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ZERO POINT OF THE SUPERNOVA HUBBLE DIAGRAM

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ABSTRACT

An empirical calibration is presented for the absolute luminosity of Type I supernovae using the most reliable distance estimates available to host galaxies of observed supernovae in the Virgo Cluster. Several estimates are presented for the absolute magnitude at maximum blue light; the best one, using planetary nebula distances, gives $M_B = -18.5 \pm 0.2$, and the others give slightly different values consistent with the errors. When combined with published Hubble diagrams for distant supernovae, this calibration leads to a Hubble constant in the range $75 \leq H_0 \leq 100$ km s^{-1} Mpc^{-1}.

Subject headings: cosmology — galaxies: distances — stars: supernovae

1. INTRODUCTION

The Hubble diagram of distant Type I supernovae (SNs I) shows them to be excellent standard candles (e.g., Barbon, Capaccioli, & Ciatti 1975; Branch & Bettis 1978; Tammann 1982; Cadonau, Sandage, & Tammann 1985; Arnett, Branch, & Wheeler 1985; Leibundgut & Tammann 1989, hereafter LT; Tammann & Leibundgut 1990, hereafter TL; Leibundgut 1990; Capaccioli et al. 1990; Miller & Branch 1990). Most authors conclude from the Hubble diagram that SNs I have an absolute (blue or photographic) magnitude at maximum brightness $M_{\max} = -(18.2 - 18.5) + 5 \log h$, where h denotes the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. Depending on the method used and data selected, the dispersion of supernovae about this relation is of the order of only 0.25–0.5 mag. The main problem in deriving the Hubble constant is to find a convincing estimate for the zero-point $M_{\max}$.

Two empirical calibrations in the literature use SNs I in nearby galaxies (Sandage & Tammann 1982; Branch 1985) and in the Virgo Cluster (LT). A third method circumvents empirical calibration using the carbon deflagration model of SNs I (Arnett, Branch, & Wheeler 1985); here it is assumed that the maximum bolometric luminosity is equal to the instantaneous radioactive decay luminosity of the mass of ^{56}Ni (calculated to be $\gtrsim 0.4\ M_\odot$) produced by deflagration waves passing through an inner portion of a Chandrasekar-mass white dwarf (Arnett 1982a). Finally the expansion parallax method estimates $M_{\max}$ by making a photometric estimate of the angular diameter of the photosphere and a spectroscopic estimate of its actual diameter (Kirshner & Kwan 1974; Arnett 1982b).

Although all four of these methods give $H_0 \approx 50 \pm 10$ km s^{-1}, none of them is empirically demonstrated to be reliable. For the nearby galaxy calibration, the SNs I that one can use are limited to two SNs in NGC 5253 and one SN in IC 4182, both of which galaxies lack reliable distance estimates. The second method suffers from the notorious uncertainties in distance estimates to the Virgo Cluster, which differ by more than 50%. The deflagration model has not yet been tested at the necessary level of quantitative detail for an accurate calibration, and the expansion parallax method depends crucially on the assumption that the photosphere is a blackbody, an assumption that may fail if, for instance, bound-bound opacity dominates (Branch 1985).

In this *Letter* we appeal instead to a variety of recently developed local distance calibrators which now make it possible to estimate directly the distances to supernova host galaxies in the Virgo Cluster. Not only does this increase the number of calibrating supernovae, but it also allows an empirical verification of the calibration using several entirely independent methods, and consequently also an empirical estimate of the errors in the calibration.

2. THE DISTANCE SCALE TO VIRGO

We begin by summarizing the excellent agreement among current high-precision distance estimates out to Virgo (see Table 1), in particular the planetary nebula luminosity function (PNLF) recently introduced by Jacoby and collaborators (Jacoby et al. 1989; Jacoby, Ciardullo, & Ford 1990; Ciardullo et al. 1989a, b). They showed that PNLF provides an excellent standard candle to galaxies as far away as Virgo Cluster. Like Cepheids and SNs I, PNLF is insensitive to the metallicity or peculiarity of host galaxies. Since the PNLF is accessible in both nearby galaxies with Cepheid distances (where it shows impressive agreement) and more distant galaxies containing SNs I, it plays a central role in our argument.

Both Cepheids and PNLF verify the reliability of the distances given by the Tully-Fisher (TF) method. With Freedman's Cepheid distances (Freedman 1990), the five galaxies (M31, M33, NGC 300, NGC 2403, and M81) are almost on a straight line both for the H-band and B-band TF relation. For the H-band, she gave

$$-M(H^c_{-0.5}) = \underset{\pm 0.08}{21.05} + \underset{\pm 0.49}{10.26}(\log \Delta v - 2.5) \quad (1)$$

in the $H^c_{-0.5}$ scheme of Aaronson et al. (1982). For the B-band we have (Fukugita et al. 1990)

$$-M(B_T^0) = \underset{\pm 0.10}{19.18} + \underset{\pm 0.48}{6.56}(\log \Delta v - 2.5) \quad (2)$$

in the B_T^0 scheme of Second Reference Catalogue of Bright Galaxies (de Vaucouleurs, de Vaucouleurs, & Corwin 1976, hereafter RC2). The scatter around the line is about 0.15 mag

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TABLE 1

DISTANCE MODULI TO SELECTED NEARBY GALAXIES

Galaxy	Cepheids	PNLF	H-TF	B-TF	$D_n\sigma$	Brightness Fluctuation
M31	24.26 ± 0.15	<u>24.26</u>	24.39	24.32	...	<u>24.29</u>
M81	27.6 ± 0.3	27.72 ± 0.25	27.74	27.89	...	...
N2403	27.8 ± 0.4	...	27.35	27.39	...	...
N2366	...	...	27.70	27.18	...	...
N4236	...	...	28.02	27.15	...	...
I2574	...	...	27.02	27.00	...	...
Leo I:						
N3379	...	30.06	...	...	<u>30.0</u> (N3379 and N3377)	29.7
N3377	...	29.96	...	...		...
N3384	...	30.02	...	...	...	...
N3351	...	...	...	29.84	...	...
N3368	...	...	...	30.28	...	...
Virgo:						
N4374	...	30.98 ± 0.08	...	...	31.16	...
N4382	...	30.79 ± 0.06	...	...	...	...
N4406	...	30.98 ± 0.06	...	...	30.81	30.8
N4472	...	30.71 ± 0.09	...	...	30.61	31.0
N4486	...	30.81 ± 0.06	...	...	30.91	...
N4649	...	30.76 ± 0.09	...	...	31.41	...
N4552	...	...	...	...	31.39	30.60
N4478	...	...	...	...	30.91	30.60
N4458	...	...	...	...	31.49	30.57
Average	...	30.84 ± 0.11	...	...	31.09 ± 0.30	30.71 ± 0.15
$\langle\text{Spirals}\rangle_{\text{ave}}$	...	...	30.90 ±0.39	31.11 ±0.45	...	...

NOTES.—Cepheid distances are from Welch et al. 1986, McAlary & Madore 1984, and Freedman 1990. PNLF distances are from Ciardullo et al. 1989a, b and Jacoby et al. 1989, 1990, calibrated using Welch et al.'s distance to M31. Tully-Fisher distances are computed from data in the literature (H I line widths and H-band photometry from Aaronson et al. 1982; B-band photometry from RC2) and calibrated by Cepheid distances by Freedman. The D_n-σ relation for ellipticals is calibrated using an average of Leo group galaxies which have PNLF distances; data are taken from Faber et al. 1989. The brightness fluctuation distances are calibrated using M31 (Tonry, Ajhar, & Luppino 1990a). For the TF average distance to Virgo spirals, data were taken from Pierce & Tully 1988 for their 31 cluster member galaxies and transformed into the $H^c_{-0.5}$ and B^0_T schemes. In the case of Cepheids, we include the error given by the scatter among different Cepheid distance estimators. For PNLF we quote the error by the original authors; the error in the PNLF Virgo average, however, is derived from the observed scatter (probably caused by the cluster depth). For the other indicators, which have larger mean errors, we show only the dispersion estimated from fits to a whole sample.

for the H band and 0.2 mag for the B band. The distance modulus to Leo I with the B-TF relation is 30.06, compared to 30.01 by PNLF (Ciardullo, Jacoby, & Ford 1989a). For M81, H-TF and B-TF give 27.74 and 27.89, respectively, which may be compared with 27.72 by PNLF and with 27.6 ± 0.3 by Cepheids. The TF estimate of the Virgo distance by Pierce and Tully ($\mu^0 = 30.97$) is also confirmed by both H- and B-band TF calibrations with the fits (1) and (2). This distance agrees accurately with $\mu^0 = 30.84$ (with empirical scatter $\sigma = 0.11$) using PNLF averaged over six galaxies.

Planetary nebula distances also allows us for the first time to calibrate the D_n-σ relation (Dressler et al. 1987) using nearby elliptical galaxies. When the Leo group galaxies NGC 3379 and NGC 3377 (Faber et al. 1989) are used for calibrators, the D_n-σ relation is written as

$$\log D_n(20.75) = 1.333 \log \sigma - 2.796 - 0.2(\mu^0 - 30.0) . \quad (3)$$

This relation is verified when applied to five galaxies in Jacoby et al.'s Virgo sample, yielding $\mu^0 = 30.93$ ($\sigma = 0.21$) compared with the PNLF estimate $\mu^0 = 30.86$ for the same five galaxies. The agreement between the two distances for individual galaxies is $\langle \mu^0_{D_n\sigma} - \mu^0_{\rm PNLF} \rangle = 0.24$. Note that Dressler's original calibration (Dressler 1987) of $D_n(19.75)$-σ relation (not using ellipticals, but using the bulge of M31) gave a zero point 0.7 mag fainter for the Virgo Cluster.

Finally, the distances from the surface brightness fluctuation technique (Tonry, Ajhar, & Luppino 1990a) agree with those from PNLF to about 0.3 mag for individual galaxies, although there is some evidence for systematic difference at the ~0.2 mag level (Tonry, Ajhar, & Luppino 1990b).

Apparently the distances to some individual galaxies in the Virgo Cluster are reliably established within an allowed error of 0.2–0.3 mag. This enables us to avoid the inherent problems of cluster membership and of cluster depth. It is no longer necessary to use statistical samples for reducing errors by $N^{1/2}$, blindly hoping that no hidden systematic errors accumulate, since one can now make empirical error estimates based on the dispersion given by different distance estimates to individual galaxies. Having several such galaxies in a single cluster then allows a check of both the distance estimates themselves and of the error estimates.

3. $M_{\rm max}$ FOR TYPE I SUPERNOVAE

Out of 15 SNs I in Virgo galaxies compiled by Capaccioli et al. (1990), we list in Table 2 11 SNs selected to match a Type Ia template light curve (10 SNs used by Capaccioli et al. and six

TABLE 2

ESTIMATE OF M_{max} FOR TYPE I SUPERNOVAE IN THE VIRGO CLUSTER SELECTED BY LIGHT CURVES

SN (1)	TYPE (2)	HOST GALAXY (3)	TYPE (4)	B_{max} (5)	DISTANCE MODULUS: PNLF (6)	*H*-TF (7)	*B*-TF (8)	D_n-σ (9)	M_{max} (10)	REFERENCES (11)
1919A	I	N4486	E	12.25 ± 0.15 (pg)	30.81	...	...	30.91	−18.13	C, LT
1939A	I	N4636	E	12.60 ± 0.10 (pg)	...	...	...	30.83	(−18.23)	C
1939B	I	N4621	E	12.00 ± 0.20 (pg)	...	...	...	31.25	...	LT
1957B	I	N4374	E	12.20 ± 0.10 (pg)	30.98	...	...	31.16	−18.78	C, LT
1960R	I	N4382	S0	11.90 ± 0.20	30.79	...	...	...	−18.89	C, LT
1961H.........	Ia	N4564	E	11.80 ± 0.10	...	...	...	31.09	(−19.29)	C, LT
1963I	I	N4178	SBc	13.30 ± 0.20	...	30.88	30.48	...	(−17.58)	C
1965I	Ia	N4753	S0p	12.50 ± 0.10	...	...	...	...	...	C
1981B	Ia	N4536	Sbc	12.50 ± 0.05	...	30.20	30.27	...	(−18.20)	C
1983G.........	Ia	N4753	S0p	12.85 ± 0.10	...	...	...	...	...	C
1984A	Ia	N4419	S(B)a	12.45 ± 0.10	...	30.66	30.80	...	(−18.48)	C, LT

NOTES.—Data on SNs are taken from the compilation of Capaccioli et al. 1990. The data virtually agree with those by LT except for SN 1919A, where LT made an extrapolation of late time observations by Balanowski 1922, while Capaccioli et al. adopted the maximum light observation of Baade 1938. Distance moduli to the elliptical host galaxies are taken from Table 1. For spirals TF distances are computed from data of Kraan-Korteweg, Cameron, & Tammann 1988 where available; for NGC 4536, velocity data are taken from Tifft and Cocke 1988, and photometry data from RC2 (*B*) and Tully (1988) (*H*). The absolute M_{max} is computed in each case from the best available indicator. M_{max} for those SNs where only a TF or D_n-σ distance is available are expected to have larger errors than PNLF galaxies and are shown in parentheses.

SNs adopted by LT). Distance estimates to the host galaxy are given in columns (6)–(9) by various methods. Since the TF and D_n-σ distance indicators have a rather large dispersion they are meaningful only for a statistical sample; the error $\pm\sigma$ (σ = intrinsic dispersion, $\sim$0.25–0.4 depending on authors) should be understood for their individual values. We list in column (10) the magnitude at the luminosity maximum based on these distance estimates.

The most accurate calibration is provided by the three supernovae with planetary nebula distances. A simple average of these three supernovae yields $M_{max} = -18.74$ with an empirical dispersion of 0.14. This value increases to $M_{max} = -18.53$ ($\sigma = 0.26$), if $m_{pg} - m_B = 0.32$ (Branch and Bettis 1978) is invoked to correct the old pg magnitude for two of these to the standard *B*-band system. (Although we include this correction because it is standard, it is not clear that it is the best one to use for these particular supernovae.) $M_{max} = -18.50$ ($\sigma = 0.48$) is obtained if we take the average of all eight galaxies, or $M_{max} = -18.75$ ($\sigma = 0.35$) for five SNs I in only E and S0 galaxies. Here the larger dispersions indicate the less accurate distance used and possible uncalibrated extinction in the host galaxies.

This calibration may be tested (albeit less accurately) using SNs I in the Coma cluster, using TF directly for the Coma distance. Capaccioli et al. compiled seven SNs I in the Coma Cluster. Averaging over six SNs with pg magnitudes gives $m_{pg} = 15.68$ ($\sigma = 0.52$). When this is combined with the TF distance (Fukugita et al. 1990) 34.4 ± 0.4,[2] we obtain -18.7 ± 0.6.

4. THE DISTANT SUPERNOVA HUBBLE DIAGRAM AND H_0

For distant supernovae, we write the Hubble relation $M_{max} = 5 \log h - b$. Tammann (1982) estimated $b = 18.19 \pm 0.14$ with $\sigma = 0.58$ mag. Arnett et al. (1985) selected six SNs I in E galaxies which satisfy $v > 3000$ km s^{-1}, yielding $b = 18.4 \pm 0.2$. More recently, TL reanalyzed all available SNs I and obtained $b = 18.13 \pm 0.09$ for 35 SNs I with *B* magnitudes and 18.41 for 27 SNs I with m_{pg}. From the figure given by TL, we find that this value increases by $\sim$0.2 mag if only SNs I in E galaxies are selected, presumably because of extinction in later types (Miller & Branch 1990). If we combine the Hubble fit of TL (18.13) with our best zero point $M_{B,max} = -18.55$ mag we obtain $h = 0.83$; we find a similar result or higher if we uniformly use only (uncorrected) pg or *E* galaxy fits throughout (see Branch 1985). Even if we combine the TL value with our highest zero point 18.75, we obtain $h = 0.75$. On the other hand, if the upper envelope of the Hubble diagram represents a more reliable value (Leibundgut 1989), we would be led to $h = 1$. We conclude that the best current estimate of the global value of H_0 derived from SNs I lies in the range $75 \leq H_0 \leq 100$ km s^{-1}.

[2] This value includes the sample incompleteness bias, and the error estimate includes all possible uncertainties and biases in each step estimating the parameters of the TF relation.

5. DISCUSSION

Our zero point for the Hubble diagram of SNs I is 0.5–1.5 mag fainter than the values previously reported, primarily because we have a estimated shorter distance to Virgo. LT adopted $M_{B,max} = -19.79 \pm 0.12$ using the estimate $(m - M)^0_{Virgo} = 31.79 \pm 0.09$. Superficially there appears to be little to choose between the two distance scales to Virgo, since both of them seem to rely on several independent distance indicators which agree to within their stated errors. We feel, however, that it is harder to disbelieve the "short" scale because of the evident precision of the indicators and make a few comments in order to justify why we have not adopted LT's arguments.

1. Since the luminosity functions of globular clusters (e.g., the Galaxy, LMC, M31, and M87) are observed to differ (Harris 1988), it is unclear what property of the function should be taken to be a standard candle. As pointed out by Jacoby et al. (1990), it correlates poorly with other standards.

2. Pritchet & van den Bergh's (1987) estimate $(m - M)^0_{Virgo} = 31.45 \pm 0.44$ is based on the light curves of six novae which scatter widely around the template curve (the average scatter about the curve is 0.86 mag, and χ^2 is about $\sim$60). Here again, there is poor correlation with other indicators; for example, the distance to M31 from novae (Cohen 1985) is $\sim$0.4 mag smaller than the Cepheid distance.

3. The D_n-σ relation is most appropriately calibrated with elliptical galaxies.

4. Kraan-Korteweg, Cameron, & Tammann (1988) derived a Tully-Fisher distance to the Virgo Cluster $(m - M)^0 = 31.60$ which differs from that of other authors by 0.6 mag (Mould, Aaronson, & Huchra 1980; Pierce & Tully 1988). Kraan-Korteweg et al. suggested that TF distances by other authors suffer from a serious sample incompleteness bias; however, the agreement of unrelated distance indicators demonstrates empirically that such bias is not as large as they supposed, at least for bright galaxies.

5. The expansion parallax method for SNs II requires a precise knowledge of the atmosphere of the supernova envelope to reliably calculate the flux (Chilukuri & Wagoner 1987).

Another approach which gives a large value of $-M_{\max}$ is to just calculate it a priori with a simple model of SNs I (Arnett et al. 1985). This argument hinges on various assumptions or approximations, for example, that the bolometric luminosity at maximum blue light is given by the instantaneous decay luminosity of ^{56}Ni, the mass of which is computed in a simple model, and that the spectrum is described by blackbody radiation with $T = 2 \times 10^4$ K for wavelengths $\lambda < 4000$ Å. Although the model is successful enough to serve as a convincing description of how SNs I work, in the absence of any evidence to the contrary, it seems at least possible that the allocation of the energy budget among kinetic energy, blue light, and other forms of radiation is not quite as predicted by the simple model. Our empirically derived value of $M_{B,\max}$ motivates a reexamination of the energy budget in models of Type I SNs.

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Note added in manuscript.—Very recently, Tonry et al. (1990b) have measured distances to NGC 4636, NGC 4621, and NGC 4374 using the surface brightness fluctuation technique; their estimated moduli of $(m - M)^0 = 30.96$, 30.73, and 31.33 for these three galaxies yield $M_{\max} = -18.36$, -18.73, and -19.13 for SNs 1939A, 1939B, and 1957B. These numbers are consistent with the estimate given in Table 2 to within 0.2–0.3 mag.

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