the selection criteria that define the sample in Table 1 (except that their redshifts are smaller than 1100 km s^{-1}, but their distances are determined by Cepheids). Observations within 5 days of maximum are available for SN 1937C (Schaefer 1994; Pierce, & Jacoby 1994, 1995) and SN 1972E (Leibundgut et al. 1991b). Only the observations of SN 1895B begin possibly 6 days after maximum (Saha et al. 1995). Furthermore, none of the objects are known to have been red. SN 1937C and SN 1972E have a mean color of $B(\max) - V(\max) = -0.03 \pm 0.10$ (Schaefer 1994; Saha et al. 1995). This is marginally bluer than the mean color of the sample in Table 1 (see § 2.2). It is also bluer than the mean color of $(B-V) = 0.09 \pm 0.04$ at B maximum determined in Paper I. No color information is known for SN 1895B.

2.2. *The Hubble Diagrams in B and V*

The Hubble diagrams in B and V based on columns (4)–(6) of Table 1 are shown in Figure 1. Open symbols are data from the Basel Atlas (source number 1 in col. [8]). Uncertain magnitudes, shown with colons in Table 1, are plotted as crosses. The 13 new data from sources 2, 3, 5, 6, and 7 are shown as closed circles. These have the highest weight as a result of the intensive manner with which the modern photometric programs have been conducted.

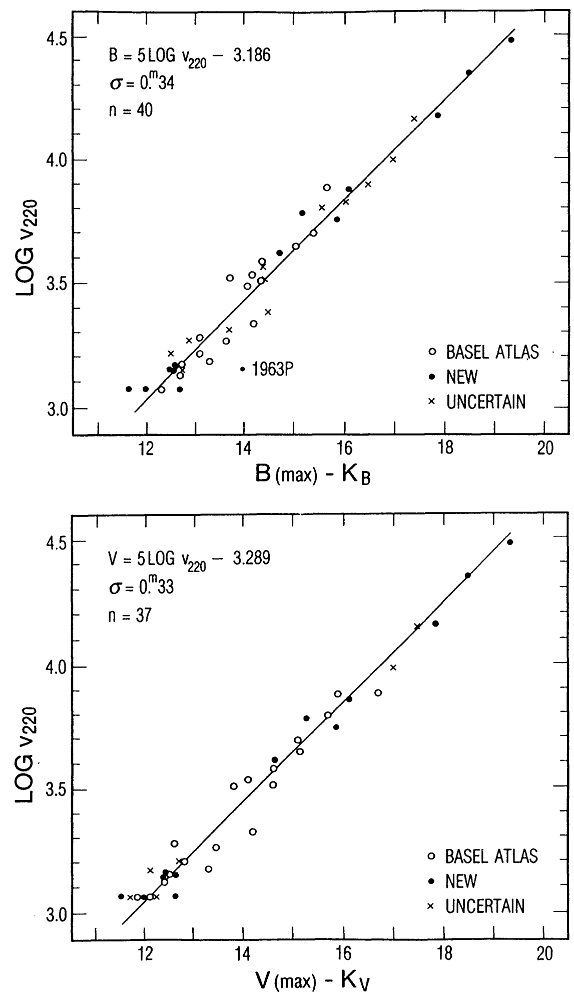

FIG. 1.—Hubble diagrams in B and V from the data in Table 1. Open circles and crosses are from the older archive literature. Closed circles are the modern data used by Phillips (1993) and Hamuy et al. (1995). Ridge lines are eqs. (1) and (2) of the text.

The seven type I supernovae in the Virgo Cluster galaxies are plotted with the fixed value of $\log v = 3.072$ corresponding to a cosmic Virgo velocity relative to the kinematic frame of the microwave background of $v = 1179 \pm 17$ km s^{-1} (Sandage & Tammann 1990; Jerjen & Tammann 1993). The four Virgo data points in B and the seven in V straddle the regression line, showing that the Virgo Cluster using v(cosmic) = 1179 km s^{-1} ties correctly to the Hubble flow.

The slope of the lines in Figure 1 is put at 5, required if the redshift-distance relation is linear and if the luminosities of the defining objects are not a function of redshift. These requirements are met if there are no evolutionary effects with time and/or effects of selection bias in the sample.

The excellent fit of the line of slope 5 to the data, especially those with the highest redshifts, proves the lack of significant observational selection bias. As before, this is a high-weight proof that the true dispersion of M(max) of SNe Ia is less than 0.3 mag, otherwise there would be an upturn in the Hubble diagram at the faintest magnitudes (Sandage & Tammann 1993) as a result of Malmquist bias in a flux-limited sample (at large distances) compared to a distance-limited sample at small distances. There is none. This is the proof that the large dispersion claimed by Hamuy et al. (1995) does not apply to this sample.

The equations of the lines in Figure 1 are

$$B(\mathrm{max}) = 5 \log v - (3.186 \pm 0.054) , \qquad (1)$$

with a dispersion of $\sigma(M) = 0.34$ mag (SN 1963P being excluded), and

$$V(\mathrm{max}) = 5 \log v - (3.289 \pm 0.055) , \qquad (2)$$

with $\sigma(M) = 0.33$ mag. The scatter in B and V for high-weight and low-weight magnitudes is not significantly different.

Subtracting equations (1) and (2) gives $B(\mathrm{max}) - V(\mathrm{max}) = 0.10 \pm 0.08$ for the average of the sample. This translates to $(B-V) = 0.08 \pm 0.08$ at B maximum because of the difference of two days between the epoch of B and V maxima. The near-perfect statistical agreement with the most probable intrinsic color at B maximum of 0.09 ± 0.04 (Paper I) bars any significant amounts of absorption for the sample in Table 1, taken as a whole.

One may argue whether the SNe Ia in the Virgo Cluster should be included. Of the seven SNe Ia, five are in spirals. Spirals in the Virgo region do not define the distance to the E galaxy core because they are spread over an area of $\sim 12°$ diameter (Binggeli, Tammann, & Sandage 1987). Hence, there is a 1 σ depth effect of 0.2 mag. Combining this with the observed dispersion of non-Virgo supernovae in Figure 1 accounts for the somewhat larger dispersion of the four Virgo supernovae in the top panel and the seven Virgo supernovae in the bottom panel than for the remainder of the sample. The dispersions of the Virgo supernovae alone are 0.45 mag in B and 0.37 in V. Furthermore, the effect on the intercept values of equations (1) and (2) by excluding the Virgo Cluster data is only 0.003 mag in B and 0.010 mag in V. This shows again that the mean Virgo point with $\langle v(\mathrm{cosmic}) \rangle = 1179 \pm 17$ km s^{-1} is consistent with the data at high redshifts, which themselves are very nearly in the kinematic frame of the microwave background (Jerjen & Tammann 1993).

Because the data in Figure 1 fit so well the expected Hubble line, we insert here a classical test of cosmology. How *linear* is the relation between recession velocity and distance, i.e., what is n in the proportionality $v \sim D^n$? In the linear case, $n = 1$ exactly. Assuming (1) that supernovae luminosities are not a function of redshift, (2) that space is Euclidean (reasonable assumptions for the modest redshifts considered), and (3) that the errors are predominantly in the magnitudes, m, we make the *Ansatz*

$$\log v = am + b ,$$

where $n = 0.2/a$.

From the B data we find $a = 0.2047 \pm 0.0053$, and from the V data $a = 0.1961 \pm 0.0047$. Hence, $n(B) = 0.977 \pm 0.027$, and $n(V) = 1.020 \pm 0.024$. The result is consistent with first ranked cluster E galaxies as the distance probe (Sandage, Tammann, & Hardy 1972), which gave $n = 0.97 \pm 0.05$. It is also consistent with the more recent result by Jerjen & Tammann (1993), using clusters with precise distance ratios to Virgo from the mean of many distance indicators. Lauer & Postman (1992), again using first ranked cluster E galaxies, also confirm the result.

The zero points in equations (1) and (2) are the crucial numbers with which to determine H_0 once the values of $\langle M_B(\mathrm{max}) \rangle$ and $\langle M_V(\mathrm{max}) \rangle$ for SNe Ia are known. The zero points here differ from the corresponding equations in Paper I (eqs. [1] and [3]) by only 0.036 mag in B and 0.024 mag in V. This excellent agreement shows, remarkably, the high accuracy of the mean photometric zero point of the older archive data.

We consider now the effect on the Hubble constant of a possible Pskovskii-Phillips (hereafter sometimes P-P) correlation of absolute magnitude and light decay-rate. Hamuy et al. (1995) claim that the value of H_0 derived by neglecting such a decay rate correlation (Saha et al. 1995) is too small by $\sim 15\%$. They base their conclusion on adopted slopes of $dM_B(\mathrm{max})/d\Delta\, m_{15} = 1.624$ in B, and $dM_V(\mathrm{max})/d\Delta\, m_{15} = 1.764$ in V (their eqs. [15] and [16]). Using these relations, they obtained $H_0(B) = 64 \pm 12$ and $H_0(V) = 67 \pm 11$ compared with $H_0(B) = 50 \pm 8$ and $H_0(V) = 54 \pm 8$ obtained by Saha et al. (1995). We repeat the calculation using the shallower slopes derived below for any possible P-P effect.

2.3. *The Effect on the Hubble Constant of a Correlation of Decay Rate and Absolute Magnitude*

The residuals in magnitude in B and in V can be calculated for each entry in Table 1 using equations (1) and (2), reading them at fixed $\log v$. In the absence of random and streaming perturbations on the velocity field, these residuals (except for errors in the photometry) will be deviations from the $\langle M(\mathrm{max}) \rangle$ mean values in B and V.

Figure 2 shows the correlation of these magnitude residuals with the seventeen $\Delta\, m_{15}$ values in Table 1. The Virgo Cluster supernovae are shown as open triangles. The tentative values are crosses. The values taken from Phillips (1993) and Hamuy et al. (1995) are closed circles. The sense of the deviations is that supernovae brighter than the ridge lines in Figure 1 have negative residuals (the ordinate). The zero points of the residuals in Figure 2 refer to the system of mean magnitudes determined by the ridge-line correlations of equations (1) and (2) with the intercept values of -3.186 and -3.289.

Several things are to be noted in Figure 2. The Virgo Cluster points show the largest individual scatter. The two outlying points are for NGC 4527 and NGC 4639. Both are spirals and are on opposite sides of the E galaxy core, with a separation of $\sim 12°$ in the sky. Hence, their distance relative to the core is uncertain, which may be the cause of the larger spread in Figure 2 for the Virgo points. However, the data are not defini-

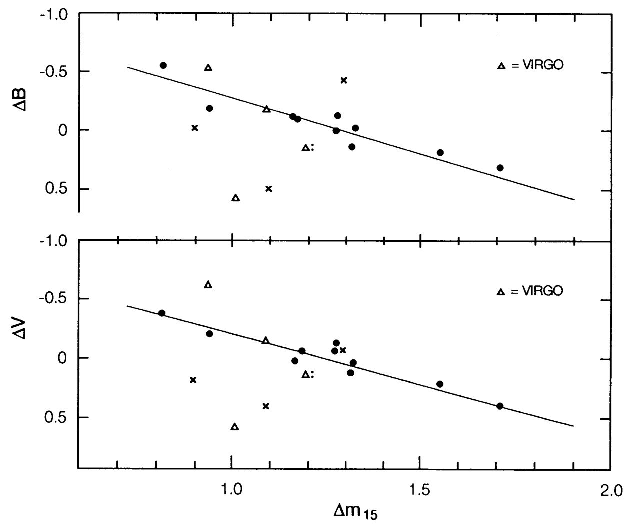

FIG. 2.—Magnitude deviations of the individual data in Fig. 1 from the ridge lines plotted vs. light decay rates for the 17 SNe with available data in Table 1. Virgo Cluster data are triangles. Less certain data are crosses. The suggested correlation lines are drawn by eye and neglect several of the deviant points. A correlation is less certain if all the data are considered.

tive. An equally defensible argument would be that the spread in Figure 2 is real. Accepting all data in Figure 2, in fact, militates against any P-P effect.

The steepest slopes one can fit (by eye) to the data, excluding the three points in the lower left, are $d\Delta B/d\Delta m_{15} = 0.88$ in the B band and $d\Delta V/d\Delta m_{15} = 0.75$ in V, compared with 2.70 and 1.95, respectively, determined by Phillips (1993, his Fig. 1). Hence, the maximum effect we derive from the present data are factors of 3.1 and 2.6 smaller than the original Phillips result. The preferred slope values of Hamuy et al. (1995) of 1.62 in B and 1.76 in V used in their rediscussion of H_0 are again larger than ours by an average factor of 2.

It should be mentioned, however, that the same authors (their eqs. [11–12]) do also discuss a solution with slopes 0.85 in B and 0.79 in V which agree with our maximum slopes. Their demonstration of shallower slopes follow if they impose a color restriction $-0.25 < (B_{max} - V_{max}) < +0.25$ and if they solve simultaneously for the zero point of the Hubble relation and for the slope of the Δm_{15} dependence of the remaining eleven supernovae. They, however, base their conclusion of a 15% effect (their equations after eq. [16]) on their final adoption of the larger slope values cited earlier.

What are the consequences for the value of H_0 if we adopt our maximum slopes as real? To answer, we require the Δm_{15} values of the calibrating supernovae used by Saha et al. (1995) in the three extant *HST* experiments.

Hamuy et al. (1995) have determined the decay rate of SN 1972E to be $\Delta m_{15} = 0.94 \pm 0.10$. Pierce & Jacoby (1994, 1995) find $\Delta m_{15} = 0.84 \pm 0.03$ for SN 1937C, while Schaefer's (1994) independent data give $\Delta m_{15} = 1.09$. A mean of $\Delta m_{15} = 0.96 \pm 0.10$ is adopted here. The data for SN 1895B do not warrant a reliable determination for it (but see footnote 2 for a later development). However, if SN 1972E *and* SN 1937C are both exceptionally slow *and hence overluminous* according to the Phillips formulation of a P-P correlation, then it is extremely unlikely that the third calibrator, which is SN 1895B, should also be overluminous relative to the average. This is because the supernovae in Table 1 are taken from a volume of about 3×10^5 times larger, on average, than the volume of the three nearby local calibrators. If SNe Ia indeed have a range of M(max) ~ 2 mag as implied by Hamuy et al. (1995), then the resulting very strong Malmquist effect surely excludes the possibility that SN 1895B is also overluminous. Hence, one is forced to the conclusion that SN 1895B, if not underluminous, must have at most average luminosity. Therefore, the average value of Δm_{15} is used for it. The important point is its vertical position in Figure 3 in its role in helping to define the offset in absolute magnitude relative to the Phillips zero point. Its horizontal position is unimportant for this zero point problem because any P-P effect in Figure 3 is so shallow.[2]

In this regard, Fisher et al. (1995) have shown independently that there does appear to be a small range in M(max) even for "Branch-normal" SNe Ia, and that this range is correlated with the measured Ca ejection velocity as measured near 80 days after maximum light. (The Ca velocity is a very shallow function of phase for times more than 50 days after maximum light and hence is often quite reliably measured even when the epoch of maximum is not well known). From their relation (Fisher et al. 1995, their Figs. 3–4), the calibrating SN 1972E is, if anything, slightly fainter than average "Branch-normal" SNe Ia. This is the opposite of the conclusions of Hamuy et al. The Fisher et al. discovery of the Ca velocity-luminosity relation supports our argument on statistical grounds that it is extremely unlikely that the nearest three SNe Ia are all overluminous relative to the average of "Branch normal" SNe.

In using the putative P-P decay rate relation, the question remains as to the average value of Δm_{15} for the SNe in Figure 1. Hamuy et al. (1995) adopt $\langle \Delta m_{15} \rangle = 1.1$. The 17 SNe in Table 1 with listed decay rates average $\langle \Delta m_{15} \rangle = 1.19 \pm 0.06$. If we conservatively adopt the latter and then take the most probable mean value of the calibrators as $\langle \Delta m_{15} \rangle = 1.03 \pm 0.05$, it follows that $d\Delta m_{15} = 0.16 \pm 0.08$ for the three calibrators in B and $d\Delta m_{15} = 0.24 \pm 0.10$ for the two calibrators in V. These values, multiplied by our maximum slopes of 0.88 in B and 0.75 in V, give what we consider to be maximum absolute magnitude "corrections" of $\Delta\langle M_B \rangle = 0.14 \pm 0.07$ and $\Delta\langle M_V \rangle = 0.18 \pm 0.08$ mag. Applying these to the adopted mean calibrations given by Saha et al. (1995) would give

$$\langle M_B(\max) \rangle \leqslant -19.51 \pm 0.16 \tag{3}$$

and

$$\langle M_V(\max) \rangle \leqslant -19.42 \pm 0.14 , \tag{4}$$

where the equal sign holds if the corrections should be applied. These calibrations combined with equations (1) and (2) give

$$H_0(B) \leqslant 54 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{5}$$

and

$$H_0(V) \leqslant 59 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1} , \tag{6}$$

[2] A new analysis of the light curve for 1895B by Schaefer (1995) has become available since this paragraph was written. Schaefer's light curve is based on his photoelectric redetermination of the comparison stars used by Walker (1923) and by his remeasurements of all the available plates. Among his conclusions are that (1) SN 1895B has a prototypical light curve of a totally normal SN Ia, fitting the standard Basel template precisely, (2) the Δm_{15} decay rate for 1895B is in fact average, and (3) the maximum magnitude of the light curve is well determined and is consistent to better than 0.1 mag with that assumed by Saha et al. (1995), and hence SN 1895B is a good calibrator.

where the errors are internal, compounded by the quoted errors in equations (1), (2), (3), and (4).

Equations (5) and (6), using the equal signs, are 8% and 9% larger, respectively, than the values obtained by Saha et al. (1994, their eqs. [17] and [18]).[3] Factored into these values are the additional change of a few percent that is a result of the difference in the intercepts of the respective Hubble diagrams compared here with those obtained in Paper I and used by Saha et al. (1995), amounting, as stated previously (§ 2.2), to 0.036 mag in B and 0.024 mag in V.

Our conclusion from these results is that the value of H_0 is not changed by the $\sim$15% effect suggested by Hamuy et al. with their steep slopes to an adopted P-P decay rate–luminosity effect, but rather by at most $\sim$9%, and more likely only 3%–4% using the Hamuy et al. data alone (see footnote 3).

It may be noted in passing that the different slopes of the B and V decay rates by Hamuy et al. (1995) also imply a variation of the color at maximum depending on the value of $d\Delta m_{15}$. The size of the variation is $\Delta(B-V) = 0.60d(\Delta m_{15})$ using the slope values of Hamuy et al., compared with the milder variation of $\Delta(B-V) = 0.13d(\Delta m_{15})$ required by the lines in Figure 2. A difference in Δm_{15} or (0.16 ± 0.08) between the sample in Table 1 and the calibrators would require, therefore, that the calibrators be bluer at maximum than the sample in Table 1 by 0.10 ± 0.05 mag according to Hamuy et al., and 0.02 ± 0.01 mag from Figure 2. The available color data are too uncertain to test this prediction.

3. DISCUSSION

Figure 2 is not convincing that a correlation exists unless the three data points with positive residuals and decay rates near $\Delta m_{15} = 1.0$ are ignored. Said differently, if all 17 SNe are considered, no significant correlation exists. Almost the total weight supporting a correlation is carried by SN 1991bc with $\Delta m_{15} = 0.82$, SN 1990af with $\Delta m_{15} = 1.56$, and SN 1990bo with $\Delta m_{15} = 1.72$. The question therefore remains: Is the correlation real?

An objection against its reality comes from the analysis made by Hamuy et al. themselves, concerning the too-small scatter of their "corrected" Hubble diagram. They find, after applying their adopted corrections for decline rate, a mean scatter about the Hubble line of only $\sigma(M) = 0.11$ mag in B and $\sigma(M) = 0.12$ mag in V for their "Tololo/Calan sample" of nine SNe Ia. Based on their quoted *observational* errors, such a small scatter is not possible.

Their individually estimated observational errors are listed in their Table 1. Their assumed mean error in log cz is 0.027, allowing for peculiar motions of $\sim$600 km s^{-1}. This translates into $\sigma(M) = 0.14$ mag if read as a magnitude error. Their mean observational photometric errors in B and V are 0.17 and 0.12 mag, respectively. Their mean error in Δm_{15} is 0.09 which, if multiplied by the respective slopes of their magnitude-decline rate relations, requires $\sigma(M) = 0.15$ and $\sigma(M) = 0.16$ mag in B and V, respectively, as a result of errors in Δm_{15} alone. Hence, the compounded magnitude error (added in quadrature) is $\sigma(M_B) = 0.27$ and $\sigma(M_V) = 0.24$ mag, which is incompatible with the claimed smaller scatter in their "corrected" Hubble diagram of $\sigma(M) = 0.11$ and 0.12 mag in B and V, respectively. Note in particular that *each* of the three error sources introduces a larger scatter than is claimed for this diagram. The obvious conclusion is that the magnitude–decline rate relation of Hamuy et al. is an artifact of small-sample statistics. Based on the statistical data alone, no correction for decay rate should be applied if their observational errors are as they state. In fact, it is hard to see how the observational errors could be smaller.

We encounter the same problem in that our scatter is also too small if we apply the slopes in Figure 2 as drawn (0.88 for B and 0.75 for V) and if we omit here again the three points which, if accepted, suggest the no-correlation case. Again, the only way to avoid the too-small-a-scatter problem is to deny the decay rate–luminosity correlation with the slopes we are discussing here.

The other statistical problem raised by a decay rate–luminosity dependence has been discussed in § 2.3. As noted there, if the luminosity range of SNe Ia is as large as the 2 mag claimed by Hamuy et al., the Malmquist effect on the *distant* SNe Ia would be overwhelming, making them much more luminous than their nearby counterparts. It is then hard to accept that at least two of the local calibrators (i.e., those with known Δm_{15} values) should be more luminous than the mean of the distant sample. No such gross Malmquist effect is visible in Figure 1.

The same objection that militates against overluminosity of the local calibrators must be raised against the recent investigation by Riess, Press, & Kirshner (1995). From an independent parameterization of the "standard" supernovae light curves, including, as was also done by Hamuy et al., supernovae that are not "Branch-normal," they concluded that the local calibrator SN 1972E is overluminous relative to a "mean" sample (presumably similar to that defining the Hubble diagram in Fig. 1) by 0.24 mag. Again, since not all three local calibrators can be overluminous because of the huge volume normalization effect in the presence of even a small intrinsic dispersion, the mean absolute magnitude, $\langle M(\max)\rangle$, of the calibrators cannot be too bright by more than a generous $\sim$0.2 mag. In consequence, the Saha et al. (1995) value of $H_0 = 52 \pm 8$ can, therefore, not be too small by more than 10%. This gives a firm *upper* limit of $H_0 < 57 \pm 8$.

The redshift luminosities, $M_B(\max)$, assuming $H_0 = 52$, are plotted in Figure 3 versus Δm_{15} for only the 13 SNe Ia in Table 1 that have reliable Δm_{15} values. They exhibit a mild luminosity dependence on Δm_{15} that, as in Figure 2, may or may not be real. The scatter in the absolute magnitude about a constant line is $\sigma(M_B) = 0.30$ mag. This small scatter is already close to the value expected from the error budget previously discussed. *Any* sloped relation which might fit the points would again decrease the observed scatter below what is known from the individual errors.

Also plotted in Figure 3 are the six not-too-red SNe Ia of the Phillips (1993) sample, shown as the small open and crossed symbols. We have used the absolute magnitudes for them that Phillips adopted, *based on the Tully-Fisher and surface brightness fluctuation methods.* The two crucially important points to note concerning these data as they relate to the debate between the long and short distance scales are (1) the $M(\max)$ values of these added points exhibit an obvious steep trend with Δm_{15}, and, most importantly, (2) their mean absolute magnitude is $\langle M_B(\max)\rangle = -18.5$, which is 1.1 mag fainter than the three

[3] If, on the other hand, we adopt the Hamuy et al. mean value of $\langle\Delta m_{15}\rangle = 1.1$, the corresponding $d\Delta m_{15}$ difference between the calibrators and the Hamuy et al. adopted mean is reduced to $d\Delta m_{15} = 0.07 \pm 0.06$, reducing the "correction" to 0.06 ± 0.05 mag in B and 0.05 ± 0.04 mag in V, giving only a $\sim$3%–4% effect in H_0 as a result of a putative P-P effect alone.

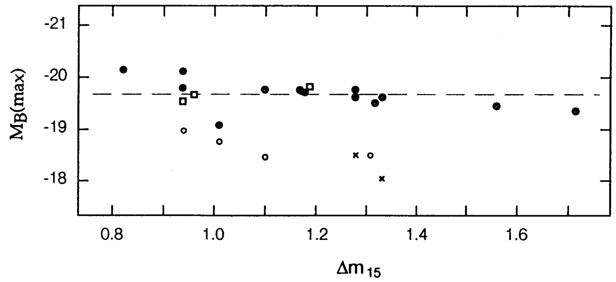

FIG. 3.—Absolute B magnitudes of the SNe in Table 1 correlated with Δm_{15} decay rates where they are known. Large filled circles are for M_B(max) values calculated from redshifted using $H_0 = 52$ km s^{-1} Mpc^{-1}. The three open squares are the three supernovae whose absolute magnitudes have been determined via Cepheids in the two extant *HST* experiments (Saha et al. 1995). SN 1895B is plotted with an assumed $\Delta m_{15} = 1.19$ corresponding to the adopted average value for all SNe Ia (see also footnote 2). Supernovae used by Phillips (1993) in his original decay rate–luminosity proposal are plotted with the absolute magnitudes adopted by him, based on distances determined by the Tully-Fisher (*small open circles*) and the surface brightness fluctuation (*small crosses*) methods, which clearly deviate from the supernovae values.

SNe Ia calibrated via Cepheids, shown as the open squares. Adding the three reddest SNe Ia used by Phillips (1993) would only enhance the discrepancy.

To emphasize in a different way that the short distance scales of de Vaucouleurs (1979) and Pierce (1994) are not supported by our present SNe Ia calibrations in equations (3) and (4), we note that de Vaucouleurs requires $\langle M_B(\max)\rangle = -18.5 \pm 0.2$ mag (his Table 9) for SNe Ia, based on his hierarchy of calibrators. Pierce (his Table 2) requires $\langle M_B(\max)\rangle = -18.74 \pm 0.14$ based solely on his version of a Tully-Fisher calibration and its use with biased data. These are both significantly fainter than the $\langle M_B(\max)\rangle = -19.65 \pm 0.13$ given by Saha et al. (1995) and are also fainter than $\langle M_B(\max)\rangle = -19.51 \pm 0.16$ from equation (3), even after the supposed correction for a maximum P-P effect we derive here.

The conclusions to be drawn from Figure 3 are that (a) if there is a P-P effect, it is less severe than discussed by Phillips (the trend shown by the closed circles is very shallow), and (b) the distance scale defined by data obtained using the TF and the SBF methods is compressed by the factor of ~antilog (1.1/5) = 1.66. We have argued elsewhere (Sandage 1988a, b, 1994a, b; Federspiel et al. 1994; Sandage, Tammann, & Federspiel 1995; Sandage & Tammann 1995) that the cause for the error using the TF method is observational selection bias that occurs when the calibration is made with a local distance-limited sample, which is then incorrectly applied to more distant galaxies in flux-limited samples.

Note that the factor of 1.66 causes a true value of $H_0 \sim 52$ to be incorrectly perceived as $H_0 \sim 86$ using the uncorrected TF method. Note also that the luminosity–light curve parameter relation claimed by Riess et al. (1995) is affected by the same problem because the distances used by them have also been obtained, we believe incorrectly, from the TF and SBF methods. We must finally address a further complicating possibility hinted at by Hamuy et al. (1995). They suggest that the variation of M(max) with Δm_{15} may be related to the stellar population of the parent galaxy from which a type Ia supernova is drawn. If so, these parameters may correlate with the color or Hubble type of the parent galaxy. We address this possibility in Figure 4, where the M_B(max) redshift luminosities (based on $H_0 = 52$) for the SNe in Table 1 are plotted against the listed Hubble types. No correlation is present.

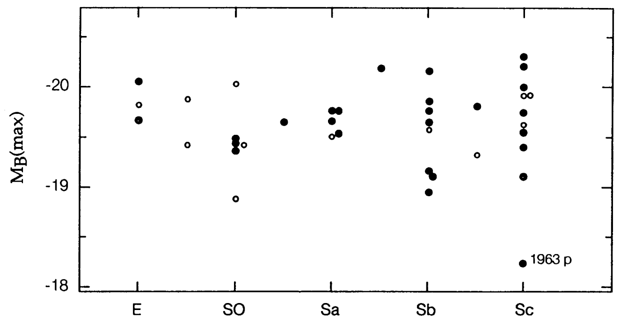

FIG. 4.—Test for a possible correlation of M_B(max) of the SNe in Table 1 with galaxy type suggested by Hamuy et al. (1995). Absolute magnitudes are calculated from the redshifts using $H_0 = 52$ km s^{-1} Mpc^{-1}. Large closed circles are the high weight data. Lower weight SNe are the small open circles. Note also that the mean line through the data agrees in absolute magnitude with the mean of the three Cepheid calibrators plotted in Fig. 3.

Furthermore, the fact that the distant SNe Ia in spirals in Table 1 are not underluminous argues against any measurable internal absorption. This is also supported by the mean color of the sample, discussed in § 2.2. However, since there must be *some* absorbed SNe Ia at great distances (just as locally), their absence in Table 1 (as a consequence of the small scatter in the Hubble diagrams in Figure 1) demonstrates that the present search techniques *depend on apparent magnitude*; that is, the searches are clearly essentially flux-limited rather than distance-limited. Only the brightest SNe are found at large distances. The consequence is, again, that the three local calibrators cannot be overluminous on average. The concern is, then, rather that the local calibrators are *underluminous*, compared to the flux-selected sample in Table 1. If so, then the value of $H_0 = 52$ derived by Saha et al. (1995) would be an *upper* limit.

However, one question remains. The parent galaxies of the three local calibrators are IC 4182 and NGC 5253. They are of galaxy types Sd/Im and Am (amorphous), respectively. No parent galaxy in Table 1 is of these types. Hence, it remains a possibility in principal that these two galaxy types produce nonaverage SNe Ia (this is the Hamuy et al. 1995 current objection). The next three galaxies on the cycles 4 and 5 *HST* program to calibrate SNe Ia via Cepheids are NGC 4536 (SN 1981B) of galaxy type Sbc, NGC 4496 (SN 1960F) of galaxy type SBc, and NGC 4639 (SN 1990N) of galaxy type SBc. The forthcoming data will address this last remaining ambiguity raised by the critics.

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Note added in proof.—M. W. Richmond et al. (AJ, 109, 2121 [1995]) have recently presented detailed photometry of the SN Ia 1994D in the Virgo galaxy NGC 4526. They derive a relatively fast decline rate of $\Delta m_{15} = 1.31 \pm 0.08$, suggesting that the SN should be somewhat underluminous if the decline rate–luminosity relation is real. However, the authors conclude that SN 1994D is brighter by $\sim$0.4 mag in B than two other Branch-normal SNe Ia, questioning thereby also the reliability of SNe Ia is standard candles. Yet their conclusion is based on a surface brightness fluctuation distance of NGC 4526. These distances are suspect because they are sensitive to metallicity (H. Lorentz et al., A & A, 277, L15 [1993]). A less ambiguous way to judge the relative luminosity of SN 1994D is to compare it to other SNe Ia in the Virgo Cluster. This comparison is powerful because NGC 4526, as an S0 galaxy, can be assumed to lie near the core of the cluster (see B. Binggeli et al., AJ, 94, 251 [1987]). The Virgo SNe Ia give $\langle m_B \rangle = 12.13 \pm 0.15$ ($n = 6$) and $\langle m_V \rangle = 12.17 \pm 0.17$ ($n = 4$) (A. Sandage & G. A. Tammann, in Topics in Astrofundamental Physics, ed. N. Sánchez, in press [1995]). A comparison of these values with the photometry of Richmond et al. shows SN 1994D to be indeed *brighter*, yet by marginal amounts of $\Delta B(\max) = 0.24 \pm 0.15$ and $\Delta V(\max) = 0.27 \pm 0.17$. Therefore, we agree with Richmond et al., although for other reasons, that the fast SN 1994D does not lend support to any proposed decline rate–luminosity relation. But we note also that the excellent new data on SN 1994D are fully consistent with the assumption that branch-normal SNe Ia are standard candles to within $\sigma(M) < 0.3$ mag.