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THE HUBBLE DIAGRAM IN V FOR SUPERNOVAE OF TYPE Ia AND THE VALUE OF H_0 THEREFROM

ALLAN SANDAGE
The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101

AND

G. A. TAMMANN
Astronomisches Institut der Universität Basel, Venusstrasse 7, CH-4102 Binningen, Switzerland, and European Southern Observatory, Karl-Schwarzschild-Straße 2, D-8049 Garching/München, Germany

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ABSTRACT

The Hubble diagram for supernovae of Type Ia is derived in V and is summarized from the literature in m_{pg} and in B. The ridge line equation of the diagram in V is $\log v_{220} = 0.2\ m_v + (0.653 \pm 0.012)$ from 34 SNe Ia. The dispersion of a single point about the ridge line is 0.36 mag. We argue from external evidence that the intrinsic dispersion is likely to be as small or smaller than $\sigma_v(\max) = 0.2$ mag.

The intrinsic $(B - V)$ color at B maximum light is 0.09 ± 0.04 mag.

The calibration of the absolute magnitudes at maximum from four concordant methods, including the determination for SN 1937C via Cepheids in IC 4182, is $\langle M_B(\max)\rangle = -19.55 \pm 0.14$ and $M_V(\max) = -19.71 \pm 0.13$. These values lead to the long distance scale with $\langle H_0 \rangle$ between 45 and 52 km s^{-1} Mpc^{-1}. This range depends on whether we use (1) the SN Hubble diagrams in the m_{pg}, B, and V bands themselves from Figure 1, or (2) the derived Virgo Cluster distance of 23.9 ± 2.4 Mpc found from the SN 1937C calibration alone at $M_V(\max) = -19.76$, applied to the six SNe Ia with adequate V photometry that have appeared in the cluster with $\langle V(\max)\rangle = 12.13 \pm 0.14$. By the precepts previously developed for the Virgo velocity relative to the cosmic frame (Sandage & Tammann 1990; Jerjen & Tammann 1992), this Virgo distance gives the cosmic value of the Hubble constant to be $H_0 = 47 \pm 5$ km s^{-1} Mpc^{-1}.

Subject headings: distance scale — supernovae: general

1. INTRODUCTION

A program has begun with the *Hubble Space Telescope* (*HST*) to determine Cepheid distances to galaxies that have produced supernovae of Type Ia. The aim is to calibrate the absolute V and B magnitudes of SNe Ia at maximum using the distances to the parent galaxies determined from Cepheids and the observed apparent magnitudes of the SNe at maximum. If such supernovae are as good standard candles as present data and their interpretation indicate (Branch & Tammann 1992; Hamuy et al. 1992, and later sections here), the Hubble constant can eventually be found from this calibration with higher precision than with all other known methods.

Furthermore, if SNe Ia can be found at sufficiently large distances, the value of the deceleration parameter, q_0, can be found (Branch & Tammann 1992). The method is to use the Mattig (1958) equation for the theoretical Hubble diagram (hereafter HD) that takes into account the redshift change in the look-back time due to deceleration. Redshifts larger than about $z \sim 0.3$ suffice to make a significant difference in the HDs for different q_0 values (Sandage 1961, 1988b).

The first SNe Ia to be calibrated in the *HST* Cepheid program was SN 1937C in the nearby parent galaxy IC 4182 (Sandage et al. 1992). the $P - L$ relation for 27 Cepheids in both the V and the I bands gives a reddening-free modulus of $(m - M)^0 = 28.36$ ($D = 4.7$ Mpc) for IC 4182. This leads to an absolute magnitude at maximum for SN 1937C of $M_V(\max) = -19.76$ (Saha et al. 1993).

The observations of the Cepheids in IC 4182 were made in the V and I bands rather than in B because the CCD detectors aboard *HST* are relatively insensitive in the blue. Hence, to use the calibration of $M(\max)$ of 1937C in the V band to find H_0 we either (1) need the Hubble diagram for type Ia SNe also in V, or (2) we must adopt a value of the mean $(B - V)^0$ color at maximum to convert a HD in B to one in V.

The second procedure was followed in the announcement paper using the various adopted colors at maximum and several versions of the HD in B given by a selection from Kowal (1968), Barbon, Capaccioli, & Ciatti (1975), Branch & Bettis (1982), Tammann (1982), Branch (1982), Cadonau, Sandage, & Tammann (1985), Tammann & Leibundgut (1990), Miller & Branch (1990), Della Valle & Panagia (1992), and Branch & Tammann (1992).

To this end, we adopted $\langle(B - V)\rangle^0_{\max} = -0.27$ due to Leibundgut et al. (1991), and $\langle(B - V)\rangle^0_{\max} = -0.16$ from Della Valle & Panagia (1992), justified in the cited papers. These colors are similar to those adopted by Barbon, Ciatti, & Rosino (1973) at -0.15, and by Pskovskii (1967) and by Cadonau et al. (1985) at -0.3, seeming to sanctify the adoptions in the announcement paper. However, for a variety of new reasons given in § 3 it now appears likely that these adoped colors are too blue, and that a safer route to H_0 is through the HD determined directly in V, circumventing the need for color data.

No discussion of the HD for SN Ia in V is available in the literature. The purpose of this paper is to give such a discussion, preparing the way for the forthcoming archive paper on the IC 4182 results (Saha et al. 1993).

In the course of the investigation we also became convinced that new precepts are needed concerning the color of SNe Ia at maximum. A new discussion of $(B - V)^0_{\max}$ is made in § 3. The conclusions, also discussed here, affect solutions to the problem of internal absorption in the parent galaxies and its effect on the HDs for the available SNe Ia samples. The absolute magnitude of SN 1937C derived from the Cepheid distance of IC 4182 is compared and combined with three other independent calibrations of M(max) for SNs Ia in § 4, giving M_V(max) $= -19.71 \pm 0.13$. This mean value can be compared with M_V(max) $= -19.76 \pm 0.16$ from SN 1937C alone.

These adopted absolute magnitude calibrations in V, and consequently in B from adoped color data, used with adopted HDs for SNe Ia in V and B, give the global values of the Hubble constant discussed in § 5.

It is to be emphasized that this paper is principally concerned with methods. A *definitive* measurement of H_0 via this route cannot be expected until a number of high-weight absolute magnitude calibrations of SN Ia relative to Cepheids have been made. The requirement is to measure the dispersion in M_B(max), M_V(max), and eventually M_I(max) for SN Ia directly, providing a final test of how good SN Ia are as standard candles. But already now, we believe that the available evidence supports the view that the intrinsic dispersion is unusually small, as discussed elsewhere (Sandage & Tammann 1990; Tammann & Leibundgut 1990; Branch & Tammann 1992; Miller & Branch 1990; Hamuy et al. 1992; Branch & Miller 1993), and in the following sections as well.

2. EVIDENCE THAT SNe Ia ARE GOOD STANDARD CANDLES

Evidence that the absolute magnitudes at maximum of type Ia SNe have only a small dispersion has been reviewed by Branch & Tammann (1992), discussing results available to about mid-1990. The evidence consists of (1) the uniformity of the light curves, (2) the homogeneity of the spectra at various times at maximum and beyond, (3) the near identity of the observed apparent magnitudes at maximum for SNe Ia in three galaxies, each of which have produced two SNe Ia, (4) the same test in the 10 galaxies in the Virgo Cluster that are parents of SNe Ia, and (5) the excellent agreement of the absolute magnitude calibration done by several independent means giving M_B(max) $= -19.6 \pm 0.2$. The combined evidence, if true, would show that SNe Ia are the best standard candles known.

There are, of course, a class of "peculiar" SNe Ia. Branch & Tammann discussed the effect on the HD of including members of this class in statistical studies. But, because the nonprototypical nature of individuals of the class can be determined *a priori* by means other than deviations from the HD, such SNe can, in any case, be excluded in objective ways (see § 2.4).

Since the time of the review by Branch & Tammann, other means have become available to support the conclusion that SNe Ia are excellent distance indicators, discussed in the following subsections.

2.1. *The Hubble Diagrams for SNe Ia in V and B*

The most direct proof is still in the tightness of the HDs that can be constructed from the historical photometry in the literature. HDs in B and $m_{\rm pg}$ have been variously discussed in the papers cited in the last section. The method of construction has been to determine the B (or pg) magnitude by fitting an adopted template light curve to the fragmentary photometric data, and reading the magnitude at the template maximum.

The template curves in $m_{\rm pg}$ and B have been constructed by Cadonau (1987), following the pioneering work of Barbon et al. (1973). As pointed out by Cadonau et al. (1985, their Fig. 1), the finally adopted curve in B has even less scatter than in $m_{\rm pg}$, presumably because the generally more modern photometry in B is more accurate. This taken as evidence that the intrinsic dispersion in the light-curve shape in the blue is smaller than is presently measured.

The template curves were extended to U and V magnitudes (Cadonau 1987) and to infrared JHK magnitudes (Elias et al. 1981, 1985; Leibundgut 1988). The individual magnitudes of four particularly well-observed SNe (SN 1972E, 1980N, 1981B, and 1981D) were found to scatter about these templates by 0.16 mag in U and J, 0.10 mag in B and V, and only 0.06 mag in H (Leibundgut 1988), comparable to the expected observational errors. Furthermore the templates were *a posteriori* very well confirmed by the photometry of 1989B (van den Bergh & Pazder 1992) and SN 1990N (Leibundgut et al. 1991b).

There are some spectral variations from object to object (Filippenko 1992). Also different expansion velocities exist at the same phase for different SNe Ia (Branch & Tammann 1992, Fig. 6). However, the model calculations of the explosion process in the cores of the (presumed) CO progenitor white dwarfs, where the central densities vary by a factor of 3, *do* produce different envelope expansion velocities, but *not* significantly different luminosities at maximum (Canal et al. 1991, Table 1).

But independent of all theoretical model expectations, the best *emprirical* proof of a small dispersion in absolute magnitude at maximum remains the tightness of the *observed* HD at redshifts large enough to avoid any local streaming motions. To this end, we have constructed the HD in V for SNe Ia at distances of the Virgo Cluster and beyond.

The SN Ia template light curve in V has been fitted to the published photometry of individual SNe Ia. The apparent V magnitudes at maximum determined from these fits are listed in Table 1. The sample is a subset of the list of Cadonau (1987) and Leibundgut et al. (1991a), restricted to SNe Ia in galaxies whose redshifts are $v_{220} > 1179$ km s^{-1}. This is the Virgo cosmological velocity (Sandage & Tammann 1990; Jerjen & Tammann 1992), corrected for the effect of the Virgo Cluster deceleration on the local expansion field (Kraan-Kortweg 1986) using an "infall" velocity (actually the retarded expansion effect due to Virgo) of 220 km s^{-1} (Tammann & Sandage 1985).

Column (2) identifies the parent galaxy. Column (3) is the corrected v_{220} velocity from the Kraan-Korteweg model. Column (4) is its logarithm. The adopted apparent V magnitude at maximum is in column (5). The resulting HD in V is shown in Figure 1*c* where it is plotted below the diagrams in $m_{\rm pg}$ and in B, both based on the discussion by Tammann & Leibundgut (1990), but including here also the SNe Ia in the Virgo Cluster.

The line in each of the diagrams has the theoretical slope of $d \log v/dm = 0.2$ required by a linear redshift-distance relation for objects with a constant mean absolute magnitude (i.e., independent of distance). This latter requirement is necessary to avoid Malmquist bias (or the nearly equivalent Schott effect) which is present in a flux-limited sample if the distance indicator has a nonzero dispersion in absolute magnitude. This last sentence brings us to the first conclusion to be derived from Figure 1.

If the magnitude at maximum of the sample in Figures 1*a*–1*c* were to have a significant dispersion, the data points at the largest redshifts, and therefore the faintest apparent magnitudes, would deviate from the straight line, being brighter than

TABLE 1

SUPERNOVAE Ia IN THE VIRGO CLUSTER AND BEYOND WITH KNOWN $V_{\max}$

SN (1)	Galaxy (2)	v_{220} (3)	log v_{220} (4)	$V_{\max}$ (5)
1939A	NGC 4636	1179*	3.072	12.2:
1956A	NGC 3992	1448	3.161	12.5
1959C	A 1308+03	3252	3.512	13.8
1960F........	NGC 4496	1179*	3.072	11.8
1960R	NGC 4382	1179*	3.072	11.7:
1962A	A 1304+2808	6374	3.804	15.7
1962E........	A 1112+2610	14250	4.154	17.5:
1964E........	UGC 6983	1507	3.178	12.1:
1965I	NGC 4753	1627	3.211	12.7:
1966K	A 1116+2833	9808	3.992	17.0:
1967C	NGC 3389	1531	3.185	13.3
1968E........	NGC 2713	3905	3.592	14.3:
1969C	NGC 3811	3454	3.538	14.1
1970J	NGC 7619	3881	3.589	14.6
1970L........	NGC 2968	1899	3.279	13.2:
1971G	NGC 4165	2172	3.337	14.2
1971L........	NGC 6384	1923	3.284	12.6
1972H	NGC 3147	3098	3.491	14.6:
1972J	NGC 7634	3252	3.512	14.6
1973N	NGC 7495	4985	3.698	15.1
1974J	NGC 7343	7621	3.882	15.9
1975N	NGC 7723	1864	3.270	13.45
1975O	NGC 2487	4974	3.697	15.50
1975P........	NGC 3583	2505	3.399	14.4:
1976J	NGC 977	4463	3.650	15.15
1979B........	NGC 3913	1341	3.127	12.4
1980N	NGC 1316	1438	3.158	12.44
1981B........	NGC 4536	1179*	3.072	12.00
1981D	NGC 1316	1438	3.158	12.40
1982B........	NGC 2268	2611	3.417	13.1
1983G	NGC 4753	1627	3.211	12.8
1983U	NGC 3227	1460	3.164	12.5:
1984A	NGC 4419	1179*	3.072	12.2
1990N	NGC 4639	1179*	3.072	12.57

NOTE.—Members of the Virgo Cluster are marked with an asterisk (*).

the line. This *is* the Malmquist bias for a flux-limited sample. From Monte Carlo simulations (see, for example, Spaenhauer 1978), one can show that the lack of a larger effect than is seen in panels *a* and *b* for $m_{\rm pg}$ and B magnitudes requires that the true (intrinsic) standard deviation in the absolute magnitudes be less than ~0.2 mag. However, the *observed* dispersions, marked in the figures, is appreciably larger than 0.2 mag, ranging from 0.65 for the $m_{\rm pg}$ data to 0.36 for V. This proves that most of the observed dispersion is due to observational errors in the magnitudes, rather than being intrinsic.

This test for the intrinsic dispersion is especially powerful because it is independent of observational errors as long as they are randomly distributed. *Hence, the (near) lack of distance-dependent deviations of the data points in Figure 1 from the straight lines proves not only that the intrinsic dispersion in absolute magnitude is smaller than 0.2 mag, but also that the samples are not affected by appreciable absorption, since at large distances only the brightest, and hence the absorption-free SNe are detected.* This latter point is particularly important for the argument in § 3 on the intrinsic colors.

The least-squares solutions of the regression lines in Figure 1, fixing the slopes to be 0.2, are

$$\text{pg:}\quad \log v_{220} = 0.2m_{\rm pg} + (0.690 \pm 0.022),\quad n = 34\ , \tag{1}$$

$$B\text{:}\quad \log v_{220} = 0.2m_B + (0.630 \pm 0.016)\ ,\quad n = 41\ , \tag{2}$$

$$V\text{:}\quad \log v_{220} = 0.2m_V + (0.653 \pm 0.012),\quad n = 34\ . \tag{3}$$

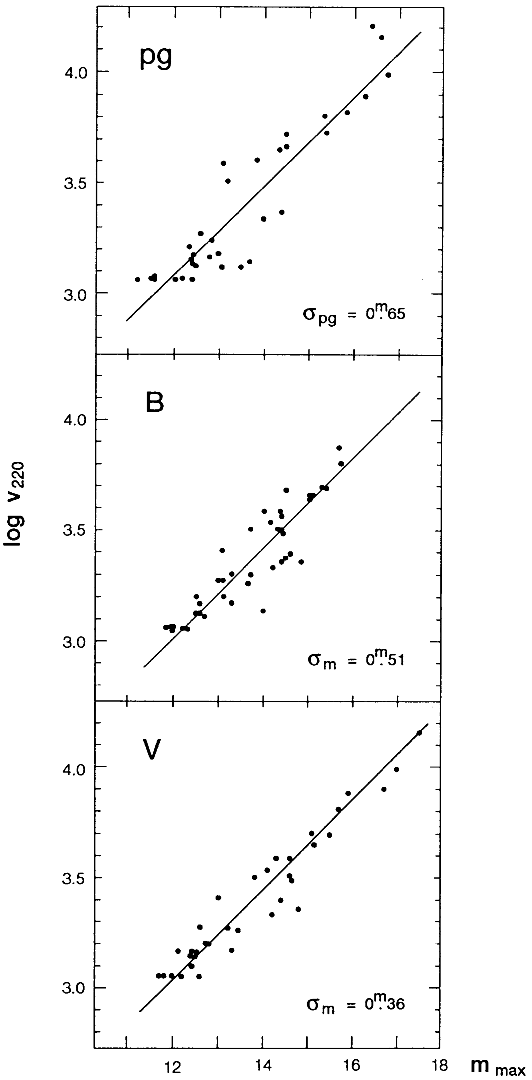

FIG. 1.—The Hubble diagrams in $m_{\rm pg}$, B, and V. The data for the diagrams in $m_{\rm pg}$ and in B are from Tammann & Leibundgut (1990). The data of the diagram in V are from Table 1 here. The lines through the data have an assigned slope of $d \log v/dm = 0.2$, required if the redshift-distance relation is linear.

An independent and particularly persuasive test of the precept that the intrinsic dispersion of M(max) is $\sigma < 0.2$ mag is the direct proof using the seven recent SNe Ia studied by Hamuy et al. (1992). This work has excellent light-curve coverage soon after discovery and close to maximum. Furthermore, the parent galaxies have large enough redshifts to avoid problems with local streaming motions. Although the sample as yet is small, the observed dispersion in absolute magnitude, reducing all galaxies to the same distance by the redshift, is $\sigma < 0.2$ mag.

The consequences of a small intrinsic dispersion, if real, are profound. The obvious implications include (1) SNe Ia theoretical models, (2) distance determinations, and (3) use in cosmology in the search for the deceleration parameter at large redshifts (Tammann 1979; Leibundgut 1990; Branch & Tammann 1992; Hamuy et al. 1993) by measuring q_0 directly from the HDs of SNe Ia.

TABLE 2

APPARENT MAGNITUDES AT MAXIMUM OF SUPERNOVAE Ia IN THE VIRGO CLUSTER

SN (1)	Galaxy (2)	Type (3)	m_{pg} (4)	m_B (5)	m_V (6)
1919A	NGC 4486	E0	11.6	...	...
1939A	NGC 4636	E0/S0(6)	12.4	...	12.2
1939B	NGC 4621	E5	12.0	...	...
1957B	NGC 4374	E1	12.2	...	...
1960F	NGC 4496	SBc III–IV	11.6	11.7	...
1960R	NGC 4382	S0(3)pec	11.5	11.9	11.7:
1961H	NGC 4564	E6	11.2	12.0	(10.7)
1981B	NGC 4536	Sbc(s) I–II	...	12.0	12.0
1984A	NGC 4419	Sa (dust only)	...	12.45	12.2
1990N	NGC 4639	SBb(r) II	...	12.65	12.57
$\langle m \rangle$			11.79	12.12	12.13
			±0.16	±0.15	±0.14
σ_M			0.43	0.36	0.32

2.2. *Summary of SNe Ia in the Virgo Cluster*

Table 2 lists the 10 SNs Ia that have occurred in the Virgo Cluster for which useful photometry exists. (Galaxies considered to be members of the Virgo Cluster were so identified a priori in another program by Binggeli, Popescu, & Tammann 1993). column (3) shows the morphological types listed in Sandage & Tammann (1987) (RSA2). Six of the 10 have appeared in galaxies of E or S0 type. Four are in spirals.

The mean apparent magnitudes with their errors and observed dispersions are shown at the foot of the table. The true scatter must be smaller than 0.40 mag because of any residual absorption effects in the spirals, observational errors, and the depth effect in the cluster which itself amounts to 0.2 mag if the diameter of the cluster core is 6°.

2.3. *Multiple SNe in Field Galaxies*

Branch & Tammann (1992, their Table 1) list three galaxies that have produced two SNe Ia each. NGC 1316 in the Fornax Cluster is a very early Sa pec with a large S0-like bulge and little dust, NGC 3913 is listed as Sd pec in the RC2 (de Vaucouleurs et al. 1976), and NGC 4753 is an S0 pec. If no absorption corrections are applied (see the next section), the peak luminosities agree to within 0.43 mag in B and 0.08 mag in V from the data listed by BT. Since some absorption probably occurs in NGC 3913, betrayed by the high value of the color of $(m_{pg} - V) = 0.6$ at maximum light of SN 1963J, the upper limit to the intrinsic dispersion in absolute magnitude from these data is 0.4 mag. The true intrinsic scatter must be smaller. Observational errors, errors in the template fits—because in some cases the data were widely extrapolated along the tempate curve—and unaccounted absorption cannot all be zero.

2.4. *Peculiar SNs Ia*

The foregoing sections describe evidence in favor of the precept that SNe Ia are good standard candles. In contrast, van den Bergh & Pazder (1992) and van den Bergh (1992) dismiss SNe Ia as distance indicators because of what they perceive to be a scattered HD produced by including (1) peculiar objects and (2) by applying "absorption" corrections based on adopted color information. We disagree with both procedures for reasons set out in this section and the next.

Peculiar SNe Ia have not been included in the HDs in Figure 1. The fact that particular supernovae can be identified by means independent of their position in the HD is sufficient reason to exclude them. Such objects can always be identified a priori. It makes no sense to include objects known to deviate from properties defined by a prototype when calibrating properties of that prototype. The three peculiar objects excluded from Figure 1 are SN 1986G, 1991bg, and 1991T.

SN 1986G had an unusual ultraviolet spectrum, although normal in the standard optical region. Furthermore, the light curves were very unusual in the infrared. In addition, it was extremely red, being the reddest SN known. Finally it is closer than the Virgo Cluster, which would have excluded it for that reason alone in these diagrams.

SN 1991bg had a very peculiar spectrum and was very red (cf. Leibundgut et al. 1993). Its very faint luminosity in the HD is not the reason for excluding it, but its spectral abnormalities and its reddness are. Note that it is improbable that its faintness and the redness are caused by absorption; the SN occurred in an elliptical galaxy.

The premaximum optical spectrum of SN 1991T was unlike that of any known SN. It is rejected from the list for this reason. However, its color of $(B - V)_{\max} = 0.15$ suggests virtually no absorption (see the next section). Its B magnitude at maximum of 11.65 is only slightly (1.3 σ) brighter (cf. Table 2) than the mean B *if* its parent galaxy, NGC 4527, is at the distance of the Virgo Cluster center. Inclusion of SN 1991T either in Figure 1 or in Table 2 would not significantly change any of the present conclusions. Nevertheless it is excluded because of its abnormal premaximum spectrum.

A more complete discussion of these and other peculiar SN Ia is given in Branch & Tammann (1992, § 2.3).

3. THE INTRINSIC $(B - V)$ COLOR OF SNe Ia AT MAXIMUM

Maximum light occurs at different times at different wavelengths. Hence a definition is required of what we mean by the $(B - V)$ color "at maximum." Enough SNe of Type Ia have adequate relative color curves to show that maximum light in U occurs ~2.8 days before B maximum, and maximum light in V ~ 2.5 days after B maximum (Leibundgut 1988; Branch & Tammann 1992). In what follows we adopt the magnitude and the color to mean at B maximum. Also, the adopted template curves give the two relations (1) $(B - V)_{B(\max)} = B_{\max} - V_{\max}$

TABLE 3

COLORS OF SUPERNOVAE Ia AT B MAXIMUM ($t_B = 0$)

FROM VARIOUS SOURCES					FROM ASIAGO			
SN (1)	Galaxy (2)	Type (3)	$(B-V)$ (4)	$(B-H)$ (5)	SN (6)	Galaxy (7)	Type (8)	$(B-V)$ (9)
1937C	IC 4182	Sdm	+0.20		1965I	NGC 4753	S0 pec	−0.18
1937D	NGC 1003	(Scd)	+0.66		1968E	NGC 2713	Sbc(s) I	−0.28
1956A	NGC 3992	SBb(rs)I	+0.15		1969C	NGC 3811	(SB(n)cd)	−0.02
1959C	A 1308+03	(SBc pec)	−0.08		1970J	NGC 7619	E3	−0.32
1960F	NGC 4496	SBc III-IV	−0.08		1970L	NGC 2968	Am or SO_3 pec	−0.22
1960R	NGC 4382	S0(3) pec	+0.18		1971L	NGC 6384	Sb(r) I.2	+0.48
1962A	A 1304+2080	[S0:]	−0.11		1972H	NGC 3147	Sb(s) I-II	−0.22
1964E	UGC 6983	[SBcd]	+0.57		1972J	NGC 7634	(SB0)	−0.32
1967C	NGC 3389	Sc(s) II.2	0.00		1973N	NGC 7495	[Sc]	+0.28
1971G	NCC 4165	(Sa:)	−0.02		1974G	NGC 4414	Sc(sr) II.2	+0.18
1971I	NGC 5055	Sbc(s) II-III	+0.18		1974J	NGC 7343	[SBbc:]	−0.32
1972E	NGC 5253	Am	−0.07	0.87	1975G	A 1359+5440	[S0:]	−0.02
1975N	NGC 7723	SBb(rs) I-II	+0.18		1975O	NGC 2487	[SBb]	−0.22
1980N	NGC 1316	Sa pec	+0.06	0.70	1975P	NGC 3583	SBc(s) II	+0.18
1981B	NGC 4536	SBc(s) I-II	−0.02	0.78	1976J	NGC 977	[S:]	−0.12
1981D	NGC 1316	Sa pec	+0.28	0.71	1978E	A 2232.8+3657	-	+0.08
1982B	NGC 2268	Sbc(s) II	−0.02		1979B	NGC 3913	[Sd:]	+0.28
1983G	NGC 4753	S0 pec	+0.28	0.47				
1984A	NGC 4419	Sa (dust only)	+0.08					
1989B	NGC 3637	$RSBO_{2/3}$/SBa	+0.55					
1990N	NGC 4639	SBb(r) II	+0.02					

The galaxy types in parentheses are from Barbon, Cappellaro, & Turatto 1989.

− 0.02, and (2) the color at V maximum is $(B-V)_{V(\max)} = (B-V)_{B(\max)} + 0.04$.

Table 3 gives the available color data at B maximum for all non-peculiar SNe Ia with at least semiadequate photometry. The listings are means from data given by Leibundgut et al. (1991a), Hamuy et al. (1991), Leibundgut et al. (1991b), and van den Bergh & Pazder (1992). They have been corrected only for reddening in our Galaxy by the precepts in the RSA catalog (Sandage & Tammann 1981, 1987).

The listed values show a large color range from $-0.32 < (B-V) < +0.66$. This is almost certainly larger than the true range of the intrinsic (reddening-free) color at maximum. The large variation can be attributed to three, possibly coexisting, effects; (*a*) reddening by dust in the parent galaxy, (*b*) a true intrinsic dispersion attributable to SNe Ia as a class having a distribution of finite width (i.e., the intrinsic colors at maximum are not all the same), and (*c*) unreliable colors due to large photometric errors, causing the true intrinsic colors to be considerably redder than the bluest colors in Table 3. Decisions on the three effects are discussed in the following paragraphs.

(*a*). If all the color variation in Table 3 were due to internal absorption in the parent galaxy rather than to a true intrinsic dispersion, then the reddening-free color would be given by the bluest SNe Ia observed. This is the premise by which Barbon et al. (1973) adopted $(B-V)^0 = -0.15$, and Pskovskii (1967) and Cadonau et al. (1985) argued for an even bluer color of $(B-V)^0 = -0.3$ mag.

However, such blue intrinsic colors for all SN Ia lead to unsolvable absorption problems. If the conventional correction for absorption in the blue of $A_B \sim 4E(B-V)$ is applied to each of the SN Ia individually, the unacceptable consequence is that the scatter in the HD (Fig. 1) is *increased*. The same holds for the SNe Ia in the Virgo Cluster. In addition, one obtains conflicts with the highly absorption-sensitive $(B-H)$ colors which, although available only for a few objects, are independent of the observed values of $(B-V)$ (Leibundgut 1988). A full discussion of these discrepancies is given by Branch & Tammann (1992).

The problem has been reversed by van den Bergh & Pazder (1992) leading them to conclude that SN Ia are not standard candles. They reject the more likely explanation, based on Figure 1, that the absorption "corrections" are unreliable. Their conclusion, which we do not support, is based on the assumptions that (1) no debilitating errors exist in the Table 3 photometry or its equivalent, (2) that SN Ia all have the same intrinsic $(B-V)$ color at maximum, and therefore that (3) "absorption corrections" must be applied.

While it is true that a very unusual absorption law of the form $A_B = aE(B-V)$, with a between 1 and 2, can decrease the scatter in the B after applying "absorption corrections" (Jõeveer 1982; Tammann 1982, 1987; Capaccioli et al. 1990; Branch & Tammann 1992), such a law has no physical basis.

Because of the impossible result that applying conventional absorption corrections *increases* the scatter in the HDs, we conclude that the evidence favors the position that no statistical absorption corrections should be applied to the bulk of the SNe Ia in Table 3. We therefore reject proposition (*a*).

(*b*). If part of the observed color variation in $(B-V)$ were to be intrinsic to SNe Ia, it would not necessarily destroy their quality as standard candles if the variation were relatively small. For example, if both M_B(max) and M_V(max) independently scattered by say 0.2 mag due to a postulated spectral energy redistribution, a color range of 0.4 mag could be accommodated, still maintaining a tight hold of 20% on the luminosity variation in each color. If additional photometric errors, and/or some moderate reddening, were also involved, then the color range in Table 2 could be understood.

There is some evidence for a varation in intrinsic color at maximum from the observations of SN 1980N and SN 1981D, both of which appeared in NGC 1316, the brightest galaxy in the Fornax Cluster. Data by Hamuy et al. (1991) show that the apparent magnitudes in U, B, and V at maximum were the same for both SNe to within 0.1 mag. The $(B - V)$ colors at maximum of 0.06 ± 0.10 for 1980N and 0.28 ± 0.10 for SN 1981D differ, but the observations are not as numerous at the crucial maximum phase for SN 1981D as for SN 1980N. Hamuy et al. are not, therefore, convinced themselves that the color difference is real, although they do not dismiss this possibility.

A second conclusion from this photometry comes from the fact that the parent galaxy is of very early Hubble type with only a small amount of dust. Hence, the observed red colors at maximum for both SNe Ia is nearly compelling for us that the mean SNe Ia color at maximum is nearer to $(B - V) = 0.1$ than to -0.3. This point is now developed further.

(*c*). An independent indication of a rather red intrinsic color at maximum comes from the HD for B and V magnitudes separately from Figure 1. Subtracting equation (2) from equation (1) gives $\langle B \rangle - \langle V \rangle = 0.14 \pm 0.10$ for SNe Ia at maximum.

(*c*.1). It was argued in § 2 that the SNe Ia that make up the Figure 1 diagrams have generally little absorption because there is no detectable luminosity bias in the HDs (the slope is $d \log v/dB = d \log v/dV = 0.2$ even for the largest redshifts in the diagrams). If there was appreciable general absorption, then only the brightest, least absorbed galaxies would appear in high redshifts. As discussed earlier, the mean line would then curve upwards at high redshifts. This does not occur in V, and only marginally in *pg* and B.

(*c*.2). A redder color than $(B - V) = 0$ is required by model calculations. Khokhlov, Müller & Höflich (1992) found almost all their models to have a typical color at maximum of $(B - V)_{V(\max)} = 0.16$, which translates to $(B - V)_{B(\max)} = 0.12$ mag.

(*c*.3). We can extend the argument in a previous paragraph concerning the two SNe Ia in NGC 1316 to include other supernovae with minimum absorption from external evidence. The data are set out in Table 4. The mean color at B maximum for the six supernovae listed there is $\langle (B - V) \rangle = 0.11 \pm 0.07$.

TABLE 4

SUPERNOVAE Ia WITH MINIMUM ABSORPTION FROM EXTERNAL EVIDENCE

SN (1)	$(B - V)$ (2)	Remarks (3)
1937C	+0.20	Cf. § 1
1962A	−0.11	In E/S0 galaxy
1972E........	−0.07	Far outlying
1980N	+0.06	Even bluer than 1981D
1981D	+0.28	Far outlying
1983G	+0.28	In S0 pec galaxy
$\langle B - V \rangle$	+0.11 ± 0.07	

(*c*.4). Several SNe Ia from Table 3 exist for which Miller & Branch (1990) have estimated a large value of absorption A_B from their underluminosity in the HD. These SNe are in inclined spirals and (presumably) are on the far side, suffering absorption.[1, 2] Dividing the absorption values of Miller & Branch by 4.2 as the absorption-to-reddening ratio for hot stars (Buser 1978) yields the color excess and intrinsic color values in Table 5. The result is $\langle (B - V) \rangle = 0.05 \pm 0.06$.

(*c*.5). Finally there are five SNe Ia in Table 3 for which the very absorption sensitive colors $(B - H)$ are available (Leibundgut 1988), summarized in Table 6 here. Note that the $(B - V)$ and $(B - H)$ colors are anticorrelated, proving that the *variation* in the listed $(B - V)$ colors is not due to absorption-induced reddening. Therefore, whatever the cause (i.e., intrinsic variation and/or photometric errors), most of the variation cannot be due to absorption. The mean of the five observed $(B - V)$ values, taken to be indicative of an intrinsic color, is $\langle (B - V) \rangle = 0.11 \pm 0.07$.

The colors from these five largely independent methods (Tables 4, 5, 6, the HD, and Table 3 itself) average to $(B - V)^0 = 0.09 \pm 0.04$, which we adopt. Although this is our best value, we are left with the unsolved problem of the very blue entries in Table 3.

Table 3 is divided into two parts. The left entries are from all sources except Asiago. The right-hand entries are the values determined at Asiago alone. It was noticed early that the bluest values are in the right-hand column. Omitting the one highest value (1971L on the assumption that it *is* reddened) gives a mean for the remaining 16 SNe Ia in column (9) of $\langle (B - V) \rangle = -0.08 \pm 0.06$ ($\sigma = 0.22$ mag). On the other hand, the 18 supernovae in column (4), eliminating only the three highest values, gives $\langle (B - V) \rangle = 0.07 \pm 0.03$ ($\sigma = 0.13$ mag). The eight SNe Ia since 1970 (where modern photometry exists), that are not heavily absorbed, give $\langle (B - V) \rangle = 0.04 \pm 0.03$ ($\sigma = 0.11$ mag).

Concerning at least the left-hand values, it may be surprising that these objects exhibit closely our adopted intrinsic color and therefore, on these precepts, suffer virtually no absorption. But note that the result conforms well with the HDs of Figure 1 from which we argued (§ 2) that SNe Ia at the Virgo Cluster distance and beyond experience no detectable luminosity (and therefore no detectable absorption) bias; the slope of the HD is 0.2 for all redshifts in the sample.

What, then, of the colors in column (9) of Table 3? These average 0.15 mag bluer than the mean of column (4), which is a difference of two standard deviations of the combined mean errors. They have also considerable scatter of $\sigma = 0.22$ mag compared with a scatter of only $\sigma = 0.11$ mag for the eight SNe Ia since 1970.

The early Asiago photometry before 1980 was generally based on local photometric standards determined by photo-

TABLE 5

SUPERNOVAE Ia WITH ABSORPTION VALUES FROM MILLER & BRANCH (1990)

SN (1)	$(B - V)$ (2)	AB (3)	$EB - V$ (4)	$(B - V)^0$ (5)
1937D	0.66	1.92	0.46	+0.20
1971I	0.18	1.22	0.29	−0.11
1975N	0.18	1.04	0.25	−0.07
1989B........	0.55	1.50	0.36	+0.19
$\langle B - V \rangle$				+0.05 ± 0.08

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[1] Only two have entered the HD of Fig. 1 because almost all of the highly absorbed objects of Miller & Branch are nearer than the Virgo Cluster. This is our cutoff distance for inclusion in Fig. 1, and therefore, no matter what other characteristics they may or may not possess, would not be in our sample. SN 1981D, for which Miller & Branch (1990) also give a high absorption, is excluded in Table 5 because it is outlying and the parent galaxy, a very early spiral, is *not* inclined. The inclusion of SN 1981D would, in any case, not change the result in Table 5.

[2] There is a natural discrimination against absorbed SNe at large distances because of the flux limitations in all discovery programs. Such faint SNe Ia in highly inclined galaxies at high redshifts would not be found in a flux-limited search program. Hence, most would not be in the sample, and therefore are not a debilitating contaminant in Fig. 1.

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TABLE 6

Supernovae Ia with $(B - H)$ Colors

SN (1)	$(B - V)$ (2)	$(B - H)$ (3)
1972E........	−0.07	0.87
1980N	−0.06	0.70
1981B........	−0.02	0.78
1981D	+0.28	0.71
1983G	+0.28	0.47:
$\langle B - V \rangle$	$+0.11 \pm 0.07$	

graphic transfers from external standards, and in two cases, without the use of an ultraviolet blocking filter (M. Capaccioli, private communication). But a definitive explanation of the very blue Asiago colors must await the remeasurement of the local standards near each of the supernovae in Table 3.

To summarize this section: We are convinced by the impossible effect of "absorption" corrections that give increased scatter for the HDs (van den Bergh & Pazder 1992) that (1) most of the SNe Ia in Tables 1 and 3 are nearly absorption-free, (2) the intrinsic color at B maximum is close to $(B - V)^0 = 0.09 \pm 0.04$, and (3) there is no compelling, evidence for an unorthodox value for the ratio of absorption-to-reddening other than $A_B \approx 4E(B - V)$ for SNe Ia.

4. MEAN CALIBRATION OF M_B AND M_V FOR SNe Ia AT MAXIMUM

If SNe Ia are as good standard candles as we have argued in § 2, the luminosity calibration of a single normal member of the class would be decisive. But even if the dispersion in M(max) is finite, provided it is small enough (i.e. $\sigma < 0.2$ mag as we have also argued), only a few such calibrations would suffice to determine $\langle M(\text{max}) \rangle$ to within say 10% (0.1 mag). This is sufficient accuracy to obtain individual galaxy distances to within 5% with a corresponding accuracy of the Hubble constant.

If this is true, the single calibration of SN 1937C in IC 4182 via the Cepheid distance to this galaxy (Sandage et al. 1992; Saha et al. 1993) would itself be nearly decisive in finding H_0 (depending on the true value of σ_{max}).

In this section we combine the determination for SN 1937C in IC 4182 with three other independent calibrations.

1. The IC 4182 calibration, based on $(m - M)^0 = 28.4 \pm 0.13$ and the revised photometry of SN 1937C discussed by Saha et al. (1993) give the absolute magnitudes at B maximum for SN 1937C as

$$M_{\text{pg}}(\text{max}) = -19.83 \pm 0.16 \,, \tag{4}$$

$$M_B(\text{max}) = -19.54 \pm 0.18 \,, \tag{5}$$

$$M_V(\text{max}) = -19.76 \pm 0.16 \,. \tag{6}$$

2. Although Type II SNe are not standard candles, nevertheless each individual event can be studied by the expanding-envelope method (a variation of Baade-Wesselink) to obtain a distance to it. A history of the development of the method, first suggested by Searle in conversation with Kirshner, is given by Kirshner (1985), as it was first applied by Kirshner & Kwan (1974) to SNs II, following the application to Type I SNe by Branch & Patchett (1973).

Many later improvements have been made such as those by Wagoner (1981, 1991) and others cited in the current literature. The most recent application of an improved method by Schmidt, Kirshner, & Eastman (1992) gives "expanding envelope" distances to 10 Type II SNe, *two of which are in the Virgo Cluster.* Their Virgo Cluster distance derived from these two events is 22 ± 3 Mpc (or $m - M = 31.7 \pm 0.3$), in excellent agreement with an earlier determination (Sandage & Tammann 1990) made largely by methods other than SNe.

As our purpose in this paper is to calibrate the peak luminosity of SN Ia, the importance of the Schmidt et al. Virgo distance is that it calibrates Table 2 for the Virgo Cluster SNe Ia independently of all other considerations of the SNe Ia phenomenon. Using their value of $(m - M)_{\text{Virgo}} = 31.7 \pm 0.3$ gives, from Table 2

$$M_{\text{pg}}(\text{max}) = -19.91 \pm 0.34 \,, \tag{7}$$

$$M_B(\text{max}) = -19.58 \pm 0.33 \,, \tag{8}$$

$$M_V(\text{max}) = -19.57 \pm 0.33 \,. \tag{9}$$

3. Branch (1985, 1992) has determined the nickel mass and the peak luminosity from the light curve of SNe Ia with the result that $M_B(\text{max}) = -19.44 \pm 0.35$. He has since increased the luminosity to

$$M_B(\text{max}) = -19.61 \pm 0.35 \,, \tag{10}$$

using an improved radiation-transport calculation by Khokhlov and collaborators (Schwarzschild 1992). From equation (10) and $(B - V)^0 = 0.09$ at B(max), it follows that M_V (at B maximum) $= -19.70 \pm 0.35$, and therefore that

$$M_V(\text{max}) = -19.72 \pm 0.35 \tag{11}$$

at V maximum.

4. Khokhlov et al. (1992) have calculated the light curves from a set of theoretical models, giving

$$M_V(\text{max}) = -19.57 \pm 0.4, \tag{12}$$

which translates back to

$$M_B(\text{max}) = -19.48 \pm 0.4 \,, \tag{13}$$

neglecting the difference in color between B and V maximum.[3]

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[3] After this paper was completed, new model calculations by Müller & Höflich (1993, hereafter MH) of the light curves of 13 individual SNe Ia became available. The unique feature of these models is that the parameters of the explosions are varied to fit the individual light curves on the assumption that the observations themselves contain no errors, and therefore that the light curve variations are real. Although we are not convinced that such differences *are* real, nevertheless, the MH models do show the sensitivity of the absolute magnitudes at maximum to various variations of initial explosion conditions. This work is an extension, in principle, of the work of Canal et al. (1991).

Müller & Höflich conclude that "the spread in the individual brightness based on the theoretical models is small for the 'standard' models ($M_V = -19.68 \pm 0.12$ mag) and somewhat larger ($M_V = -19.21 \ldots -19.47$) for the 'non-standard' models."

On the assumption that is consistent with our precept that the standard template is invariant, we derive from

$$\log H_0 = 0.2 M_V(\text{max}) + (5.653 \pm 0.012) \,,$$

which follows straightforwardly from eq. (3) of the text, that

$$H_0 = 52 \pm 10 \text{ km s}^{-1} \text{ Mpc}^{-1} \,,$$

using $\langle M_V \rangle = -19.68 \pm 0.12$ from the MH standard model, fitted to the V in Fig. 1*c*.

The error in this value of H_0 is calculated as if the (true) range in Fig. 1*c* is ± 0.4 mag, although we believe this to be unrealistically high by the arguments of this paper. It is also higher than the ± 0.12 mag from the MH "standard model."

But even if all SNe Ia do not conform to the "standard model." and some were fainter following MH, as if light curve variations are real, such faint SNe Ia would be discriminated against in Fig. 1 due to their lower chance of discovery in a flux-limited search program.

The averages of the various equations (4)–(13), weighted by the inverse square of the quoted errors, are

$$M_{\rm pg}({\rm max}) = -19.84 \pm 0.14 \ , \qquad (14)$$

$$M_B({\rm max}) = -19.55 \pm 0.14 \ , \qquad (15)$$

$$M_V({\rm max}) = -19.71 \pm 0.13 \ , \qquad (16)$$

as our final calibration using the extant literature data deemed to be reliable.

Note that equation (15) differs by 1 mag brighter than the calibration adopted by de Vaucouleurs (1985, 1993) upon which he has based his short distance scale and high value of the Hubble constant.

It is also useful to note that the calibration here agrees with the prevous independent analyses of Tammann (1987), and of Leibundgut & Tammann (1990) from different precepts using earlier data.

5. THE INTERIM VALUE OF H_0

The Hubble constants determined from equations (4)–(16), applied in an obvious way to the HDs of Figure 1, using equations (1)–(3), are

$$H_0({\rm pg}) = 52.7 \ {\rm km\ s^{-1}\ Mpc^{-1}} \ , \qquad (17)$$

$$H_0(B) = 52.5 \ {\rm km\ s^{-1}\ Mpc^{-1}} \ , \qquad (18)$$

$$H_0(V) = 51.4 \ {\rm km\ s^{-1}\ Mpc^{-1}} \ . \qquad (19)$$

The formal errors, based only on the quoted errors for the position of the ridge lines in Figure 1, are close to ±4 km s^{-1} Mpc^{-1}. The true errors depend, of course, on the actual dispersion of the peak luminosity of SNe Ia.

If the observational calibration of SN 1937C alone via the Cepheids in IC 4182 were used, i.e., $M_V({\rm max}) = -19.76 \pm 0.16$ from equation (6), then $H_0 = 50 \pm 7$. Here the error allows, besides the uncertainty on M_V itself from equation (6), an additional scatter of $\sigma(M_{V_{\rm max}}) = 0.2$ mag for a single SN.

It is the value of this intrinsic dispersion that must be determined next by the extension of the *HST* program mentioned in the Introduction so as to finally test the arguments we have used here in § 2.

Finally, if we adopt the calibration of SN 1937C from the Cepheids in IC 4182 as definitive at $M_V({\rm max}) = -19.76 \pm 0.16$, then the modulus of the Virgo Cluster from the SNe Ia data in Table 2, which shows a mean magnitude of $\langle V \rangle = 12.13 \pm 0.14$, is $(m - M)^0 = 31.89 \pm 0.21$. This is a distance of 23.9 ± 2.4 Mpc. It has been shown elsewhere (Sandage & Tammann 1990) that the tie into the global value of H_0 via the Virgo Cluster distance is

$$H_0 = 52(21.9/D_{\rm Virgo}) \ , \qquad (20)$$

giving thereby

$$H_0 = 47 \pm 5 \ {\rm km\ s^{-1}\ Mpc^{-1}} \ . \qquad (21)$$

It is clear that this value is independent of any and all assumptions concerning the form of the HD of SNe Ia. This is because equation (20), that ties the Virgo Cluster expansion velocity into the global cosmological field, was derived by a route that is *nearly independent of supernovae data* (Sandage & Tammann 1990, Fig. 1), showing, incidently, that the solution to the distance scale dilemma proposed by Turner, Cen, & Ostriker (1992) cannot be correct.

It remains only to state that the Virgo Cluster distance of 22 Mpc ($m - M = 31.7$) from Type II SNe by Schmidt et al. (1992) is in precise agreement with the distance determined from globular clusters, and also in good agreement with the D_n-σ method, and the relative size of the Galaxy, of M31, and of M101 compared with field spirals (Sandage & Tamman 1990; Tammann 1992a; Sandage 1993b, c).

The Tully-Fisher method, when properly corrected for observational bias also gives this large distance (Kraan-Korteweg, Cameron, & Tammann 1988; Sandage 1988a, 1993a, b; Sandage, Tammann, & Federspiel 1993). Only the metal-dependent surface brightness fluctuation method (cf. Tammann 1992a) and the planetary nebulae method, both of which, it must be stated, do have internal consistency checks, are in contradiction with this result (Bottinelli et al. 1991; Tammann 1992b).

It is in the nature of science to believe that further work will, beyond any doubt, eventually solve these present discrepancies. Some of the present methods must simply be wrong.

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