Supernova 1991T and the Value of the Hubble Constant

Brad K. Gibson

Centre for Astrophysics & Supercomputing, Swinburne University,
Mail #31, P.O. Box 218, Hawthorn, Victoria, Australia 3122

and

Peter B. Stetson

Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics,
National Research Council, 5071 W. Saanich Rd., Victoria, B.C., Canada V9E 2E7

ABSTRACT

Based upon multi-epoch *Hubble Space Telescope* observations, we present the discovery of sixteen high-quality Cepheid candidates in NGC 4527. Corrected for metallicity effects in the Cepheid period-luminosity relation, we derive a distance, including both random (r) and systematic (s) uncertainties, of 13.0 ± 0.5(r)±1.2(s) Mpc. Our result is then used to provide a calibration of the peak B-, V-, and I-band luminosities of the peculiar Type Ia supernova SN 1991T, a resident of NGC 4527. Despite its documented spectroscopic peculiarities, after correction for the decline rate–luminosity correlation the corrected peak luminosity is indistinguishable from those of so-called "normal" Type Ia SNe. With now nine local calibrators at our disposal, we determine a robust value for the Hubble Constant of $H_0=73\pm2$(r)±7(s) $\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

Subject headings: Cepheids — distance scale — galaxies: distances and redshifts — supernovae: general

1. Introduction

When corrected for the shape of their light curves, the peak apparent brightnesses of Type Ia supernovae (SNe) provide an outstanding secondary distance indicator (e.g., Phillips et al. 1999; Jha et al. 1999; Saha et al. 1999; Gibson et al. 2000a). First, the extreme luminosity of the SNe allows one to probe substantially further into the unperturbed Hubble flow, in comparison with competing secondary indicators such as the Tully-Fisher relation and surface brightness fluctuations. Second, the intrinsic scatter is smaller than that of other indicators. While attempts have been made to provide a purely theoretical calibration for the peak luminosity (e.g., Höflich & Khokhlov 1996),

remaining model uncertainties still favor the observational approach. The *Sandage/Tammann/Saha Type Ia SN HST Calibration Project* (Saha et al. 1999, and references therein) was designed to provide just such a calibration, by determining the Cepheid distances to eight nearby galaxies (IC 4182, NGC 5253, 4536, 4496A, 4639, 3627, 3982, 4527) host to Type Ia SNe. This original program has been supplemented with two additional calibrators situated within NGC 3368 (Tanvir et al. 1999) and NGC 4414 (Turner et al. 1998). Table 1 of Gibson et al. (2000a) provides a complete list of the galaxies and SNe covered by all these calibration programs, including a subjective quality ranking.

Of the ten nearby Type Ia SNe targeted by the various teams, only one is classified as spectroscopically peculiar — SN 1991T. While the data suggest that SN 1991T was a supernova with peculiar surface abundances (no evidence for Si, Ca, or S absorption during the early phases of the explosion), and had a light curve in B and V that was marginally broader than usual, in most other ways it seems to have been a normal Type Ia explosion (Phillips et al. 1992). Derivation of the Cepheid distance to NGC 4527, the host galaxy to SN 1991T, provides a direct test of the robustness of the technique as applied to potentially peculiar SNe.

In what follows, we present the Cepheid distance to NGC 4527, provide a calibration for the peak B-, V-, and I-band luminosities of SN 1991T, and present an improved determination of the Hubble Constant. As will be seen, the derived peak luminosities do not appear to be affected by the spectroscopic peculiarities of the SN.

2. Analysis

The SAB(s)bc spiral galaxy NGC 4527 was observed at 17 epochs over the 69 d window spanning 04/11/99-06/19/99, as part of the *Sandage/Tammann/Saha Type Ia Supernova Calibration Project* (*HST* PID#7504; Saha et al. 1999, and references therein). As for previous galaxies in this program (and the *HST Key Project on the Extragalactic Distance Scale*), cosmic-ray split 2500 s exposures in F555W (V: 12 epochs) and F814W (I: 5 epochs) were taken.

Following the well-documented methodology of the *HST Key Project* (e.g., Gibson et al. 2000a, and references therein), the data were processed with ALLFRAME (instrumental photometry – Stetson 1994) and TRIAL (calibration and variable finding – Stetson 1996).[1] As was done in Gibson et al. (2000a) and Freedman et al. (2001), the WFPC2 photometric zero point and charge-transfer corrections adopted are essentially those of Stetson (1998), which are nearly identical to those of Whitmore et al. (1999) and Dolphin (2000). The quoted systematic uncertainty in our final result incorporates a component which allows for imprecision in our current understanding of the spatial and temporal variations of the WFPC charge-transfer inefficiency. An initial candidate

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[1] An independent reduction will be provided by the Sandage/Tammann/Saha Team (Saha et al. 2001), but at the time this paper was submitted their results were not yet available.

list of 25 Cepheids was identified by TRIAL; light-curve inspection reduced this number to a final list of 16 high quality Cepheids, the properties of which are listed in Table 1. Epoch-by-epoch photometry for each of the Cepheids, local calibration standards, and accompanying light curves have been made available on the HST Key Project archive.[2]

In Figure 1 we show the apparent V- and I-band Period-Luminosity (PL) relations for the 16 Cepheids in NGC 4527 (upper and middle panels, respectively). The apparent moduli, in conjunction with (i) the assumption of a standard reddening law, (ii) an LMC true modulus $\mu_\circ(\mathrm{LMC})=18.45\pm0.10$ mag (Freedman et al. 2001), and (iii) a set of LMC PL relations (Udalski et al. 1999), leads to the distribution of de-reddened moduli shown in the lower panel, the mean of which implies a true modulus $\mu_\circ=30.482\pm0.085$ mag ($d_\circ=12.5\pm0.5$ Mpc). The quoted random uncertainty includes those due to photometry, extinction, and the dereddened PL fit (corresponding to R_{PL} in Table 7 of Gibson et al. 2000a). This distance assumes the Cepheid PL relation has no metallicity dependency (i.e., $\gamma_{\mathrm{VI}}=+0.0$ mag dex^{-1}; cf. Kennicutt et al. 1998).

The mean reddening inferred from these Cepheids is E(V−I)=0.268±0.031; since no Cepheid field H II region abundance analysis exists for NGC 4527, it is tempting to infer a metallicity based upon this line-of-sight reddening. However, plotting H II region metallicity 12+log(O/H) versus line-of-sight of reddening E(V−I), for each of the Cepheid fields of the 30 galaxies in Table 5 of Freedman et al. (2001), yields what is effectively a scatter plot over the limits $0.1\lesssim$E(V−I)$\lesssim0.3$ and $8.50\lesssim12+\log(\mathrm{O/H})\lesssim9.35$. For the derived NGC 4527 Cepheid reddening, 12+log(O/H) could plausibly lie anywhere within this range. Therefore we adopt the very conservative value of 12+log(O/H)=8.9±0.4 for the metallicity of the Cepheid field in NGC 4527. Under this assumption, the true modulus for NGC 4527 increases by 0.08 mag for $\gamma_{\mathrm{VI}}=-0.2$ mag dex^{-1}, to $\mu_\circ=30.562\pm0.085$ mag ($d_\circ=13.0\pm0.5$ Mpc) and will be used in what follows.

The functional form for the adopted Hubble relations in our analysis is described in Freedman et al. (2001) and is written

$$\mathrm{B,V,I_{max}} - 5\log(\mathrm{cz_{CMB}}) = a(\Delta m_{15}(\mathrm{B})_t - 1.1) + b, \tag{1}$$

where, from Phillips et al. (1999), $\Delta m_{15}(\mathrm{B})_t = \Delta m_{15}(\mathrm{B})_{\mathrm{obs}} + 0.1\,[\mathrm{E(B-V)_{Gal}} + \mathrm{E(B-V)_{Host}}]$. $\mathrm{E(B-V)_{Gal}}$ and $\mathrm{E(B-V)_{Host}}$ represent the Milky Way foreground and host galaxy reddenings, respectively, and are tabulated by Phillips et al. (1999) for each SN employed in our analysis.[3] The relevant coefficients and dispersions employed are $\sigma(\mathrm{B})=0.15$, $a(\mathrm{B})=+1.102\pm0.187$, $b(\mathrm{B})=-3.677\pm0.050$,

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[2]http://www.swin.edu.au/astronomy/bgibson/H0kp/ and
http://www.ipac.caltech.edu/H0kp/

[3]For SN 1991T, the adopted foreground+host reddening was E(B−V)=0.16±0.05 (Phillips et al. 1999; Tbl 2). The host reddening was derived from the favored late-time color excess technique; as noted by Phillips et al., the color excess at maximum light should not be employed for 1991T-like events. Despite the uncertainty in deriving reddenings for 1991T-like events, only a radical alteration of the inferred ($\gtrsim$100% increase in E(B−V), from 0.16 to $\gtrsim$0.35) could have more than a 1σ effect on the final weighted mean for $\mathrm{H_0}$.

σ(V)=0.14, a(V)=+1.016±0.160, b(V)=−3.624±0.044, σ(I)=0.16, a(I)=+0.975±0.168, and b(I)=−3.259±0.041, and were derived from the subset of 36 SNe from the Calán/Tololo (Hamuy et al. 1996) and CfA (Riess et al. 1998) surveys with (i) 3.5<log(cz_{CMB})<4.5, and (ii) |B_{max}−V_{max}|<0.20. Other functional forms (e.g., Phillips et al. 1999; Jha et al. 1999; Gibson et al. 2000a) lead to results indistinguishable from those described here. Equation 1, coupled with the zero points provided by the Cepheid distances to NGC 4527, 4639, 4536, 3627, 3368, 5253, 4414, 4496A, and IC 4182 provides a value for the Hubble Constant.

Before deriving H_0, we first ensured that the Cepheid distances for the other eight calibrators were on the same footing as that for NGC 4527, as described here. Using the same WFPC2 photometric zero point (Stetson 1998), LMC true modulus (Freedman et al. 2001), and LMC apparent PL relations (Udalski et al. 1999) described above, we re-fit PL relations for each galaxy to the identical Cepheids employed by Gibson et al. (2000a).[4] Table 2 shows the results of our re-fitting procedure assuming no-metallicity dependence in the Cepheid PL relation ($\mu_\circ$) and assuming a mild metallicity dependency of γ_{VI}=−0.2 mag dex^{-1} (μ_Z). The number of Cepheids employed in the fit n_{Ceph} and the internal random uncertainties σ_μ(r) are also listed.

The primary source of the difference between the distances listed here in Table 2, versus those presented earlier in Gibson et al. (2000a), comes from the adoption of the Udalski et al. (1999) LMC PL relations (in lieu of those of Madore & Freedman 1991). The Udalski et al. relations are based upon the homogeneous OGLE dataset, while the Madore & Freedman relations were derived from a more heterogeneous sample culled from a variety of sources. The former also benefit from exceedingly well-sampled light curves, and a factor of three greater number of Cepheids employed in the fitting. The Udalski et al. I-band PL relation is ∼0.10 mag dex^{-1} flatter in slope which acts to reduce the distances of the SN calibrator galaxies by ∼8% in the mean. The OGLE photometry and re-fitted LMC PL relations has been confirmed by the independent analysis of Sebo et al. (2001, in preparation).

Using the SN photometry and reddenings tabulated by Gibson et al. (2000a; Table 5), supplemented now with the apparent peak magnitudes (Lira et al. 1998; Table 7) and Galactic+intrinsic reddenings (Phillips et al. 1999; Table 2) for SN 1991T, the B-, V-, and I-band peak luminosities for the nine calibrating SNe can be calculated. These are listed in columns 3-5 of Table 3, assuming the metallicity-corrected true moduli μ_Z listed in Table 2. While not shown, the corrected peak luminosity for SN 1991T (e.g. $M_{B,corr}^{max}$=−19.40±0.24) is indistinguishable from that of the mean of the full sample of nine calibrators (<$M_{B,corr}^{max}$>=−19.32±0.08). While only one datum, there exists no evidence to suggest that spectroscopically peculiar Type Ia SNe need be dismissed *a priori* from future extragalactic distance scale work.

These calibrated peak luminosities can be used in conjunction with the Hubble relations de-

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[4]This differs slightly from that of Freedman et al. (2001) who re-fit PL relations for each galaxy, but employed Cepheid samples which differed from those published in the earlier papers in the series. This difference is inconsequential though in terms of its effect upon H_0.

scribed by equation 1 to provide SN and color-dependent Hubble constants. Columns 6-8 of Table 3 list H_0(B,V,I) for each of the nine calibrators. The weighted mean of H_0(B), H_0(V), and H_0(I), for the full sample, yields $H_0 = 73 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$, with a *random* uncertainty of $\pm 2 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$.

After Freedman et al. (2001; Table 15), seven sources of error were incorporated into the *systematic* error budget. Uncertainties in the LMC zero point, crowding, and large scale bulk flows each enter in at the ± 0.10 mag level; the metallicity dependency of the Cepheid PL relation at the ± 0.08 mag level; the WFPC2 zero point uncertainty at the ± 0.07 mag level; reddening and bias in the Cepheid PL fitting at the ± 0.02 mag level each. In quadrature, the overall systematic error budget amounts to 0.205 mag, corresponding to 10% in H_0. Significantly improving the precision to which we can derive H_0 via Cepheid calibration of secondary distance indicators will require a factor of two reduction in uncertainty in *each* of these five remaining dominant sources of systematic uncertainty. Until then, we are limited to 10% precision.

Of these seven sources of systematic error, two were not included in the formal acconting in early papers in the HST Key Project series: that due to crowding and that due to bulk flows. Bulk flows were explored in a preliminary sense by Gibson et al. (2000a), but neglected in the quoted systematic error budget (as it was in the companion papers published in the February 1, 2000 issue of The Astrophysical Journal). More extensive modeling, including a more sophisticated multi-attractor model for the local universe, allows for a $\pm 5\%$ systematic uncertainty (Freedman et al. 2001).

The effects of crowding have been claimed to be the dominant source of error plaguing the Cepheid-based extragalactic distance scale (Stanek & Udalski 1999), a claim that has not been substantiated by either empirical WFPC2 tests (Gibson, Maloney & Sakai 2000b) or artificial star tests (Ferrarese et al. 2000). Regardless, a systematic uncertainty of $\pm 5\%$ was still deemed plausible by Freedman et al. (2001), and for consistency with their analysis, we assume the same.

The final important modification to the systematic error budget used by Gibson et al. (2000a) is the adoption of a revised LMC true modulus. While Gibson et al. (2000a) assumed $\mu(\mathrm{LMC}) = 18.50 \pm 0.13$, based upon a frequentist and Bayesian analysis of the Gibson (2000) compilation of published LMC true moduli, Freedman et al. (2001) demonstrate that a downward revision to $\mu(\mathrm{LMC}) = 18.45 \pm 0.10$ is appropriate. This decrease has been driven primarily by the introduction of three new LMC distance indicators, all of which support $\mu(\mathrm{LMC}) < 18.5$: luminosity of the red clump, eclipsing binaries, and the indirect constraint provided by the maser distance to NGC 4258.

The remaining four sources of systematic uncertainty have either been discussed already, or are negligible in comparison with the others (and for brevity, not discussed further). Details pertaining to the latter terms (reddening constraints provided by NICMOS photometry and bias in the Cepheid PL fits due to short-end period cutoff) are provided by Freedman et al. (2001).

In combination, the above random (r) and systematic (s) error budget yields a final result for the Hubble Constant of

$$H_0 = 73 \pm 2 \, (\mathrm{r}) \pm 7 \, (\mathrm{s}) \, \mathrm{km \, s^{-1} \, Mpc^{-1}}. \tag{2}$$

Restricting the analysis to the seven best calibrators (i.e., dropping SN 1960F and 1974G) has no affect on H_0. Ignoring the metallicity dependency in the Cepheid PL relation (i.e., using $\gamma_{VI}=+0.0\,\mathrm{mag\,dex}^{-1}$, as opposed to the $\gamma_{VI}=-0.2\pm0.2\,\mathrm{mag\,dex}^{-1}$ employed here) increases H_0 by $3\,\mathrm{km\,s}^{-1}\,\mathrm{Mpc}^{-1}$.

3.   Summary

A Cepheid-based distance to NGC 4527, host to the peculiar Type Ia SN 1991T, has been derived using the same software pipeline and unbiased Cepheid PL analysis employed throughout the HST Key Project on the Extragalactic Distance Scale series of papers. The corrected peak luminosity is indistinguishable from that of spectroscopically normal SNe, demonstrating the robustness of the corrected peak luminosity as a secondary distance indicator. SN 1991T is only the fourth calibrator SN for which accurate I-band photometry exists. NGC 4527, in conjunction with re-derived distances for eight other Type Ia SN-host galaxies, and a full accounting of random and systematic uncertainties, yields a robust value of the Hubble Constant of $H_0=73\pm2(r)\pm7(s)\,\mathrm{km\,s}^{-1}\,\mathrm{Mpc}^{-1}$.

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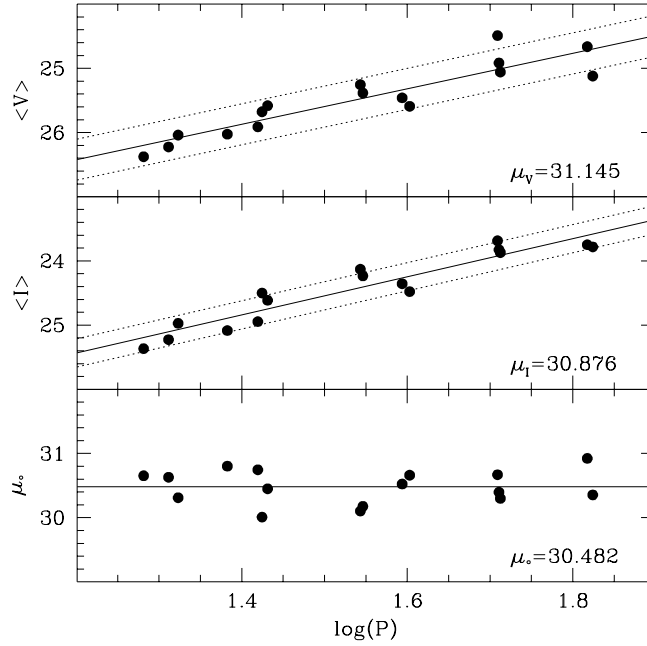Whitmore, B., Heyer, I. & Casertano, S. 1999, PASP, 111, 1559

Fig. 1.— Apparent period-luminosity relations in the V- (*upper panel*) and I-bands (*middle panel*) based upon the 16 high-quality Cepheid candidates discovered in NGC 4527 (the properties for which are listed in Table 1). The solid lines are least-squares fits to this entire sample, with the slope fixed to be that of the Udalski et al. (1999) LMC PL relations, while the dotted lines represent their corresponding 2σ dispersion. The inferred apparent distance moduli, ignoring metallicity effects, are then μ_V=31.145±0.056 (internal) and μ_I=30.876±0.046 (internal). *Lower Panel*: Distribution of individually de-reddened Cepheid true moduli, as a function of period. The mean corresponds to $< \mu_\circ >$=30.482±0.066 (internal).

Table 1.   Properties of Cepheids Detected in NGC 4527

ID	Chip	X	Y	$<V>$	$<I>$	$<P>$
C01	1	241.4	235.9	25.38±0.02	24.23±0.03	35.19±0.32
C02	1	375.9	236.7	26.22±0.03	25.23±0.06	20.49±0.33
C03	1	492.7	679.3	26.04±0.03	24.97±0.05	21.04±0.44
C04	1	403.6	522.0	25.68±0.02	24.50±0.03	26.58±0.35
C05	1	485.1	489.9	25.06±0.02	23.87±0.03	51.58±1.31
C06	2	83.1	260.1	25.46±0.02	24.36±0.04	39.25±0.33
C07	2	128.2	276.2	25.91±0.03	24.95±0.04	26.27±0.42
C08	2	138.9	251.6	24.49±0.02	23.69±0.02	51.17±0.76
C09	3	130.0	528.4	26.38±0.03	25.37±0.06	19.12±0.34
C10	3	134.6	387.5	25.59±0.02	24.48±0.03	40.07±0.63
C11	3	369.9	265.0	24.92±0.02	23.83±0.03	51.38±2.14
C12	3	782.6	326.6	26.03±0.03	25.08±0.04	24.13±0.17
C13	4	508.9	169.4	25.12±0.02	23.78±0.02	66.70±1.43
C14	4	391.8	670.0	25.25±0.03	24.13±0.04	34.94±0.53
C15	4	457.3	757.4	25.58±0.03	24.61±0.04	26.99±0.47
C16	4	137.3	176.4	24.66±0.03	23.75±0.03	65.69±3.24

Table 2.   Adopted True Distance Moduli $\mu_\circ$, Metallicity-Corrected Moduli μ_Z, and Internal Random Uncertainties $\sigma_\mu(\mathrm{r})$[a]

Galaxy	n_Ceph	$\mu_\circ$	μ_Z	$\sigma_\mu(\mathrm{r})$
NGC 4527	16	30.482	30.562	±0.085
NGC 4639	17	31.524	31.624	±0.084
NGC 4536	27	30.693	30.763	±0.069
NGC 3627	17	29.794	29.944	±0.169
NGC 3368	7	29.956	30.096	±0.098
NGC 5253	7	27.485	27.415	±0.119
IC 4182	28	28.207	28.187	±0.076
NGC 4496A	51	30.750	30.804	±0.067
NGC 4414	9	31.154	31.294	±0.105

[a]All distances are on the Stetson (1998) WFPC2 photometric zero point, assume the Udalski et al. (1999) LMC PL slopes and apparent zero points, and are referenced to an LMC distance of 49.0 kpc. The Cepheids employed in the PL fitting are identical to those used by Gibson et al. (2000a). Metallicity-corrected distance moduli assume $\gamma_\mathrm{VI} = -0.2\,\mathrm{mag\,dex^{-1}}$ and Cepheid field metallicities as tabulated by Gibson et al. (2000a; Table 1). The random uncertainties are derived following Gibson et al. (2000a) and correspond to item R_PL of Table 7 therein.

Table 3. Values of the Hubble Constant H_0

Galaxy	SN	M_B^{max}	M_V^{max}	M_I^{max}	$H_0(B)$	$H_0(V)$	$H_0(I)$
		Metallicity-Corrected: $\gamma_{VI} = -0.2\,\mathrm{mag\,dex}^{-1}$					
NGC 4527	1991T	-19.56 ± 0.23	-19.59 ± 0.19	-19.21 ± 0.13	71.7 ± 9.5	68.7 ± 7.7	68.8 ± 6.9
NGC 4639	1990N	-19.36 ± 0.16	-19.31 ± 0.13	-18.91 ± 0.10	73.6 ± 7.8	73.7 ± 6.9	74.6 ± 6.9
NGC 4536	1981B	-19.28 ± 0.15	-19.26 ± 0.12	n/a	75.1 ± 8.0	74.3 ± 7.0	n/a
NGC 3627	1989B	-19.20 ± 0.25	-19.15 ± 0.22	n/a	69.2 ± 9.8	69.9 ± 8.9	n/a
NGC 3368	1998bu	-19.42 ± 0.16	-19.39 ± 0.14	-19.12 ± 0.12	72.9 ± 7.9	72.2 ± 7.0	68.8 ± 6.8
NGC 5253	1972E	-19.21 ± 0.22	-19.14 ± 0.22	-18.74 ± 0.23	87.7 ± 12.1	87.4 ± 11.4	88.4 ± 12.4
IC 4182	1937C	-19.57 ± 0.28	-19.51 ± 0.24	n/a	74.4 ± 11.9	74.1 ± 10.3	n/a
NGC 4496A	1960F	-19.21 ± 0.32	-19.43 ± 0.30	n/a	79.8 ± 13.5	70.3 ± 11.2	n/a
NGC 4414	1974G	-19.50 ± 0.32	-19.52 ± 0.26	n/a	67.5 ± 11.4	65.3 ± 9.2	n/a
Weighted Mean (All nine SNe)					74.0 ± 3.2	72.4 ± 2.8	72.4 ± 3.8
Weighted Mean (Excluding SN 1960F and 1974G)					74.2 ± 3.5	73.3 ± 3.0	72.4 ± 3.8