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Bradley E. Schaefer

Yale University

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THE PEAK BRIGHTNESS OF SN 1960F IN NGC 4496 AND THE HUBBLE CONSTANT

BRADLEY E. SCHAEFER[1]
Department of Physics, Yale University, P.O. Box 208121, New Haven, CT 06520-8121; schaefer@grb2.physics.yale.edu
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ABSTRACT

The light curve of the Type Ia supernova SN 1960F (in NGC 4496) is important because the *Hubble Space Telescope* has measured the distance to the host galaxy by means of Cepheid variables, and thus the Hubble constant can be derived. Important parameters in this derivation include the peak magnitude as well as the decline rate of the supernova. In this Letter, I report on the results of my quantitative light-curve template fitting to all published data. These reported data are widely discrepant yet can be made all consistent after the brightnesses of the comparison stars are brought onto the Johnson system. I find the peak B and V magnitudes to be 11.77 ± 0.07 and 11.51 ± 0.18. The decline rate of SN 1960F is $\Delta m_{15} = 1.06 \pm 0.08$. These values can then be used to derive the Hubble constant as soon as the distance modulus to NGC 4496 (μ) is measured, where the H_0 equals 50 km s^{-1} Mpc^{-1} $10^{0.2[(31.58 \pm 0.13) - \mu]}$. With the recent report from A. Saha that $\mu = 31.1 \pm 0.1$, I find $H_0 = 62 \pm 5$ km s^{-1} Mpc^{-1}. A review is presented of 10 Type Ia events from which an average Hubble constant of 55 ± 3 km s^{-1} Mpc^{-1} is found.

Subject headings: cosmology: observations — distance scale — galaxies: individual (NGC 4496) — supernovae: individual (SN 1960F)

1. INTRODUCTION

Type Ia supernovae are good standard candles (Branch & Tammann 1992 and references therein; Hamuy et al. 1995; Tammann & Sandage 1995) that can be used to measure the Hubble constant (H_0). To calibrate their brightness, the *Hubble Space Telescope* has recently measured the distance to several host galaxies containing Type Ia events (Saha et al. 1994, 1995). This program has been continued with a measurement of the distance to the host galaxy of SN 1960F (NGC 4496) with Cepheids (Saha 1995). To utilize their distance, the peak magnitude for SN 1960F is needed.

Unfortunately, the published photometry of SN 1960F is wildly scattered (cf. Fig. 17 of Leibundgut et al. 1991a). That is, the many reported light curves all run roughly parallel yet with offsets of up to 0.6 mag. I find that the scatter is primarily caused by large discrepancies in the adopted magnitudes for comparison stars. Taken at face value, the systematic errors must be so large that the peak magnitude would be too uncertain to be useful for Hubble constant measurements. While some of these light curves might have near-zero offset, there is no unbiased means of identifying the quality data from the literature alone. However, this systematic error can be corrected by measuring the comparison star brightnesses on a modern magnitude scale and then correcting the original observations. These corrected magnitudes can be fitted to standard Type Ia light-curve templates to yield the peak magnitude and decline rate. In this Letter, I will give a complete analysis of all published photometry for SN 1960F.

2. OBSERVATIONS

SN 1960F was discovered by Humason (1960) on 1960 April 17 roughly at the time of maximum. The new star appeared in the outskirts of the SB galaxy NGC 4496 at around twelfth magnitude. Premaximum brightnesses on patrol plates were reported by Huth (1960). Five groups immediately began extended photometric series in the photographic magnitude system (Bertola 1964; Kulikov 1960; Kuzmin & Eelsalu 1960; Mannino 1962; Tempesti 1961). Tempesti (1961) and Tsvetkov (1983) have examined the original plates of Huth (1960) and Kulikov (1960), respectively. Only one visual magnitude has been published (Jones 1960). Bertola (1960), Bloch, Chalonge, & Dufay (1964), and Vorontsov-Velyaminov & Savelyeva (1961) present a detailed series of spectra that establish SN 1960F as a normal Type Ia event.

Albert Jones made 14 unpublished visual observations with a 12.5 inch reflector. Only the five observations before JD 2,437,060 have reliably identified comparison stars. These data are 11.68 on JD 2,437,050.9, 11.70 on JD 2,437,051.0, 11.86 on JD 2,437,058.0, 11.90 on JD 2,437,059.0, and 12.05 on JD 2,437,059.9.

The adopted comparison star magnitudes have been explicitly quoted for all observations. These adopted values are widely discrepant for measures of the same star. For example, star d of Tempesti is quoted to have a photographic magnitude of 12.19 (Tempesti 1961), 12.73 (Bertola 1964), 12.49 (Kulikov 1960), 12.95 (Mannino 1962), 12.70 (Kuzmin & Eelsalu 1960), and 12.74 (Tsvetkov 1983).

I have measured the Johnson B and V magnitudes for all comparison stars with the CCD camera on the 0.9 m telescope at the Cerro Tololo Inter-American Observatory. Complete sets of observations were carried out on each of two nights (1995 June 28 and 30), both during photometric conditions. The calibration from standards (Landolt 1992) was carried out independently for the two nights. The total number of standard stars measures is 25 and 24 over air-mass ranges of 1.16–2.41 and 1.17–2.21, respectively. Each comparison star was measured from 2 to 6 times, with the usual scatter of from 0.01 to 0.02 mag. The final B and V magnitudes are presented in Table 1.

These B and V magnitudes must be converted to photographic magnitudes to allow a direct comparison with the photographic observations. I have adopted the formula

$$m_{\rm ph} = B + 0.18(B - V) - 0.29. \tag{1}$$

This conversion has proved accurate for both stars and supernovae (Arp 1961; Mihalas 1963; Hamuy et al. 1991; Pierce & Jacoby 1995; Schaefer 1995a).

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[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, operated by AURA, Inc., under contract with the National Science Foundation.

TABLE 1

COMPARISON STAR MAGNITUDES

DESIGNATION[a]								
T	B	K	M	k	T	B	V	$m_{\rm ph}$
···	a	a	a	···	a	9.78	9.07	9.62
···	···	···	···	a	···	11.15	10.64	10.95
b	b	b	···	c	b	12.35	11.30	12.25
···	···	···	···	b	···	11.68	10.87	11.54
c	···	···	···	e	···	12.80	12.14	12.63
d	c	c	b	d	c	12.73	12.05	12.56
e	···	···	···	···	···	12.85	12.05	12.71
f	···	···	c	···	···	13.44	12.80	13.27
···	···	···	···	f	···	13.00	12.20	12.85
g	···	···	···	g	···	13.75	13.09	13.58
h	···	···	d	···	···	14.19	13.46	14.03
···	···	···	···	h	···	14.16	13.61	13.96
···	···	···	h	···	···	15.41	14.92	15.21
l	···	d	f	···	···	14.37	13.67	14.20
···	···	···	l	···	···	16.11	15.31	15.97
m	···	···	···	···	···	14.42	13.76	14.25
n	···	···	e	···	···	14.28	13.57	14.12
p	···	···	···	···	···	14.42	13.54	14.29
q	d	e	g	···	d	14.47	13.70	14.31
r	···	f	···	···	···	15.25	14.53	15.08
s	e	g	i	···	e	15.35	14.60	15.19
t	···	h	···	···	···	15.84	15.27	15.65
v	···	k	···	···	···	16.37	15.62	16.21

[a] Each column gives the letter designation of the star from the references T = Tempesti 1961, B = Bertola 1964, K = Kulikov 1960, M = Mannino 1962, k = Kuzmin & Eelsalu 1960, and t = Tsvetkov 1983.

With these accurate comparison star magnitudes, I have searched for systematic errors in the values adopted for each series of photometric measures. I find that in all cases there is a simple relation between the adopted magnitudes and my modern values:

$$m_{\rm ph} = m_{\rm ph}({\rm Tempesti}) + 0.42, \tag{2}$$

$$m_{\rm ph} = m_{\rm ph}({\rm Bertola}) * 0.975 + 0.12, \tag{3}$$

$$m_{\rm ph} = m_{\rm ph}({\rm Kulikov}) * 1.057 - 0.63, \tag{4}$$

$$m_{\rm ph} = m_{\rm ph}({\rm Mannino}) * 1.083 - 1.35, \tag{5}$$

$$m_{\rm ph} = m_{\rm ph}({\rm Kuzmin}) * 1.296 - 3.94, \tag{6}$$

$$m_B = m_B({\rm Tsvetkov}). \tag{7}$$

The observed rms scatters are 0.10, 0.03, 0.04, 0.14, 0.07, and 0.06 mag.

Color terms in equations (2)–(7) are statistically insignificant. Nevertheless, the color ranges of the comparison stars are not so large that real color terms could exist yet not be apparent. At most, the derived brightness of the supernova could change by ~0.1 mag, and indeed, this might be the source of some of the observed scatter in the peak of the final light curve. The derived peak magnitude will change by much less, unless all six series of early observations have similar and significant color terms.

With equations (2)–(7), I have rereduced the observations to produce photographic magnitudes on a modern scale. I have used the later reports of Tempesti (1961) and Tsvetkov (1983) instead of the preliminary magnitudes of Huth (1960) and Kulikov (1960). These values were then converted to Johnson B magnitudes by equation (1). The adopted colors for these conversions were the $B - V$ from the standard template of Leibundgut et al. (1991a) with an intrinsic $B - V$ at peak of 0.00 mag (Leibundgut et al. 1991a; Branch & Miller 1993; Hamuy et al. 1995; Schaefer 1995c). Variations in either the adopted template or the adopted peak color will have only small effects on the derived magnitudes. The resulting B light curve is plotted in Figure 1.

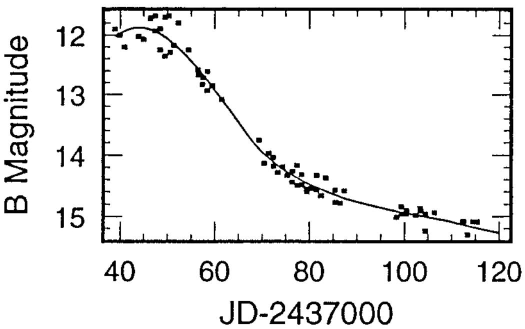

FIG. 1.—Light curve for SN 1960F. This light curve for SN 1960F is composed of observations from many observers. The published magnitudes are widely scattered, yet the scatter is greatly reduced when they are corrected to a modern magnitude system. All available data for the first 80 days after peak B light are plotted, along with the best-fit "slow" Type Ia light curve template. The observed rms scatter around the peak is 0.24 mag with a closely Gaussian distribution, so the 16 observations constrain the peak magnitude to within roughly 0.06 mag.

The near-peak observations are of particular importance and should be tested for possible systematic errors. A Kolmogorov-Smirnov test shows good agreement between a Gaussian distribution with zero mean and the distribution of deviations of near-peak photometry from the best-fit template (see below). This result holds whether all observers or individual observers are tested. Other Kolmogorov-Smirnov tests demonstrate that each pair of observers has deviations consistent with being drawn from the same distribution.

No error bars are quoted for any of the observations. All B measures are based on the same techniques, so it is reasonable to assign the same uncertainties to all observations. Following Schaefer (1994), I will adopt a 1 σ uncertainty of 0.15 mag for a collection of photographic magnitudes from a variety of sources. This choice will also make the reduced χ^2 of the best template fit close to unity. The uncertainty for Jones's visual observations is taken as 0.2 mag.

3. PEAK MAGNITUDE

This light curve can quickly yield an approximate peak magnitude and decline rate. The peak magnitude can be estimated by simply averaging the data within a few days of peak. These magnitudes must be corrected for the difference from the peak. (Here, the choice of template is not important.) For a peak on JD 2,437,045 (Bertola 1960; Tsvetkov 1983; Leibundgut et al. 1991a; and see below), this average is 11.87 ± 0.10, 11.84 ± 0.07, 11.88 ± 0.07, 11.91 ± 0.07, and 11.89 ± 0.06 mag for observations within 2, 3, 4, 5, and 6 days of peak. For this calculation, I will take the peak B magnitude as 11.88 ± 0.07. These uncertainties were calculated with the observed rms scatter of the individual observations, so any excess scatter near the peak is correctly accounted for. The magnitudes from 10 to 20 days after peak were fitted to a line, such that the magnitude 15 days after peak is 12.94 ± 0.04. Thus, the estimated decline is 1.06 ± 0.08 mag in the first 15 days.

A better method for deriving the peak B magnitude of SN 1960F follows the technique presented in Hamuy et al. (1995). They quantitatively fitted the observed light curve to light-curve templates of varying decline rates. The quantitative aspect of the fitting eliminates bias, allows for all data to be of utility, and allows for error bar calculations. One of their five light-curve templates is adopted from Leibundgut et al. (1991a) and is appropriate for an average Type Ia event. M. Phillips and M. Hamuy have provided me with four other templates that span the range of decline rate. Decline rate has been quantified by the convenient parameter Δm_{15}, which is the fading in B magnitudes undergone in the first 15 days after the peak. The five templates are for SN 1991T, Leibundgut's average, SN 1992A, SN 1986G, and SN 1991bg, for which Δm_{15} is 0.94, 1.10, 1.33, 1.73, and 1.88 mag, respectively.

Each fit for a given template has only two free parameters: the date of peak B light and the maximum B magnitude. The best fit (see Fig. 1) was chosen as that which had the lowest χ^2 for any date of maximum. The 1 σ statistical uncertainties were taken as the range of parameters over which the χ^2 value has risen by unity above the minimum.

A possible systematic uncertainty in this procedure is the template accuracy at late times. Observations later than 80 days after peak are likely to be dominated by these errors, and the available templates extend only this far. So the one observation later than 80 days after peak was excluded, thus leaving 68 B observations for the fits.

The χ^2 values of the template fits are 70, 87, 175, 151, and 319 for the five templates from slow to fast. This demonstrates that SN 1960F had a somewhat slower than normal light curve. The best-fit template has Δm_{15} equal to 0.94 mag, but the lack of very slow templates does not allow for a precise measure of Δm_{15}. Ideally, additional slow templates could be used to constrain reliably the minimum χ^2. But for now, any fit would depend critically on the unknown shape of the χ^2 curve. Instead, I will adopt the decline rate derived at the start of this section, $\Delta m_{15} = 1.06 \pm 0.08$.

The date of maximum is within a day of JD 2,437,045 for all templates, with the three slowest templates each yielding JD 2,437,044.2 ± 0.6.

The fitted B maximum is 11.88 ± 0.02 for the slow template ($\Delta m_{15} = 0.94$) and 11.73 ± 0.02 for the standard template ($\Delta m_{15} = 1.10$). These values can be interpolated to the case with $\Delta m_{15} = 1.06 \pm 0.08$, to yield a peak B magnitude of 11.77 ± 0.07.

How sensitive is this result to the details of my analysis? I have performed the identical analysis with several alternative methods. (1) The template fitting procedure can be avoided with the procedure described in the first paragraph of this section. This method averages the near-peak measures and computes the error bar from the observed rms scatter. Here, the derived $m_{\rm max} = 11.88 \pm 0.07$ is 1 σ different. (2) The sensitivity to the template at late times can be tested by repeating the fits for data only within 20 days of peak. I find $m_{\rm max}$ values of 11.88 ± 0.03, 11.86 ± 0.03, and 11.71 ± 0.03 with χ^2 values of 47, 45, and 63 for the slow, standard, and moderately fast template fits, respectively. Again, the alternative procedure yields a peak magnitude within 1 σ of the value from the full 80 day fit. (3) The sensitivity to my adopted uniform observational error bars can be tested by fits that use the observed rms scatter around equations (2)–(7) instead. I find $m_{\rm max} = 11.68 \pm 0.09$, which again is within 1 σ of the value found for uniform uncertainties. With these three alternatives yielding consistent peak magnitudes, I conclude that my results are robust against changes in procedural details.

The peak V magnitude was found from template fits to the five measures of Jones, with the time of B peak set to JD 2,437,044.2. The fitted peak V magnitudes were 11.55 ± 0.18 for the slow template and 11.49 ± 0.15 for the standard template. For the decline rate derived from the B light curve, the final peak V magnitude is 11.51 ± 0.18.

The peak magnitudes should be corrected for the extinction. The extinction from our Milky Way should be zero (Leibundgut et al. 1991a). SN 1960F appears near the edge of a face-on galaxy, so the local extinction is expected to be close to zero. The $B - V$ color at peak is 0.26 ± 0.19, consistent with zero extinction. The high-resolution spectra of Bloch et al. (1964) show no indication of calcium absorption lines, so again the extinction is zero. I will take $A = 0.00^{+0.1}_{-0.0}$ in the B band.

4. HUBBLE CONSTANT

These magnitudes can be used to establish the Hubble constant as soon as the distance modulus to NGC 4496 (μ) is measured. The Hubble constant is

$$H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}\, 10^{0.2(m_{\rm max} - \mu - A - M_{\rm max,50})}, \tag{8}$$

where $M_{\rm max,50}$ is the peak absolute magnitude for a fiducial H_0 of 50 km s^{-1} Mpc^{-1}. Type Ia events have been reliably calibrated to be

$$M_{\rm max,50} = 0.847\, \Delta m_{15} - 20.80 \qquad [B\text{-band}] \tag{9}$$

$$M_{\rm max,50} = 0.787\, \Delta m_{15} - 20.75 \qquad [V\text{-band}] \tag{10}$$

with a 1 σ scatter of 0.15 and 0.09 mag (eqs. [11]–[12] of Hamuy et al. 1995; see § 5).

In the B band, $m_{\rm max} = 11.77 \pm 0.07$, $A = 0.00^{+0.1}_{-0.0}$, $\Delta m_{15} = 1.06 \pm 0.08$, and $M_{\rm max,50} = -19.90 \pm 0.16$. In the V band, $m_{\rm max} = 11.51 \pm 0.18$ and $M_{\rm max,50} = -19.92 \pm 0.11$. The two bands are consistent and can be combined to give

$$H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}\, 10^{0.2[(31.58 \pm 0.13) - \mu]}. \tag{11}$$

Recently, Sandage and co-workers have reported a preliminary value of $\mu = 31.1 \pm 0.1$ (Saha 1995). This leads to $H_0 = 63 \pm 5$ km s^{-1} Mpc^{-1}.

5. SUMMARY

To get H_0 from Type Ia supernovae, three inputs are needed: relative calibration based on distant events, distances to nearby events, and peak magnitudes for the nearby events. Recently, great progress has been made in making each input of high reliability.

For many years, the relative calibration (i.e., $M_{\rm max,50}$) of Type Ia peak magnitudes was unclear, with possibilities of a standard candle calibration (Kowal 1968; Sandage & Tammann 1982, 1985; Cadonau, Sandage, & Tammann 1985; Branch & Tammann 1992; Rood 1994), a decline rate calibration (Pskovskii 1984 [but see Boisseau & Wheeler 1991]; Phillips 1993; Hamuy et al. 1995), or even no useful calibration (van den Bergh & Pazder 1992; van den Bergh & Pierce 1992). But this deadlock has now been broken in favor of the decline rate relation. In particular, the input data for the third possibility has been shown to be fatally flawed (e.g., Sandage & Tammann 1993; Schaefer 1995c), while the existence of a correlation between decline rate and peak absolute magnitude is significantly established. The correlation slope is much shallower than derived from the nine events in Phillips (1993), as is shown by Hamuy et al. (1995), Tammann & Sandage (1995), Branch, Romanishin, & Baron (1996), as well as with

TABLE 2

THE HUBBLE CONSTANT FROM SUPERNOVAE

Supernova	Band	$m_{\rm max}$	Δm_{15}	μ	H_0[a]
SN 185[b]	. . .	. . .	. . .	. . .	. . .
SN 1006	V	−5.4 ± ~1[c]	Unknown[c]	11.01 ± 0.18[c]	120 − 330[c]
SN 1572[d]	V	−4.53 ± 0.09[c]	1.88 ± 0.3[c]	11.86 ± 0.17[c]	66^{+12}_{-9}
SN 1604[e]	. . .	. . .	. . .	. . .	. . .
SN 1895B	B	8.26 ± 0.11[f]	1.1 ± 0.2[f]	28.08 ± 0.10[g]	51 ± 12[f]
SN 1937C	B	8.71 ± 0.14[h]	1.10 ± 0.2[h]	28.36 ± 0.09[i]	52 ± 4[h]
	V	8.72 ± 0.06[h]	1.10 ± 0.2[h]	28.36 ± 0.09[i]	48 ± 8[h]
SN 1960F	B	11.77 ± 0.07	1.06 ± 0.08	31.1 ± 0.1[j]	65 ± 6
	V	11.51 ± 0.18	1.06 ± 0.08	31.1 ± 0.1[j]	58 ± 7
SN 1972E	U	8.05 ± 0.1[k]	0.94 ± 0.1[l]	28.08 ± 0.10[g]	40 ± 6[m]
	B	8.61 ± 0.21[l]	0.94 ± 0.1[l]	28.08 ± 0.10[g]	58 ± 10[l]
	V	8.61 ± 0.12[l]	0.94 ± 0.1[l]	28.08 ± 0.10[g]	58 ± 10[l]
	H	9.35 ± 0.04[n]	0.94 ± 0.1[l]	28.08 ± 0.10[g]	55 ± 7[m]
SN 1981B	U	11.74 ± 0.06[o]	1.07 ± 0.09[o]	31.18 ± 0.05[j]	55 ± 10[o]
	B	12.04 ± 0.04[o]	1.07 ± 0.09[o]	31.18 ± 0.05[j]	65 ± 12[o]
	V	11.98 ± 0.04[o]	1.07 ± 0.09[o]	31.18 ± 0.05[j]	58 ± 11[o]
	H	12.94 ± 0.02[o]	1.07 ± 0.09[o]	31.18 ± 0.05[j]	68 ± 9[o]
SN 1990N	B	12.65 ± 0.05[p]	1.15 ± 0.10[p]	32.00 ± 0.23[q]	62 ± 8
	V	12.57 ± 0.05[p]	1.15 ± 0.10[p]	32.00 ± 0.23[q]	61 ± 7

[a] The Hubble constant in units of km s^{-1} Mpc^{-1}.

[b] SN 185 is certainly not a Type Ia event, as the two seriously proposed remnants are from Type II events. In any case, it is most probable that "SN 185" is not even a supernova (Schaefer 1996).

[c] Schaefer 1996.

[d] SN 1572 might well be a Type Ib event (Schaefer 1996).

[e] SN 1604 is almost certainly not a Type Ia supernova (Bandiera 1987; Schaefer 1996).

[f] Schaefer 1995a.

[g] Saha et al. 1995.

[h] Schaefer 1994.

[i] Saha et al. 1994.

[j] Saha 1995.

[k] Leibundgut et al. 1991a.

[l] Hamuy et al. 1995.

[m] Schaefer 1995c.

[n] Elias et al. 1985.

[o] Schaefer 1995b.

[p] Leibundgut et al. 1991b.

[q] Sandage et al. 1996.

extensive new data from the Calan-Tololo survey (M. Hamuy 1995, private communication). The relative calibration in equations (9) and (10) (from eqs. [11] and [12] of Hamuy et al. 1995) represent this consensus.

Before the launch of the *Hubble Space Telescope*, the only supernovae with reliable distances (independent of H_0) were the four reputed Type Ia events in our own Galaxy (Branch & Tammann 1992). Now the *Hubble Space Telescope* observations of Cepheid distances to the host galaxies of six Type Ia events (Sandage et al. 1992, 1994, 1996; Saha et al. 1994, 1995; Saha 1995) have transformed the situation to one in which a useful number of reliable distances are known.

This paper is the sixth in a series (Schaefer 1994, 1995a, 1995b, 1995c, and 1996) in which I reevaluate the peak brightnesses of historical supernovae for Hubble constant purposes. I have sought out all existing data, measured comparison stars on modern magnitude systems, remeasured original plates with microdensitometry, employed quantitative template fitting, and utilized a new heliacal rise technique. These advances have yielded reliable peak magnitudes with quantitative error bars.

Results for all four pretelescopic "Type Ia" supernovae as well as the five *Hubble Space Telescope* events are summarized in Table 2. The four historical events are unsuitable for H_0 work (Schaefer 1996) and are hereafter disregarded. Each event has a H_0 derived for each observed color. Twelve of 15 measures are within 1 σ of 56 km s^{-1} Mpc^{-1}, while a *majority* of measures are inconsistent at greater than the 1 σ level with any value higher than 68 km s^{-1} Mpc^{-1}. Thus, this route to the Hubble constant strongly favors a value in the 50s.

The 15 measures can be combined to yield an overall value. This combination was done one color at a time so that calibration uncertainties could be isolated. These uncertainties are systematic across all measures in a color and range from 4% (in V band) to 10% (in H band). The weighted average for each color then has its uncertainty increased to account for calibration errors. A final weighted average over the four colors yields the combined Hubble constant of 55 ± 3 km s^{-1} Mpc^{-1}. If only the four modern supernovae are considered, then the Hubble constant is 56 ± 3 km s^{-1} Mpc^{-1}.

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