The observations of the Cepheid variables in the Large Magellanic Cloud (LMC) have shown that the absolute magnitude of the Cepheid variable is reduced by a factor of two or more compared to the absolute magnitude of the Cepheid variable in the Solar System. The reduction is thought to be due to the effect of the Cepheid variable on the distance to the LMC.

The Cepheid variable is a variable star that has a periodic brightness variation due to the changing size of the star. The Cepheid variable is used to measure the distance to other stars and galaxies. The Cepheid variable is also used to study the structure and evolution of stars.

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1. Introduction

Supernovae of type Ia (SNe Ia) are the prime distance indicators for the determination of the Hubble constant \( H_0 \) since they can be followed out to large distances, and since it is possible to determine Cepheid distances with HST for the nearest of their host galaxies and hence to calibrate their luminosity at maximum (Sandage et al. 1992). This immediately yields the distances of the more distant SNe Ia because they are – if restricted to blue objects – the best standard candles known with a luminosity scatter of less than \( \sigma_M = 0.25 \). As standard candles they are now so heavily relied upon that they are even used for the much more sensitive test for the cosmological constant \( \Lambda \) (Riess et al. 1998b; Perlmutter et al. 1999). A wealth of excellent photometric data for SNe Ia has been accumulated since 1985 by the Calán/Tololo team (Hamuy et al. 1996b) and others. They reach out to \( \sim 30,000 \) km s\(^{-1}\), i.e. far enough to avoid the effects of peculiar and streaming motions. In parallel, the HST Supernova Project has by now provided Cepheid-calibrated luminosities for six nearby SNe Ia (Saha et al. 1999), not counting SN 1895 B for which only the B magnitude is known. These are augmented by two additional calibrators from Tanvir et al. (1995) and Turner et al. (1998). With a total of eight calibrators and three dozen more distant SNe Ia, the statistics rests on solid ground.

The one remaining question is whether the calibrators and the distant SNe Ia are genuine twins, or whether the different selection criteria cause systematic differences between the samples. For instance, the Cepheid distances of the calibrators imply that they lie in galaxies containing young-population stars, whereas the distant SNe Ia have also been observed in S0 and E galaxies. Various second parameters have been proposed to correlate with SN luminosity; they can serve as a control of luminosity differences between the nearby calibrators and the distant SNe Ia. From the point of view of the physicist the most interesting second parameters are several spectral features which are known to correlate with luminosity (Nugent et al. 1995; Fisher et al. 1995, 1999; Riess et al. 1998a; Mazzali et al. 1998). But the available data are too sparse to be useful in the present context. One is therefore reduced to empirical second parameters such as light curve shape, SN color, Hubble type and position in the parent galaxy. Second parameters have been discussed by, e.g., Phillips (1993); Tammann & Sandage (1995); Vaughan et al. (1995); Hamuy et al. (1996a,c); Tripp (1998); Tripp & Branch (1999); Saha et al. (1999); Riess et al. (1999); Jha et al. (1999); Phillips et al. (1999); Suntzeff et al. (1999); Gibson et al. (2000a).

The difficulty to find a correlation between SN Ia luminosities and the second parameters in face of an intrinsic scatter of \( \sigma_M \lesssim 0.25 \) is that very accurate relative distances are required. Cepheid distances and, e.g., Tully-Fisher distances are not sufficiently accurate for the purpose. SNe Ia in the Virgo cluster cannot be assumed to lie at the same distance because of the important depth effect of the cluster. Regress must therefore be taken to the relative distances that are indicated by recession velocities. All velocities \( v > 1200 \) km s\(^{-1}\) are taken as indicative of the relative distances. This is permissible because the errors assigned to the relative distances and to the resulting relative absolute magnitudes make allowance for reasonable values of the peculiar velocities (Section 2.1).
The purpose of the present paper is to discuss the correlation of second parameters with the peak luminosity of SNe Ia — using an enlarged and well-defined sample of distant SNe Ia — and to determine the value of the Hubble constant. The SNe Ia magnitudes, after correction for decline rate $\Delta m_{15}$ and color $(B-V)$, have a scatter of only $\sigma_{M} \angle 0.013$. In fact the magnitude-corrected SNe Ia define the Hubble diagram so well that a flat Universe model with $\Omega_M=0.3$, $\Omega_{\Lambda}=0.7$ gives a marginally better fit than an $\Omega_M=1$ model. The corrected magnitudes, if combined with the corrected absolute magnitudes of eight Cepheid-calibrated SNe Ia, determine $H_0$ with a very small statistical error.

The organization of the present paper is as follows. In Section 2 the available data for blue SNe Ia are compiled, and their luminosity calibration by means of eight SNe Ia with known Cepheid distances is discussed. The SNe Ia colors and extinctions are discussed in Section 3. The Hubble diagram is shown in Section 4. In Section 5 the SN Ia luminosities are discussed in function of decline rate $\Delta m_{15}$, SN color $(B-V)$, Hubble type $T$, and position in the parent galaxy. The effective Hubble diagram with decline-rate and color corrected magnitudes is shown in Section 6, and the resulting values of $H_0$ are derived. Alternative solutions are explored in Section 7, and the conclusions are given in Section 8.

2. The Photometric Data

2.1. Blue SNe Ia within $v \lesssim 30\,000 \, \text{km s}^{-1}$

The available data for all SNe Ia ($n=67$) with $(B_{max}-V_{max}) \leq 0.20^4$ (after correction for Galactic reddening following Schlegel et al. (1998)), and with $v \lesssim 30\,000 \, \text{km s}^{-1}$ (the two largest accepted velocities are $v=30\,269 \, \text{km s}^{-1}$ of SN 1992aq and $v=37\,325 \, \text{km s}^{-1}$ of SN 1996ab) are compiled in Table 1.

The individual columns bear the following information:

(1): The supernova designation. If followed by an acceptance sign $\checkmark$ the SN is included in the fiducial sample (see below). (2): The Hubble type of the parent galaxy as coded by de Vaucouleurs (1974), but slightly simplified for the early and latest types: E: T=3; E/S0: T=-2; S0: T=-1; S0/a: T=0; Sa: T=1; Sab: T=2; Sb: T=3; Sbc: T=4; Sc, Sd, Sm & Im: T=5. The Am galaxy NGC 5253 (SN 1972 E) has tentatively been ascribed the type T=5. (3): The decimal logarithm of the galaxy redshift velocity cz. Most redshifts are from the Lyon/Mendon Extragalactic Database (LEDA; http://www-obs.univ-lyon1.fr); additional redshifts were taken from Hamuy et al. (1996b) and Riess et al. (1999). They were corrected for the motion of the Sun relative to the centroid of the local group (Yahil et al. 1977) and for a self-consistent VirgoSchmal model with a local infall vector of $220 \, \text{km s}^{-1}$ (Kraan-Korteweg 1986); beyond $v_{20} = 3000 \, \text{km s}^{-1}$ an additional correction

\footnote{In the following we write for $(B_{max}-V_{max})$ and $(V_{max}-I_{max})$ more conveniently $(B-V)$ and $(V-I)$.}
for the motion of 630 km s\(^{-1}\) relative to the CMB dipole anisotropy (Smoot et al. 1992) was applied. Varying the size of the local co-moving volume between 2000 and 10 000 km s\(^{-1}\) has no significant effect on the present conclusions. For the members of three clusters the following mean velocities were assumed: for Cen A group members \(v_{220} = 290\) km s\(^{-1}\) (Kraan-Korteweg 1986), for Virgo cluster members, as assigned by Binggeli et al. (1993), \(v_{220} = 1179\) km s\(^{-1}\) (Jerjen & Tamann 1993), for Fornax cluster members, as assigned by Ferguson & Sandage (1988), \(v_{220} = 1440\) km s\(^{-1}\) (Tamann & Federspiel 1997). The errors of \(\log v\) in units of 0.01 are shown in parentheses; they are compounded from the observational errors and the peculiar velocities, assumed to be 200 km s\(^{-1}\) within 1500 km s\(^{-1}\), 400 km s\(^{-1}\) for 1500 < \(v\) < 3000 km s\(^{-1}\), and 600 km s\(^{-1}\) beyond 3000 km s\(^{-1}\). \(\text{(4)-(6):}\) \(B\)-, \(V\)-, and \(I\)-band apparent peak magnitudes. They are in the Cerro Tololo system of fitting light curve templates (Hamuy et al. 1996b,c). The template fitting for the observations by Rieiss et al. (1999) was done by us. All magnitudes are corrected for Galactic absorption. Where applicable, the K-correction (Hamuy et al. 1993) was taken into account. The magnitude errors in units of 0.01 were taken from the original literature or were estimated by us. \((7):\) The Galactic absorption \(A_V\) from Schlegel et al. (1998), assuming \(A_B=4.3E(B-V)\), \(A_V=3.3E(B-V)\), and \(A_I=2.0E(B-V)\) throughout. \((8):\) \(\Delta m_{15}\) being the decline in magnitudes of the \(B\) light curve during the first 15 days after maximum, as defined by Phillips (1993). The magnitude errors in units of 0.01 were taken from the original literature or were estimated by us. \((9):\) The onset of the photometric data given in days before (minus signs) and after (plus signs) \(B\) maximum. \((10):\) References for the photometric data \(B\), \(V\), \(I\) and \(\Delta m_{15}\). \((11)-(13):\) Absolute magnitudes at maximum as calculated from the apparent magnitudes in columns (4) to (6) and from the recession velocities in column (3). A flat matter universe \((\Omega_M=1)\) and a value of \(H_0 = 60\) km s\(^{-1}\) Mpc\(^{-1}\) is assumed. As a consequence all listed absolute magnitudes scale, except for peculiar velocities, with \(5 \log (H_0/60)\). The errors in units of 0.01 are compounded from the errors given in columns (3) and (4) to (6), respectively. No absolute magnitudes were calculated for SNe Ia in the field with \(v_{220} < 1200\) km s\(^{-1}\) because their velocity distances are too unreliable due to peculiar motions, and for five SNe Ia in Virgo cluster galaxies because of the considerable cluster depth. For four SNe Ia of Table 1 independent absolute magnitudes from Cepheid distances are given in Table 3; they are marked with asterisks.

In the following the overluminous SN 1991T (Phillips et al. 1992) and its twin SN 1995ac (Garnavich et al. 1996) are left out because they are spectroscopically peculiar, leaving in Table 1 59 blue SNe with \((B-V)<0.20\) and \(v_{220} \geq 1200\) km s\(^{-1}\). The observations of six SNe Ia after 1985 in Table 1 begin only eight days after maximum or later. Their extrapolated maximum magnitudes may be less accurate (Phillips et al. 1999). In the diagrams to follow they are shown with small symbols, but they have no systematic effect on any of the conclusions below and are included in the equations below with their errors as given in Table 1. The observations of SN 1992au begin only 15 days after \(B\) maximum and are not considered in the following.

In Table 2 data are compiled that are relevant for a localization of the SNe Ia of Table 1 within their host galaxies. Columns (1) to (6) are self-explanatory. The diameters \(D_{25}\) (in arcsec), given
in column (7) where available, are taken from the on-line Asiago Supernova Catalogue (Cappellaro 1998) and the RC3 (de Vaucouleurs et al. 1991). Columns (8) and (9) give the supernova offsets in the E/W and N/S directions as taken from Cappellaro (1998) and from Riess et al. (1999). The projected galactocentric distances of the SNe in units of the galaxy radius \( r_{25} (= D_{25}/2) \) are given in column (10); they are distance-independent.

2.2. The Cepheid-calibrated SNe Ia

Table 3 lists the nine SNe Ia for which Cepheid distances and therefore absolute magnitudes are known. The apparent or true distance moduli from Cepheids and their sources are given in columns (4) to (7). The moduli from the WFPC 2 are corrected by \( +0.05 \) for the photometric short exposure/long exposure zeropoint effect (Stetson 1995; Saha et al. 1996a). The apparent \( B, V, \) and \( I \) magnitudes at maximum (uncorrected for Galactic absorption) and their sources are in columns (8) to (11). The total color excesses \( E_{B-V} \) (Galactic and within the host galaxy) and their sources are listed in columns (12) to (13). The absorption-corrected apparent magnitudes \( B^0, V^0, \) and \( I^0 \) are given in columns (14) to (16). The absolute magnitudes \( M_B^0, M_V^0, \) and \( M_I^0 \) follow in columns (17) to (19). For the first four SNe Ia the absolute magnitudes are derived by subtracting the apparent distance moduli from the respective apparent magnitudes on the plausible assumption that the Cepheids and the corresponding SN Ia suffer the same (small) amount of absorption. In the remaining cases either the Cepheids have variable absorption or the SN suffers additional absorption in its host galaxy. In these cases the absolute magnitudes come from subtracting the true distance moduli from the true magnitudes. Finally, the decline rates \( \Delta m_{15} \) in column (20) are taken from the references in column (11). The straight and weighted mean absolute magnitudes of eight SNe Ia in Table 3 are given at the bottom of the Table. The bright SN 1895B is not included because its \( V \) maximum is known too poorly. — The adopted absolute magnitudes are in fortuitous agreement with theoretical models of blue supernovae (Höflich, P., & Khokhlov 1996) and Branch's (1998) discussion of the physical properties of SNe Ia.

Five SNe in Table 3 are not included in Table 1. SN 1895B has no reliable color information. SNe 1989B and 1998bu are observed to be much redder than \( (B-V)=0.20 \). SNe 1974G and 1981B are known, in spite of their rather blue color, to suffer reddening in their host galaxy.

The eight Cepheid distances adopted in Table 3 have been re-analysed by Gibson et al. (2000b) (hereafter G00). They have used ALLFRAME photometry and the associated method of detecting variable stars. They claim that their re-analysis places their galaxy distances on the same footing as the distances of galaxies contained in the Mould-Freedman-Kennicutt (MFK; e.g. Mould et al. 2000) program. However, this claim is questionable for several reasons:

(i) While the MFK team has consistently quoted photometry from ALLFRAME (though DoPHOT magnitudes have also been presented for comparison), their list of Cepheids comprised objects independently detected by both ALLFRAME and DoPHOT. The Sandage/Saha consor-
tium have based their Cepheid selection and photometry on DoPHOT alone. A salient result of the G00 re-analysis is that the agreement of the photometry of stars that are \textit{in common} between them and the Sandage/Saha team must be excellent, because if one compares only the 118 Cepheids in common in six galaxies (as given in Table 3 of G00), the difference in the magnitudes averages to be $\Delta V = 0''044 \pm 0''002$, $\Delta I = 0''038 \pm 0''004$, in the sense that the ALLFRAME-based magnitudes are brighter. Thus if the procedure that was actually used to derive distances by the MFK team in their program is applied, the agreement between ALLFRAME- and DoPHOT-based magnitudes in $V$ and $I$, and hence in moduli, is as good as one can expect, and the confidence in the DoPHOT-based results is bolstered.

However, G00 have added Cepheids found only by ALLFRAME. These “extra” Cepheids drive a distinctly different result, increasing the mean difference DoPHOT-moduli (of the Sandage/Saha team) minus ALLFRAME-moduli (of G00) to 0''17. Had G00 reported results that are truly on the same footing as the rest of the MFK team analysis, they would not have seen the 0''17 “discrepancy”.

ii) G00 specially point out that in the case of NGC 4536 Saha’s et al. (1996a) Cepheids in Chip 2 of the WFPC2 give a distance modulus that is larger by 0.66 mag, which is the result of differences in the photometry in $V$ and/or $I$ by order of 0.25 mag. G00 do not see this discrepancy in their own reduction: their photometry in all four chips are in mutual agreement, and also in nominal agreement with Saha’s et al. (1996a) photometry in chips 1, 3, and 4. It is worth emphasising that the region of the galaxy imaged in chip 2 is different in character from that in chips 3 and 4 (chip 1 is similar to chip 2, but there are too few Cepheids to make a statistically significant difference): the latter are dominated by the outer spiral arms, but chip 2 shows the more amorphous inner regions. Such changes in environment can contribute different levels of confusion noise, and consequently result in mis-calibration of the zero-point. To be consistent with their work in other galaxies and having no external information on which chip is best, Saha et al. (1996a) have combined their Cepheids, as measured, in a single PL relation and have derived an average distance modulus, their rationale being that the exceptional chip-to-chip variation of NGC 4536 may just be the result of an unusually large \textit{statistical} fluctuation. The point illustrates that the chip-to-chip variations of the aperture correction in crowded regions is the weakest link in WFPC2 photometry. Cepheid moduli from the WFPC2 therefore always carry an uncertainty of 0.10-0.15 mag. The error is random from galaxy to galaxy and is therefore reduced by a sufficient number of calibrators.

(iii) The analysis of G00 differs also from the present one in the way the reddening is handled, both of the Cepheids as well as of the SNe Ia. The G00 approach is to always de-redden the Cepheids, and then to obtain the de-reddened modulus to the host galaxy. This approach is unavoidable if the extinction of the Cepheids is much larger than that of the SN Ia (NGC 4639 with SN 1990N), if the Cepheids have differential reddening (NGC 3627), or/and if the SNe Ia have large, but pre-determined redenings (SN 1974G, 1981B, 1989B, and 1998bu). Yet de-reddening procedures demand exquisite photometry, since the ratio of total to selective absorption amplifies the uncertainties in the photometry. Therefore, instead of going through the de-reddening twice
(once for the Cepheids and once for the SNe Ia), it is preferable to assume that the reddening of the Cepheids and of the SNe Ia is the same whenever the reddening is small (≤0.03). In that case the SN luminosity is obtained by simply subtracting the apparent distance modulus from the apparent SN magnitude. This procedure has been applied for the first four entries in Table 3.

After the reddening corrections of G00 are applied, the “discrepancy” of 0.17 drops to 0.04, 0.07, and 0.15, in $M_B$, $M_V$, and $M_I$, respectively. The consequence of this calibration then is — if applied to the fiducial sample — that the value of $H_0(I)$ becomes larger by five percent than $H_0(B)$ while with the present calibration in Table 3 the values of $H_0$ agree almost exactly in all three passbands (cf. Section 4).

Remaining systematic error sources, which may affect the calibrators, are discussed in Section 6.

3. The Colors of SNe Ia

3.1. Justification for the blue sample of SNe Ia

In Table 1 and in the following sections only SNe Ia with $(B-V) \leq 0.20$, called blue SNe Ia, are considered. This color cut needs justification. In Figure 1 all SNe Ia between 1985 and 1996 with known peak magnitudes are plotted, unrestricted as to color $(B-V)$. The restriction to SNe Ia after 1985 is here and in the following indicated because the advent of CCD photometry has much improved the photometric accuracy. The SNe Ia colors are only corrected for Galactic reddening. 44 SNe Ia are strongly concentrated toward a mean color of $(B-V)=0.02$ with a scatter of only $\sigma_{B-V}=0.05$. This small scatter is even the more surprising as Hamuy et al. (1996b, Table 6) list an average observational error in color of 0.06. The true color scatter of this subsample could therefore be arbitrarily small. As far as spectra of this blue subsample are known they are all Branch-normal (Branch et al. 1993), the only exceptions being the twins SN 1991 T and 1995ac with peculiar early spectra. As mentioned before they are excluded in the following.

The 10 SNe Ia in Fig. 1 with $(B-V)>0.20$ contain a high fraction of spectroscopically peculiar objects, like the very red and strongly underluminous SN 1991bg and the low-expansion velocity SN 1986G and their counterparts, as well as some presumably strongly reddened SNe Ia. These red SNe Ia clearly form a very heterogeneous group.

It is obvious that if SNe Ia are to be used as standard candles, one must concentrate on the homogeneous class of blue SNe Ia.

3.2. The true colors of SNe Ia

Even the sample of 42 blue SNe Ia may be affected by some internal reddening. Their true colors are best reflected by SNe Ia that have occurred in E/S0 galaxies or lie in the outer regions
of spirals. Outlying SNe Ia are here defined as having \(r/r_{25}>0.4\), where \(r\) is the radial distance from the center of the host galaxy (in arcsec), and \(r_{25}\) is the de Vaucouleurs radius of that galaxy (in arcsec). The \(r/r_{25}\) values are listed in Table 4 for all SNe for which the necessary data are available. The relative radial distance \(r/r_{25}>0.4\) corresponds roughly to the limit to which the spiral structure can be traced.

Table 4 lists the mean colors \(<B-V>\) and \(<V-I>\) of all SNe Ia in E/S0 galaxies, of the outlying SNe Ia in spirals, and of the calibrators in Table 2. The three groups have closely the same mean colors, i.e. \(<B-V>=-0.012\pm0.051\) and \(<V-I>=-0.276\pm0.078\). The overall means are therefore adopted as the true colors of SNe Ia in E/S0s and spirals alike.

Phillips et al. (1999) have instead derived the intrinsic colors by assuming that all SNe Ia with \(E(B-V)_{\text{true}}<0.06\) are unreddened. (For their new method to derive \(E(B-V)_{\text{true}}\) see the original paper). They give \(E(B-V)\) and \(E(V-I)\) values for 40 SNe Ia with B- and 32 SNe Ia with I-magnitudes in their Table 1. If these color excesses are applied to the magnitudes in Table 1 one obtains mean colors of \(<B-V>=-0.051\pm0.007\) and \(<V-I>=-0.331\pm0.013\), i.e. noticeably bluer by \(~0.04\) than adopted in Table 4. It seems therefore that the color excesses of Phillips et al. (1999) are too large. The difference is not trivial when converted to absorption, i.e. \(A_B\approx0.16\); it has, however, no effect on \(H_0\) as long as the adopted colors of the calibrators and the distant SNe Ia are the same.

### 3.3. Blue, yet reddened SNe Ia

The question remains whether some of the SNe Ia in the inner regions of the spirals, i.e. \(r/r_{25}<0.4\), are affected by internal absorption. Figure 2 shows the correlation as to color \((B-V)\) with radial distance for all SNe Ia for which the necessary data are available. There are five inner SNe Ia in spirals which are redder than \((B-V)=0.06\). Since their absolute magnitudes are also fainter than average they are strong candidates for some internal absorption. They are listed in Table 5 together with two additional SNe Ia that fulfill the same color and magnitude requirement, but for which \(r/r_{25}\) is not available.

The colors \((B-V)\) and \((V-I)\) in columns 3 and 4 of Table 5 are from data in Table 1. These colors and the adopted mean color in Table 4 give the excesses \(E(B-V)\) and \(E(V-I)\). If these are averaged, giving double weight to the former and assuming \(E(B-V)=0.6\ E(V-I)\), one obtains the mean excesses \(E(B-V)\) in column 5, which in turn lead to the absorption-corrected apparent (columns 6 to 8) and absolute (columns 9 to 11) magnitudes of the SNe Ia. They are on average close to the absolute magnitudes of the unreddened SNe Ia. Phillips et al. (1999) have given reddening values for four objects in Table 5; they are also above average. The strongest argument for the internal extinction is, however, that at given \(\Delta m_{15}\) they are fainter on average by \(0.38\) in \(B\), \(0.30\) in \(V\), and \(0.14\) in \(I\) than their unreddened counterparts (cf. below, Section 5.1). This magnitude difference practically disappears once the extinction corrections have been applied.
Because the seven SNe Ia of Table 5 being reddened cannot be proved beyond doubt, they are excluded henceforth. If they had been retained without absorption correction they would slightly decrease the value of $H_0$; if included after the absorption correction they would not have a net effect on $H_0$.

It is reassuring that the remaining 10 SNe Ia in spirals, which have $r/r_2<0.4$ or for which no information is available as to radial distance, have closely the same mean colors as the unreddened SNe Ia (Table 4).

4. The Hubble Diagram

After the exclusion of SNe 1991T and 1995ac, and the I-band magnitude of SN 1992au, as well as the seven SNe Ia in Table 5, Table 1 contains 35 (29 of which have also I-magnitudes) blue, unreddened SNe Ia after 1985 and with $v>1200$ km s$^{-1}$. They are referred to in the following as the fiducial sample. Their Hubble diagrams in $B$, $V$, and $I$ are shown in Fig. 3. Fitted to the data is a Hubble line assuming a flat Universe with $\Omega_M=0.3$ and $\Omega_\Lambda=0.7$ (for a justification of this choice cf. Section 6). In that case the Hubble line is described by (cf. Carroll, Press, & Turner 1992)

$$m_{B,V,I} = 5\log \left( \frac{c}{H_0} (1+z) \int_0^{z} \left[ ((1+z)^2 - z(2+z)\Omega_\Lambda^{-1/2} - (1+\Omega_M z) \right]^{1/2} dz \right) + M_{B,V,I} + 25.$$  

(1)

Inserting the weighted values $M_{B,V,I}$ of the calibrators from Table 3 the best fit to the data is achieved by weighted $\chi^2$ solutions in $B$, $V$, and $I$. They give as a preliminary result a Hubble constant$^5$ of $H_0(B)=58.3\pm1.1$, $H_0(V)=57.9\pm1.8$, and $H_0(I)=58.8\pm2.6$, with a mean value of

$$H_0(BVI) = 58.3 \pm 2.0.$$  

(2)

The scatter about the Hubble lines in Fig.3 is $\sigma_B=0.214$, $\sigma_V=0.181$, and $\sigma_I=0.161$ mag, proving in favor of the use of SNe Ia as standard candles. The scatter is somewhat larger within $v=10,000$ km s$^{-1}$ than beyond, which must be due to the influence of peculiar motions. The quoted values of $\sigma$ are therefore upper limits of the intrinsic luminosity scatter.

5. The Correlation of SN Ia Luminosities with Second Parameters

Even the small scatter of $\sigma_B=0.21$ in the Hubble diagram of the fiducial sample spans a total range of SN Ia luminosities of $\sim 0.6$. This is enough of a variation to ask whether their individual luminosities depend on second parameters. If that is the case one must make sure that the calibrators in Table 3 have the same mean second parameters as the SNe of the fiducial sample.

$^5$In the remainder of this paper a value of the Hubble constant is always understood in terms of km s$^{-1}$ Mpc$^{-1}$. 
Even the SNe Ia with Branch-normal spectra (Branch et al. 1993) show some spectral variations which apparently correlate with the expansion velocity, the effective temperature — presumably a result of variable amounts of $^{56}$Ni produced in the explosion —, and the peak luminosity (Nugent et al. (1995), cf. also Mazzali et al. (1998)). Attempts to homogenize all blue SNe Ia to a common mean spectrum and thus to make them even better standard candles are doomed, as stated before, because too few SNe Ia of the fiducial sample have the necessary spectral information.

As a consequence one has searched for purely empirical second parameters that correlate with the peak luminosity. The first success was the decline rate $\Delta m_{15}$ of the $B$ light curve, which measures the decline in magnitudes during the first $15$ days after $B$ maximum (Phillips 1993). Other second parameters followed like the SN light curve shape (Riess et al. 1996; Perlmutter 1998), the SN color ($B-V$) at $B$ maximum (Tammann 1982; Tripp 1998), the color (Branch et al. 1996b) or the Hubble type (Hamuy et al. 1995; Saha et al. 1997, 1999) of the parent galaxy, or the position within the latter (Wang et al. 1997; Riess et al. 1999). There is a considerable literature on the subject.

The dependence of SNe Ia luminosities on second parameters is re-investigated here on the basis of an enlarged, well-defined sample.

### 5.1. Decline Rate $\Delta m_{15}$

The $B$, $V$, $I$ residuals, read in magnitudes, from the Hubble line in Fig.3, i.e. $\delta m = m_{\text{obs}} - m_{\text{fit}}$, are plotted versus the decline rate $\Delta m_{15}$ in Fig.4.

The clear dependence of SN luminosity on $\Delta m_{15}$ is expressed by the following linear regressions (weighted by the errors in $M_{B, V, I}$ as given in Table 1, columns (11) to (13)):

\[
\begin{align*}
\delta m_{B}^{15} &= 0.48_{-0.13}^{+0.15} (\Delta m_{15} - 1.2) - 28.410_{-0.161}^{+0.161}, \quad \sigma = 0.194, \quad n = 35 \quad (3) \\
\delta m_{V}^{15} &= 0.50_{-0.11}^{+0.11} (\Delta m_{15} - 1.2) - 28.304_{-0.143}^{+0.143}, \quad \sigma = 0.151, \quad n = 35 \quad (4) \\
\delta m_{I}^{15} &= 0.39_{-0.13}^{+0.13} (\Delta m_{15} - 1.2) - 28.118_{-0.171}^{+0.171}, \quad \sigma = 0.144, \quad n = 29 \quad (5)
\end{align*}
\]

If the linear regressions are made by allowing for the errors both in $m$ and $\Delta m_{15}$ one finds somewhat steeper slopes. However, any steeper slope introduces a dependence of the luminosity on $\Delta m_{15}$ of opposite sign (i.e. SNe Ia with large values of $\Delta m_{15}$ become too bright). If errors both in $m$ and $\Delta m_{15}$ are considered one has to impose the additional condition that any dependence of absolute magnitude (or $\delta m$) on $\Delta m_{15}$ vanishes. In this case one recovers equations (3) to (5). Some authors have also suggested steeper slopes by forcing a relation through all kinds of SNe Ia including the heterogeneous set of red objects (cf. Section 3.1). Equations (3) to (5) apply explicitly only to SNe Ia which fulfill the conditions imposed on the fiducial sample. The decisive point is that these conditions (with the exception of recession velocity), i.e. reasonably good photometry in $B$ and $V$, blue intrinsic colors ($B-V$), and Branch-normal spectra wherever known, are perfectly met also by
the calibrators, and hence they must comply with the same equations. (It may be noted in passing that the calibrators alone suggest an even somewhat shallower slope).

Correcting the SNe Ia magnitudes for $\Delta m_{15}$ according to equations (3) to (5) has two effects: i) it reduces the scatter in $m$ to the indicated values, and ii) it increases $H_0$ because the calibrators have somewhat smaller $\Delta m_{15}$ on average than the fiducial sample (cf. Section 6 below).

5.2. SN color ($B$-$V$)

The residuals $\delta m = m_{\text{obs}} - m_{\text{fit}}$ from the Hubble line in Fig. 3 are plotted versus SN color ($B$-$V$) in Fig. 5. Weighted linear regressions through the data in Fig. 5 give

$$\delta m_B^\text{col} = 2.55_{-0.49}^{+0.46}[(B-V) + 0.01] - 28.371_{-0.017}^{+0.017}, \quad \sigma = 0.160, \quad n = 35 \quad (6)$$

$$\delta m_V^\text{col} = 1.50_{-0.44}^{+0.40}[(B-V) + 0.01] - 28.348_{-0.024}^{+0.024}, \quad \sigma = 0.164, \quad n = 35 \quad (7)$$

$$\delta m_I^\text{col} = 1.17_{-0.43}^{+0.43}[(B-V) + 0.01] - 28.083_{-0.029}^{+0.029}, \quad \sigma = 0.148, \quad n = 29 \quad (8)$$

In spite of the considerable observational errors of ($B$-$V$) the dependence on luminosity is significant. In fact comparison of the luminosity scatter in equations (6) to (8) with the ones in equations (3) to (5) shows that ($B$-$V$) is as efficient as the decline rate $\Delta m_{15}$ to reduce the scatter. This is in line with the conclusion of Tripp (1998). The dependence of the SN Ia luminosity on color must be mainly an intrinsic effect of SNe Ia (Tammann & Sandage 1995). The proposal that it is due to absorption in the parent galaxy (Riess et al. 1996) has been criticized before (Branch et al. 1996; Saha et al. 1997a). Indeed, if the Galactic absorption law applies on average, the coefficient of the color term in equations (6) to (8) would have to be ~4, ~3, and ~2, respectively, which is excluded at the 3-4 sigma level. The decisive proof against absorption being the main source of the color variations is the fact that SNe Ia become brighter in $I$ as their $(V-I)$ colors become redder (Saha et al. 1999), which is here confirmed.

The color correction has no effect on $H_0$ derived below, because the calibrators and the fiducial sample have closely the same colors (cf. Table 4).

5.3. Combining decline rate $\Delta m_{15}$ and color ($B$-$V$)

The colors ($B$-$V$) of the SNe Ia of the fiducial sample do not correlate with the decline rates $\Delta m_{15}$. These two parameters being orthogonal should hence be combined for an optimum homogenization of the blue SNe Ia. If the residuals $\delta m = m_{\text{obs}} - m_{\text{fit}}$ of the fiducial sample are fit simultaneously by a least-squares solution for two free parameters linear in $\Delta m_{15}$ and ($B$-$V$) one obtains

$$\delta m_B^{\text{corr}} = 0.44_{-0.13}^{+0.13}(\Delta m_{15} - 1.2) + 2.46_{-0.46}^{+0.46}[(B-V) + 0.01] - 28.400_{-0.161}^{+0.161}, \quad \sigma_B = 0.129 \quad (9)$$
\[ \delta m_V^{\text{corr}} = 0.47 \pm 0.11 (\Delta m_{15} - 1.2) + 1.39 \pm 0.40 \left[ (B - V) + 0.01 \right] - 28.391 \pm 0.143, \sigma_V = 0.129 \]  
\[ \delta m_I^{\text{corr}} = 0.40 \pm 0.13 (\Delta m_{15} - 1.2) + 1.21 \pm 0.43 \left[ (B - V) + 0.01 \right] - 28.105 \pm 0.171, \sigma_I = 0.122 \]

The coefficients are similar and their errors are equal to those appearing in equations (3) to (8). They are also in statistical agreement with those proposed by Tripp (1998) and Tripp & Branch (1999). A Fisher F-test for an additional term (Bevington & Robinson 1992) shows that the inclusion of a second parameter is significant at the 99.9 percent level. The scatter is now reduced to \( \lesssim 0.13 \) which is significantly less than from either \( \Delta m_{15} \) or \( (B-V) \) corrections alone. In fact the scatter is now of the same order as an (optimistic) estimate of the combined observational errors in \( m, \Delta m_{15} \), and \( (B-V) \).

### 5.4. Hubble Type

A correlation between the SNe Ia luminosities and the color of the parent galaxy has been pointed out by Branch et al. (1996b). Instead of galaxy color we consider here, following Hamuy et al. (1995) and Saha et al. (1997, 1999), the Hubble type of the parent galaxy because many of them have known Hubble types but no colors.

The left panel of Fig. 6 shows the correlation of the residuals \( m_{\text{obs}} - m_{\text{fit}} \) on the Hubble type \( T \) (from Table 1, column 2). A weighted least-squares fit gives for the \( V \) residuals, where the effect is most pronounced, \( m_{\text{obs}} - m_{\text{fit}} \sim \alpha (0.017 \pm 0.013) T \), which is only moderately significant. Taken at face value it implies that SNe Ia in E galaxies (\( T=3 \)) are on average fainter by \( \Delta V = 0.14 \pm 0.10 \) mag than their counterparts in Sc spirals (\( T=5 \)). The type dependence is somewhat stronger for SNe Ia within 10000 km s\(^{-1} \) and disappears at large distances; this can presently only be explained by invoking a statistical fluke. The luminosity dependence on the stellar population is presumably due to metallicity effects and/or different structures of the progenitor white dwarfs.

After homogenization of the fiducial sample as to decline rate \( \Delta m_{15} \) and color \( (B-V) \) according to equations (9) to (11) any significant dependence of the \( m^{\text{corr}} - m_{\text{fit}} \) on \( T \) disappears. The reason is that there is a clear correlation of the decline rate \( \Delta m_{15} \) and the Hubble type. However, correcting the magnitude residuals by \( T \) instead of \( \Delta m_{15} \) is less effective, leaving a larger scatter about the Hubble line.

### 5.5. Galactocentric distance

In view of the dependence of SNe Ia luminosities on the Hubble type it is reasonable to ask whether the luminosities of SNe Ia depend on their distance \( r_{\text{offset}} \) from the center of their host galaxy, expressed in units of the galaxy diameter \( r_{25} \). The residuals \( m_{\text{obs}} - m_{\text{fit}} \) are plotted versus the relative galactocentric distance \( r_{\text{offset}} / r_{25} \) in the left panel of Fig. 7 for all SNe Ia of the fiducial sample for which \( r_{25} \) is known. The interpretation of the formally significant fit of \( m_{\text{obs}} - m_{\text{fit}} \)}
\[ m_{fit} \sim (0.27 \pm 0.11) r_{\text{offset}} / r_{25}, \] in all three colors, requires some caution because of the type mix and the uneven distribution in galactocentric distance. For spirals alone the effect is insignificant. Also the luminosity scatter does not significantly change with radial distance. This is in variance with Wang et al. (1997) and Riess et al. (1999) who suggested a larger luminosity scatter for the inner SNe Ia than for the outer ones. Their results depend heavily on the spectroscopically peculiar objects SN 1986 G, 1991 bg, and 1991 T, which happen to lie at small galactocentric distances; they are excluded here (cf. Section 2). Once the magnitude residuals are corrected for differences in decline rate and color through equations (9) to (11), the remaining slope of 0.11\pm0.08 (cf. Fig. 7, right panel) becomes even more marginal. Riess et al. (1999), discussing absolute galactocentric distances, came to the same conclusion. In any case the dependence of the luminosity on galactocentric distance has zero effect on the value of \( H_0 \) derived below.

6. The value of the Hubble constant

After correcting the magnitudes of the SNe Ia of the fiducial sample for differences in the decline rate \( \Delta m_{15} \) and the color \( (B-V) \) by means of equations (9) to (11), they define a Hubble diagram with a much reduced scatter, i.e. \( \sigma_B \sim \sigma_V \sim \sigma_I \lesssim 0.13 \) (Fig. 8). In fact the Hubble diagram is now so well defined that one may ask if a stand on a specific model Universe is required for relatively local SNe with \( v \lesssim 30000 \text{ km s}^{-1} \). The situation is visualized in a differential Hubble diagram (Fig. 9). Three different model Universes are fitted to the data:

1) A flat universe with \( \Omega_M = 1.0 \) (q_0=0.5; Sandage 1961, 1962). Taking the corresponding Hubble line and inserting the absolute magnitudes of the calibrators, corrected from equations (9) to (11) to be \( M_B^{\text{opt}} = -19.48 \pm 0.07, M_V^{\text{opt}} = -19.47 \pm 0.06 \), and \( M_I^{\text{opt}} = -19.19 \pm 0.09 \), leads to a \( \chi^2 \) solution with \( \chi^2_{V,B} = 0.696 \) \( (\sigma_B = 0.130) \) and \( H_0(B) = 60.2 \pm 2.1 \). The values in \( V \) and \( I \) are very similar (60.1/60.0). The data give a somewhat better fit (at the 1 \( \sigma \) level) on the assumption that \( H_0 \) is locally higher than the asymptotic value, i.e. \( H_0(v < 10000 \text{ km s}^{-1}) = 60.8 \) \( (\sigma_B = 0.137) \) and \( H_0(v > 10000 \text{ km s}^{-1}) = 59.6 \) \( (\sigma_B = 0.118) \) (Saha et al. 1999; Tammann et al. 1999). The difficulty with this solution is that the observational evidence speaks against a matter density as high as \( \Omega_M = 1.0 \) (for reviews cf., e.g., Bahcall 1997; Dekel et al. 1997; Tammann 1998).

2) An open Universe with \( \Omega_M = 0.2 \) (q_0=0.1; Sandage 1961, 1962). As compared to case 1) the \( \chi^2 \) solution gives a better fit with \( \chi^2_{V,B} = 0.633 \) \( (\sigma_B = 0.124) \) and \( H_0(B) = 60.3 \pm 2.0 \). The solutions for \( V \) and \( I \) are again very similar (60.2/60.1). The fit could still be improved with a smaller \( \Omega_M \), but \( \Omega_M = 0.2 \) is about as low as independent observations allow. The main difficulty here is, however, that the CMB fluctuations strongly suggest a flat universe with \( \Omega_{\text{total}} = 1.0 \) (Melchiorri et al. 1999; Macias-Perez et al. 2000).

3) A flat Universe with \( \Omega_M = 0.3, \Omega_A = 0.7 \) (q_0=0.55). This is the model favored when including high-redshift SNe Ia out to \( z \sim 0.8 \) (Perlmutter 1998; Perlmutter et al. 1998, 1999; Riess et al. 1998b; Schmidt et al. 1998). The fit to the fiducial sample by means of equation (1) is with \( \chi^2_{V,B} = 0.631, \)
\[ \chi^2_{\nu V} = 0.802, \hspace{1em} \chi^2_{\nu I} = 0.589 \] (\(\sigma_B = 0''124, \sigma_V = 0''123, \sigma_I = 0''116\)) somewhat better than with the two previous cases. However, an F-test shows that the improvement of the total \(\chi^2\) from three colors as compared to the case with \(\Omega_M = 1, \hausdorffconstant\), has a probability of not being a result of chance of only \(\sim 70\%\). The corresponding values of the Hubble constant are \(\Hausdorffconstant(B) = 61.0 \pm 2.1\), \(\Hausdorffconstant(V) = 60.9 \pm 1.8\), and \(\Hausdorffconstant(I) = 60.7 \pm 2.6\).

Not surprisingly, the specific choice of the cosmological model has only a minor effect on \(\Hausdorffconstant\). In all three cases \(\Hausdorffconstant < 60 \leq 61\). Taking case 3) as the most consistent solution, a value of

\[ \Hausdorffconstant = 60.9 \pm 4.0 \hspace{1em} (2\sigma \text{ error}) \] (12)

is found. The errors account only for the statistical error of the absolute magnitude calibration (Table 3) and for the scatter about the Hubble line.

The solution in equation (12) is still affected by systematic errors. Sources of systematic errors and our estimate of their sizes are:

1. The zeropoint of the DoPHOT photometry, on which six of the eight Cepheid distances in Table 3 are based, was independently checked by G00 as discussed in Section 2.2. They suggest that the DoPHOT magnitudes are too faint by 0''04. On the other hand, a new zeropoint determination of the DoPHOT photometry shows that the previous zeropoint is still too bright by 0''02 (Saha et al. 2000). Correspondingly, a zeropoint error of \(\pm 0''04\) is allowed for.

G00 have proposed a total reduction of the distances of the Sandage/Saha team by 0''17 on average. Yet it was shown in Section 2.2 that if G00 had used only those Cepheids found in common by both ALLFRAME and DoPHOT photometry (as appears to have been done for all the other galaxies studied by the MFK team) they would have obtained distances that are consistent within the statistical errors with those in Table 3. The smaller distances of G00 depend on the additional Cepheids found by ALLFRAME alone.

2. Photometric blending of the Cepheids may lead to a systematic underestimate of the distances (Mochejska et al. 1999). Stanek & Udalski (1999) have proposed that the effect, increasing with distance, can amount to 0''3 at 20 Mpc. Counter-arguments by Gibson et al. (2000a), also supported by Ferrarese et al. (2000), were judged to be weak (Paczyński & Pindor 2000). In general, it may be noted that the discovery mechanism for Cepheids favors large-amplitude Cepheids, while the amplitudes of blended Cepheids are reduced in function of the importance of the blend; moreover, many small-amplitude Cepheids have been excluded from our discussion because of their less convincing light curves. Indeed, a detailed analysis (Saha et al. 2000) of the effect in \(V\) and \(I\) of skewed error distributions from object confusion and surface brightness fluctuations reveals that the distance modulus of NGC 4639 has been underestimated by only 0''07. This galaxy is the most distant one in Table 3, and the effect must be smaller for the others. An average distance modulus increase of \(0''03\pm 0''03\) seems reasonable.

3. The adopted zeropoint of the Cepheid PL relation of \((m-M)_{\text{LMC}} = 18.50\) is likely to be too
small by $0''06\pm0''10$ (Federspiel et al. 1998; Gratton 1998; Madore & Freedman 1998; Feast 1999; Walker 1999; Gilmozzi & Panagia 1999). Smaller LMC moduli suggested on the basis of statistical parallaxes of RR Lyr stars and red-giant clump stars depend entirely on the sample selection and on the absence of metallicity and evolutionary effects, respectively. The higher LMC modulus will increase all moduli by $0''06\pm0''10$.

(4) The effect of metallicity variations on the Cepheid distances is a long-standing problem. Much progress has been made on the theoretical front. Saio & Gautschy (1998) and Baraffe et al. (1998) have evolved Cepheids through the different crossings of the instability strip and have investigated the pulsational behavior at any point. The resulting, highly metal-independent $M(\text{bol})$ have been transformed into PL relations at different wavelengths by means of detailed atmospheric models; the conclusion is that any metallicity dependence of the PL relations is nearly negligible (Sandage et al. 1998; Alibert et al. 1999). Bono et al. (1998) have suggested a much stronger metallicity dependence, but their conclusions depend entirely on the precarious treatment of convection at the red boundary of the instability strip.

From an observational point of view not even the sign of the metallicity effect on the luminosity is unanimously accepted. Based on [O/H] measurements the calibrating galaxies of Table 3 have a range of metallicities (Kennicutt et al. 1999). Allowing for this effect, G00 have suggested that their distances should be increased by $0''07$ on average. Kennicutt et al. (1998) and Feast (1999) recommend, on the other hand, that for the present no metallicity correction should be applied, but that for an uncertainty of $\gtrsim 0.1 [\text{Fe/H}]^{-1}$ (Feast 1999) should be allowed for. As a compromise it is adopted here that the distance moduli in Table 3 are underestimated by $0''04\pm0''10$ on average.

(5) There is the general trend of an incomplete Cepheid sampling near the photometry threshold to yield too short distances (Sandage 1988; Lanoix et al. 1999). According to Narasimha & Mazumdar (1998) and Mazumdar (1999) this effect has caused a distance underestimate of $\sim0''3$ in the extreme case of M100 (Ferrarese et al. 1996). This bias can be minimized by introducing a period cutoff, if the data allow so, at an appropriate low-period limit. Since the Cepheid moduli in Table 3 were derived in cognizance of the selection bias, the net effect on the luminosity calibration in Table 3 is most likely less than $0''1$. Here a systematic error of $0''05\pm0''05$ is allowed for.

(6) An overestimate of the absorption of the calibrating SNe Ia will lead to a spuriously low value of $H_0$, and vice versa. The opposite holds for over-corrected SNe Ia in the field. Yet a differential error of the extinction can be excluded at the level of $0''01$, because the calibrating SNe and those of the fiducial sample have nearly identical corrected colors (cf. Table 4). An error of the adopted mean color of SNe Ia has no effect on the distance scale because calibrating and field SNe Ia would be equally affected by the resulting change of the absorption. Concurrently the close agreement of $H_0$ from $B$, $V$, and $I$ data speaks against hidden absorption problems. Absorption corrections can therefore not affect $H_0$ by more than $\pm 3$ percent.

A ratio of $R_V=A_V/E(B-V)=3.3$ was adopted here. With $R_V=3.0$ the calibrators would become fainter by $0''038$ on average, but the fiducial sample only by $0''014$. Therefore, while preferring
a value of $R_V=3.3$, a systematic uncertainty of the distances of $\pm 0.02$ should be allowed for.

It may be noticed that the nine SNe Ia of the fiducial sample with Galactic absorptions $A_V>0.2$ have brighter absolute magnitudes $M_B^0$ (Table 1) than their 26 counterparts with smaller Galactic absorption. The mean difference amounts to $0.21\pm0.04$ and is somewhat smaller in $V$ and $I$, as is to be expected if the Galactic extinction corrections due to Schlegel et al. (1998) were somewhat too large for large values. If the nine strongly corrected SNe Ia are excluded, the Hubble line in Fig. 3 shifts faintwards by $0.05\pm0.04$, and $H_0$ is reduced by 2 percent. Furthermore the scatter in Fig. 8 shrinks to $\sigma_B=0.114$.

Finally, if the seven somewhat red SNe Ia in Table 5, which were excluded here on the assumption of internal absorption, were intrinsically red and hence included in the present analysis, they would slightly affect equations (9) to (11) and decrease $H_0$ by one percent. If they had been included after corrections for absorption, they would increase $H_0$ by much less than one percent.

(7) The coefficients of the $\Delta m_{15}$-term in equations (9) to (11) carry a random error of $\pm 0.13$. This is to be multiplied with the mean difference $<\Delta m_{15}>$(fiducial sample) $-<\Delta m_{15}>$(calibrators) = 0.17 to give a systematic error of the distances of $\pm 0.02$.

Phillips et al. (1999) have pointed out that the decline rate $\Delta m_{15}$ is slightly affected by absorption. If this effect had been applied, the differential decline rate between calibrators and field SNe Ia would be changed by $\delta \Delta m_{15} = 0.008$ with vanishingly small effect on $H_0$.

(8) The redshift velocities were corrected for the CMB dipole motion on the assumption that the co-moving volume extends to 3000 km s$^{-1}$. If instead the volume size was varied between 2000 and 10000 km s$^{-1}$, it would affect $H_0$ by less than one percent, as stated in Section 2.1. G00 have considered a very specific local flow model and concluded that in this case $H_0$ would be increased by two percent. This is taken as indication that the deviations from pure Hubble flow could influence $H_0$ by hardly more than $\pm 2$ percent.

Most of the systematic errors, which are assumed to give 90-percent margins, tend to increase the true distance scale. If they are added linearly, $H_0$ in equation (12) would be reduced by a factor (0.91$\pm$0.07); if they are added in quadrature, instead, the reduction factor becomes (0.96$\pm$0.08). Multiplying the latter with equation (12) gives

\[
H_0 = 58.5 \pm 6.3 \quad (2\sigma \text{ error}),
\]

which is finally taken as our most probable value of the Hubble constant as inferred from Cepheid-calibrated SNe Ia, including random and systematic errors.

7. Alternative solutions

The second-parameter problem in finding $H_0$ could be avoided altogether, if the distant SNe Ia and the local calibrators had (nearly) identical second parameters. This can be approximated
by choosing a suitable subset of the fiducial sample. Excluding the 14 SNe Ia of the fiducial sample with the largest $\Delta m_{15}$ values ($\Delta m_{15} \geq 1.3$), one is left with a rest sample of 21 objects with $<\Delta m_{15}> = 1.08 \pm 0.02$, i.e. the same as for the calibrators.

Fitting the 21 (uncorrected) SNe Ia to equation (1) by a $\chi^2$ solution and inserting the weighted absolute magnitudes of the calibrators in Table 3 gives $H_0(B) = 58.8$, $H_0(V) = 58.8$, and $H_0(I) = 59.9$. This solution is not yet fully satisfactory, because on average the calibrators are now redder by $\Delta(B_0 - V_0) = 0.030 \pm 0.018$ and the Hubble type of their parent galaxies is still later by $\Delta T = 2.9 \pm 0.7$. But it should be noted that the result is rather close to the corresponding, fully corrected value of $H_0 = 60.9$ in equation (12).

As the sample of known blue SNe Ia with $v < 30,000$ km s$^{-1}$ will increase, this alternative solution will become more rigorously applicable and circumvent all corrections for second parameters.

Another alternative solution is given by confining the analysis to SNe Ia in spirals. Seven of the eight adopted calibrators lie in spirals. The population assignment of SN 1972 E is ambiguous because its parent galaxy is of Hubble type Ab; the inclusion here of SN 1972 E does not affect the result. Nineteen of the SNe Ia of the fiducial sample after 1983 are in spirals ($T \geq 0$). Combining them with the calibrators and fitting them to equation (1) yields $H_0(B) = 59.0$, $H_0(V) = 59.1$, and $H_0(I) = 59.1$. The spirals-only solution is remarkable because the mean solution of $H_0 = 59.1$ is smaller by only 3% than the solution fully corrected for $\Delta m_{15}$ and $(B_0 - V_0)$ in equation (12).

Thus both the exclusion of fastest-declining SNe Ia and the restriction to only SNe Ia in spirals provide useful simple approximations for the determination of $H_0$.

8. Conclusions

A fiducial sample of 35 well observed, blue (Branch-normal) SNe Ia with minimum absorption in their parent galaxies and with $1200 < v < 30,000$ km s$^{-1}$ has been compiled from the literature. For 29 SNe Ia also $I$-magnitudes are known. The intrinsic color of SNe Ia is found to be $(B-V) = 0.012 \pm 0.008$, $(V-I) = 0.276 \pm 0.016$ from objects in E/S0 galaxies and outliers in spirals; the scatter in color of $\sigma = 0.05$ for individual objects is surprisingly small.

The fit of the SNe Ia sample, although quite local ($z \leq 0.1$), to a Hubble line is somewhat dependent on the cosmological model adopted. Among various models, the marginally best fit is obtained for a flat Universe with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, which is presently also favored by external data. In this case the scatter about the Hubble line is $\sigma = 0^\circ.21 - 0^\circ.16$, depending on the pass band. But the magnitude residuals correlate with decline rate $\Delta m_{15}$ and color $(B-V)$. If the dependency on either of these parameters is removed, the scatter is reduced to $\sigma = 0^\circ.19 - 0^\circ.14$. A simultaneous correction for $\Delta m_{15}$ and color $(B-V)$ decreases the scatter to $\sigma \leq 0^\circ.13$ in all three colors. This illustrates the unique potential of SNe Ia as distance indicators.

If the SNe Ia of the fiducial sample are assigned the absolute magnitudes $M_B$, $M_V$, and $M_I$
of eight local SNe Ia whose Cepheid distances are known, one obtains closely the same value of $H_0=58.3\pm2.0$ for the three passbands. This solution is remarkably robust against various assumptions and corrections. Bootstrapping the calibrators by excluding two or three objects, does not change their mean absolute magnitude. The eight calibrators lie essentially all in spirals and they have correspondingly a somewhat smaller average $\Delta m_{15}$ than the fiducial sample. If they are adjusted to the latter’s mean $\Delta m_{15}$, $H_0$ is increased by 4 percent to $H_0=60.9\pm2.0$. A correction for $(B-V)$ does not change this value because the calibrators and the fiducial sample have closely the same mean color. Any remaining dependencies on Hubble type and galactocentric distance are insignificant and have no effect on $H_0$. Alternative solutions considering either SNe Ia only in spirals or SNe Ia with small $\Delta m_{15}$ — making the sample more similar to the calibrators — yields $H_0\approx59$. The effect of systematic errors is mainly one-sided (photometric zeropoint, skewness of photometric errors, the LMC zeropoint of the PL relation, selection effects of Cepheids, and possibly metallicity effects), leading to too high values of $H_0$. If they are taken into account one obtains at the 90 percent confidence level $H_0=58.5\pm6.3$.

External results on $H_0$ from SNe Ia should be compared with $H_0=60.9\pm2.0$ from equation (12), because the subsequent corrections for systematic errors have not been applied yet in other papers. The results of Saha et al. (1999) and Tripp (1998) are indistinguishable from the above result despite of the re-definition of the “fiducial sample” here, of variations of other input data, and of independent corrections for $\Delta m_{15}$ and $(B-V)$. The value of $H_0=62(\pm2)$ derived by Tripp & Branch (1999) from a sample of six calibrators and 13 field SNe Ia in spirals and fully corrected for $\Delta m_{15}$ and $(B-V)$ is in satisfactory statistical agreement with equation (12), too.

The somewhat higher value of $H_0=63.9\pm2.2$ by Suntzeff et al. (1999), based on only five of the calibrators in Table 3, is fully explained by their adopted steeper luminosity dependence on $\Delta m_{15}$, which is closely the same as was derived by Phillips et al. (1999), who included spectroscopically peculiar SNe Ia like SN 1986 G, 1991 T, 1991 bg, and 1995ac. Had Suntzeff’s et al. (1999) $\Delta m_{15}$-correction been applied to our fiducial sample, we would have obtained $H_0=59.7$ for the SNe Ia with $\Delta m_{15}<1.2$ ($n=17$), and $H_0=64.6$ for the ones with $\Delta m_{15}\geq1.2$ ($n=18$). Since seven of the eight calibrators fall into the first category the lower value of $H_0$ is more nearly correct. The 3-$\sigma$ discrepancy demonstrates that their $\Delta m_{15}$-correction introduces an over-correction, making the calibrators with a small mean $\Delta m_{15}$ too faint and the field SNe Ia with large $\Delta m_{15}$ too bright. This is the price to be paid if one attempts to derive a global correction formula which encompasses also peculiar objects that are extraneous of the SNe Ia sample to which it should be applied. — G00 have followed closely the line of Suntzeff et al. (1999), but they have reduced in addition the mean absolute magnitude of the calibrators by $\sim0.2$ on the basis of quite objectionable additional Cepheids (cf. Section 2.2); their high value of $H_0=68$ (based on six calibrators) then follows by necessity. The repetition of one or two calibrating galaxies with the forthcoming Advanced Camera System on HST will bring a definitive decision on the merits of the additional Cepheids of G00, which were rejected here because their photometry relies so far only on ALLFRAME.

Jha et al. (1999) have derived $H_0=64.4\pm5.4$ from a sample of 42 distant SNe Ia and only four
Cepheid-calibrated SNe Ia. Seven of these objects have not been used here as either being too red or having peculiar spectra (SN 1992K, 1995ac). The SNe Ia are standardized by a "multi-color light curve shape" (MCLS) method giving simultaneously the absorption and a light-curve parameter substituting $\Delta m_{15}$ (Riess et al. 1996, 1998b). Unfortunately the individual data are not given, and the discussion is restricted to $V$ magnitudes denying a control on the consistency of colors. In spite of this, there is some question as to the grip of the MLCS light-curve parameter. The calibrators as well as the distant SNe Ia have still a magnitude scatter of $\sigma_V = 0^m 16$ after the correction, which is larger than $\sigma = 0^m 14$ obtained by Phillips et al. (1999) and significantly larger than $\sigma_V \leq 0^m 13$ found here by means of the corrections due to equation (10).

This discussion confirms previous investigations suggesting that if one attempts to derive $H_0$ from SNe Ia to within $\pm 10$ percent, a major stumbling block are the second-parameter corrections. If the relatively mild $\Delta m_{15}$-corrections found here can be agreed upon it is clear that $H_0$ will settle close to 60 with a tendency for a small downward correction due to various (small) systematic errors.

Future Branch-normal SNe Ia in the field, preferably with $v \geq 3000 \text{ km s}^{-1}$, will help to settle the problem of light-curve shape corrections. The importance of these corrections will decrease as it will become possible to define sufficiently large sub-samples of field SNe Ia which have the same mean second parameters as the calibrating SNe Ia. Additional field SNe Ia are forthcoming (Nugent & Aldering 1999). Finally, the advent of the new Advanced Camera System on HST will allow to check the present Cepheid distances and to increase the number of calibrating SNe Ia.

At present the evidence from SNe Ia is best reflected at the 90-percent confidence level by a value of the Hubble constant, including random and systematic errors, of $H_0 = 58.5 \pm 6.3$.

We are grateful to B. Leibundgut for sharing some template-fitting software, M. Hamuy for providing us with a set of I band K-corrections, and B. Reindl for useful discussions. G.A.T. has profited from a Workshop on Supernovae (June 1999) at the Aspen Center for Physics. B.R.P. and G.A.T. acknowledge financial support of the Swiss National Science Foundation.
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Stetson, P.B. 1995, private communication

This preprint was prepared with the AAS LaTeX macros v5.0.
Fig. 1.— The color distribution of all known SNe Ia after 1985 with \( v \leq 30,000 \text{ km s}^{-1} \). Open symbols are for SNe Ia with \( v < 10,000 \text{ km s}^{-1} \), closed symbols are for more distant SNe Ia. The binned intervals embrace \( \Delta (B-V) = 0.05 \). A Gaussian fit to all SNe Ia with \( (B-V) \leq 0.10 \) gives \( (B-V) = 0.020, \sigma_{B-V} = 0.053 \).

Fig. 2.— Blue SNe Ia after 1985 plotted against the relative radial distance \( r/r_{25} \). Circles stand for spiral, squares for E/S0 host galaxies. Small symbols represent SNe Ia with observations starting eight days after \( B \) maximum or later. Triangles are the calibrators from Table 3.

Fig. 3.— The Hubble diagrams in \( B, V \), and \( I \) for the fiducial sample. Circles are SNe Ia in spirals, squares in E/S0 galaxies. Small symbols are SNe Ia whose observations begin eight days after \( B \) maximum or later. Solid lines are fits to the data assuming a flat universe with \( \Omega_M = 0.3 \) and \( \Omega_A = 0.7 \); dashed lines are linear fits with a forced slope of 0.2 (corresponding approximately to \( \Omega_M = 1.0 \) and \( \Omega_A = 0.0 \)). Not considered for the fits are the diamonds and the crosses representing SNe Ia reddened according to Table 5 or observed before 1985, respectively.

Fig. 4.— Relative absolute magnitudes (i.e. residuals from the Hubble line in Fig. 3) for the SNe Ia of the fiducial sample in function of the decline rate \( \Delta m_{15} \). Circles are SNe Ia in spirals, squares in E/S0 galaxies. Open symbols are SNe Ia with \( 1200 < v < 10,000 \text{ km s}^{-1} \), closed symbols are for the more distant SNe Ia. Small symbols are SNe Ia whose observations begin eight days after \( B \) maximum or later. Neither the SNe Ia before 1985 with known \( \Delta m_{15} \) (shown as crosses) nor the seven blue, but reddened SNe Ia (shown as X's) are considered for the weighted least-squares solutions (solid lines).

Fig. 5.— Relative absolute magnitudes (i.e. residuals from the Hubble line in Fig. 3) for the SNe Ia of the fiducial sample in function of their color \( (B-V) \). Symbols as in Fig. 4. Neither the few SNe Ia before 1985 (shown as crosses) nor the seven blue, but reddened SNe Ia (shown as X's) are considered for the weighted least-squares solutions (solid lines).

Fig. 6.— Relative absolute magnitudes (i.e. residuals from the Hubble line in Fig. 3) for the SNe Ia of the fiducial sample in function of their Hubble type \( T \). Symbols as in Fig. 4. Left panel: \( m_{o b s} - m_{f i t} \). Right panel: \( m^{corr} - m_{f i t} \), i.e. after magnitude corrections according to equations (9) to (11).

Fig. 7.— Relative absolute magnitudes (i.e. residuals from the Hubble line in Fig. 3) for the SNe Ia of the fiducial sample in function of their projected galactocentric distances \( r/r_{25} \). Symbols as in Fig. 4. Left panel: \( m_{o b s} - m_{f i t} \). Right panel: \( m^{corr} - m_{f i t} \), i.e. after magnitude corrections according to equations (9) to (11).

Fig. 8.— The Hubble diagrams in \( B, V \), and \( I \) for the 35 (29) SNe Ia of the fiducial sample with magnitudes \( m^{corr} \) (i.e. corrected according to equations (11) to (13)). Symbols as in Fig. 3. The solid line is for a model with \( \Omega_M = 0.3, \Omega_A = 0.7 \), the dashed line for \( \Omega_M = 1.0, \Omega_A = 0.0 \).
Fig. 9.— Differential Hubble diagrams ($m_{corr} - m_{fid}$) vs log v in $B$, $V$, and $I$ for the 35 (29) SNe of the fiducial sample. Symbols as in Fig. 3. The dashed line is for a flat cosmological model with $\Omega_M=1.0$, $\Omega_{\Lambda}=0.0$; the theoretical apparent magnitudes $m_{fid}$ correspond to this model. The full line is for a flat model with $\Omega_M=0.3$, $\Omega_{\Lambda}=0.7$; the dotted line is for an open universe with $\Omega_M=0.2$, $\Omega_{\Lambda}=0.0$. 
fig. 4
fig. 5
fig. 6
fig. 7
fig. 8
Table 1—Continued

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<th>B</th>
<th>V</th>
<th>I</th>
<th>A_v</th>
<th>Δmag g</th>
<th>1σ_abs</th>
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Note. — An acceptance sign √ behind the SN name marks a SN that is belonging to the fiducial sample. An asterisk * indicates a calibrator whose Cepheid-based absolute magnitude is given in Table 3.
Table 2. Host Galaxy and Positional Parameters of Blue SNe Ia

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<th>SN</th>
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<th>T</th>
<th>α</th>
<th>δ</th>
<th>D25</th>
<th>E(JW)</th>
<th>N/S</th>
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<td>475</td>
<td>430</td>
<td>408</td>
<td>0.20</td>
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<td>157</td>
<td>444</td>
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<th>δ</th>
<th>D25</th>
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<th>N/β</th>
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Table 3: Absolute B, V, and I magnitudes of blue SNe Ia calibrated through Cepheid distances of their parent galaxies

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<th>log v a</th>
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<th>(m-M) AV</th>
<th>(m-M) I</th>
<th>ref.</th>
<th>B AB</th>
<th>V AB</th>
<th>I AB</th>
<th>ref.</th>
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mean (straight, excl. SN 1895 B) | -19.57(04) | -19.56(04) | -19.36(06) | 1.06(05) |
mean (weighted, excl. SN 1895 B) | -19.55(07) | -19.53(06) | -19.25(09) | 1.08(02) |

a The velocities used are corrected for Virgo-centric infall assuming a local infall velocity of 220 km s⁻¹
b The mean velocity v = 291 km s⁻¹ of the Cen A group is used
c The mean velocity v = 1179 km s⁻¹ of the Virgo group is used
d The mean velocity v = 652 km s⁻¹ of the Leo group is used

Table 4: Intrinsic Colors of Unreddened Blue SNe Ia After 1985

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<th>(V-I)</th>
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<td>-0.326(018)</td>
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Table 5: Reddened SNe Ia of the present sample

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