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THE CEPHEID DISTANCE TO NGC 5253: CALIBRATION OF M(max) FOR THE TYPE Ia SUPERNOVAE SN 1972E AND SN 1895B

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ABSTRACT

The apparent V distance modulus of NGC 5253, parent galaxy to the Type Ia supernovae SN 1972E and SN 1895B, is $(m - M)_{AV} = 28.06 \pm 0.06$ mag (internal error) determined from 11 Cepheid variables discovered with the *Hubble Space Telescope*. The internal differential absorption between the Cepheids and the two SNs is taken to be zero based on four independent methods.

The absolute magnitudes of SN Ia 1972E are $M_B(\text{max}) = -19.53 \pm 0.12$, and $M_V(\text{max}) = -19.46 \pm 0.12$. The absolute magnitude of SN Ia 1895B is $M_B(\text{max}) = -19.69 \pm 0.21$, based on $B(\text{max}) = 8.4 \pm 0.2$ determined by correcting Walker's comparison stars, in 1923, to the modern photoelectric zero point in B.

Combining these data with the data for SN 1937C in IC 4182 determined earlier gives mean values of $\langle M_B(\text{max}) \rangle = -19.55 \pm 0.08$ mag based now on three SNs calibrations relative to Cepheids, and $\langle M_V(\text{max}) \rangle = -19.58 \pm 0.09$ mag based on two Cepheid determinations.

Using the extant Hubble diagrams in B and V for SNs Ia gives the global values of the Hubble constant as $H_0(B) = 52 \pm 8$ km s^{-1} Mpc^{-1}, and $H_0(V) = 55 \pm 8$ km s^{-1} Mpc^{-1}. The quoted error is the *external* uncertainty assuming an intrinsic dispersion of 0.3 mag about the Hubble diagram for SNs Ia.

Subject headings: Cepheids — distance scale — galaxies: individual (NGC 5253) — supernovae: individual (SN 1972E, SN 1895E)

1. INTRODUCTION

The results set out here are part of a program to determine M(max) empirically for a sample of "normal" supernovae of Type Ia. Much evidence exists that such SNs Ia have an intrinsic dispersion of less than 0.3 mag in $\langle M(\text{max}) \rangle$. This is not contradicted by studies such as that by Phillips (1993) where a wider range of M(max) is found because of the presence of three peculiar SNs Ia in the sample of eight SNs which he considered.[6]

The amorphous galaxy NGC 5253 has produced the supernovae 1895B and 1972E. Based on the light curve, SN 1895B was probably of Type Ia. Its spectrum, as described by Johnson (1936), shows features consistent with Type Ia. The referee, who also examined the spectrum, has stated "I would estimate that the spectrum is consistent with a SN Ia about 10–20 days past max."

SN 1972E was beyond doubt of Type Ia because it has been defined as a prototype that establishes the characteristics of the class (Oke & Searle 1974; Branch et al. 1993). The principal data for this classification are those of Ardeberg & de Groot (1973) and Kirshner et al. (1973).

NGC 5253 is a member of the nearby Centaurus Group (Kraan-Korteweg & Tammann 1979, their group B6) for which distance estimates range from 8 Mpc (Sandage & Tammann 1974, 1975) in an early study, to 2.5 Mpc (Phillips et al. 1992). Most other estimates range between 3 and 4.5 Mpc (corresponding to distance moduli of $m - M$ between 27.4 and 28.3) such as those by Sersic (1960), de Vaucouleurs (1980), Hesser et al. (1984), Della Valle & Melnick (1992), Stropbell, Bland-Hawthorn, & Malin (1993), and Branch et al. (1994).

We have continued our program of calibrating the absolute magnitudes of SNs Ia at maximum by finding Cepheid distances of the parent galaxies. We report here the discovery of Cepheids in NGC 5253 using the *Hubble Space Telescope*.

2. SEARCH FOR CEPHEIDS

Observations at 20 epochs in the F555W passband and five epochs in the near IR F785LP bandpass were made with *HST* over a 49 day interval from 1993 May 31 to 1993 July 19. The positioning of the WFC frames relative to the position of NGC 5253 is shown in Figure 1 (Plate L1), overlaying a ground-based image. The positions of SNs 1895B and 1972E are shown (see also Caldwell & Phillips 1989).

The reduction of the CCD frames and the search for variables was done independently at STScI and at Basel using the procedures described for IC 4182 (Sandage et al. 1992; Saha et al. 1994a). Photometry of each object at each epoch was obtained, and if the variation from epoch to epoch was sufficiently above noise, the object was flagged and examined further. Photometry at STScI was done by a variant of DoPHOT (Schechter, Mateo, & Saha 1993), and at Basel using an independent program ROMAFOT (Buonanno et al. 1979, 1983).

Twelve definite Cepheids have been discovered, each confirmed by both groups. Many more candidates, most of which are certainly Cepheids, exist near the detection limit of the

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[6] Variations within the Ia class are beginning to be studied (Phillips 1993), suggesting a finer classification within the SNs Ia general class. Studies of the subtle differences in the spectra and the rate of decline of the light curve may eventually provide an even tighter calibration of M(max) than we are attempting here for all "normal" SNs Ia, treated as a single class, as defined and classified by Branch, Fisher, & Nugent (1993).

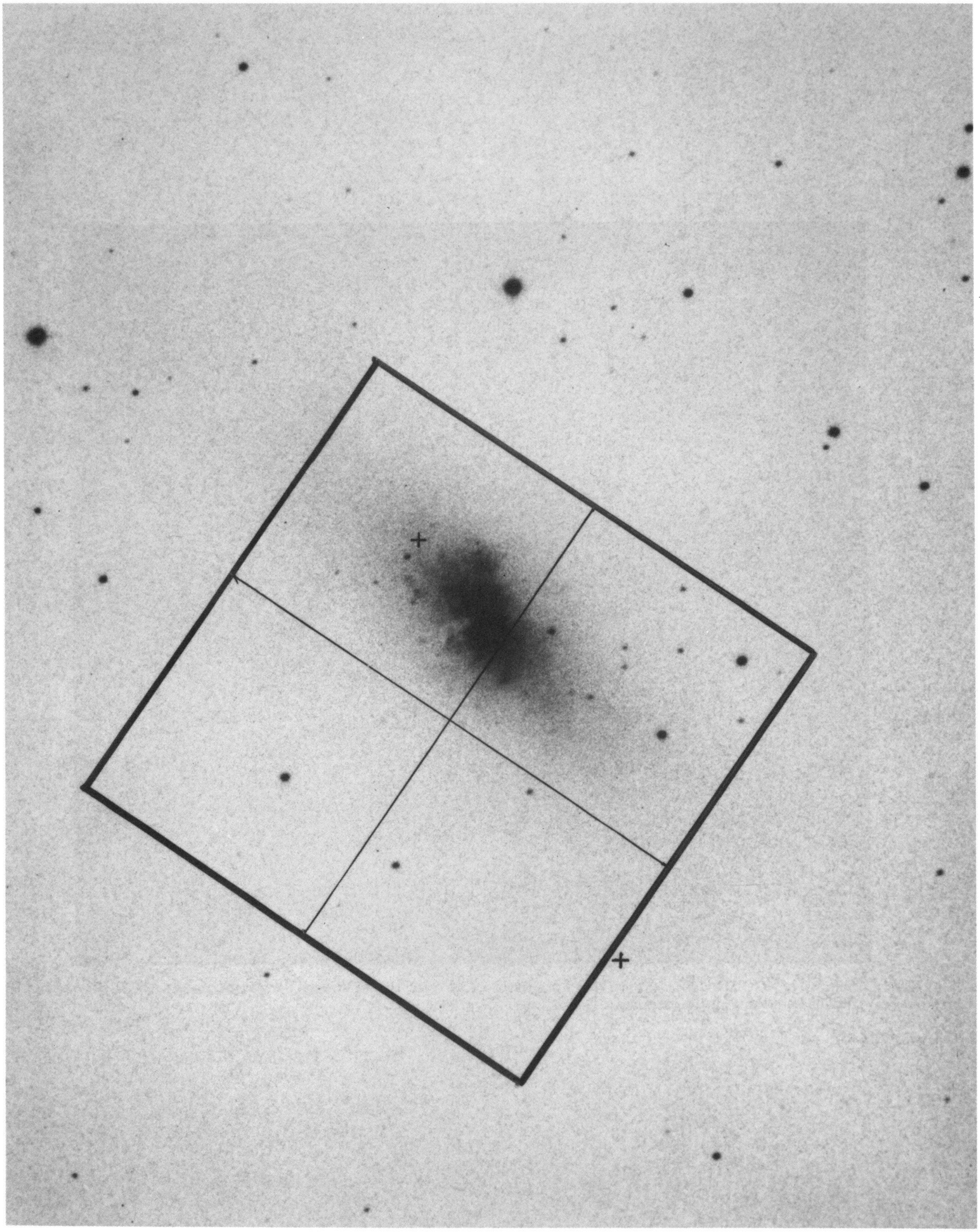

FIG. 1.—Ground-based image of NGC 5253 taken with the Las Campanas Observatory 2.5 m DuPont reflector with the WFC frame position overlain. The approximate positions of SN 1895B and SN 1972E are shown.

material. We are conservative in this *Letter* by restricting the present search limit to a high S/N level so as to report data that have the smallest statistical errors. Results of the complete search to fainter magnitude limits than we report here will be set out in the archive paper (Saha et al. 1994b).

All periods but one are unique. An alias occurs for one of the faintest variables, giving possible periods of 2.58, 3.90, and 6.62 days. This variable was not used in the analysis.

The periods of the 11 variables range from 16.1 to 3.97 days, unlike the data in IC 4182 where a number of Cepheids with periods larger than 16 days were found.

3. THE MAGNITUDE SCALE

Determination of magnitude zero points from the WFC data was done independently at Basel and Baltimore, identically to that described in Saha et al. (1994a) for IC 4182, and then compared. The STScI and Basel mean Cepheid magnitudes define the same F555W system to within 0.045 ± 0.04 mag and have been averaged.

However, we were concerned that the sensitivity of WFC may have changed between the Faber (1991) report (i.e., the *HST* SV magnitudes) and the time of the NGC 5253 observations. Therefore, calibration frames in the *HST* archive were reduced for the two subdwarfs BD +28°4211 and BD +75°325, taken in a time closest to our data. A correction of −0.14 mag (our final magnitude system is brighter) was found to F555W relative to the *HST* SV zero point. The data reported here are on the corrected system. We found that no correction was needed in the F785LP zero point.

Because the zero point of our magnitude scale is at the heart of the problem, we sought an independent test of our photometry. To this end John Tonry offered to provide V and I magnitudes that he had determined from the ground by CCD photometry in the field of NGC 5253. These were transformed to the F555W and F785LP system defined by Harris et al. (1991) and Hunter et al. (1992). The transformed values were compared with our final *HST* values. Based on 15 uncrowded stars between $V = 18.5$ and 21.8 on three of the four WFC chips, the independent data show agreement in zero point as Tonry − us $= 0.014 \pm 0.03$ mag (the data are set out in Saha et al. 1994b). On the basis of this, no correction has been made to our F555W scale. The comparison in $\langle I \rangle$ gives a correction to our scale of -0.03 ± 0.06 mag (in the sense of Tonry − us). This correction is insignificant within the errors and has not been applied.

4. LIGHT CURVES AND THE $P-L$ RELATION

Four representative light curves in F555W are shown in Figure 2. The $P-L$ relation for the total sample is shown in Figure 3.

As for the IC 4182 work, the slope of the $P-L$ relation has been fixed by an a priori Cepheid calibration based on Galac-

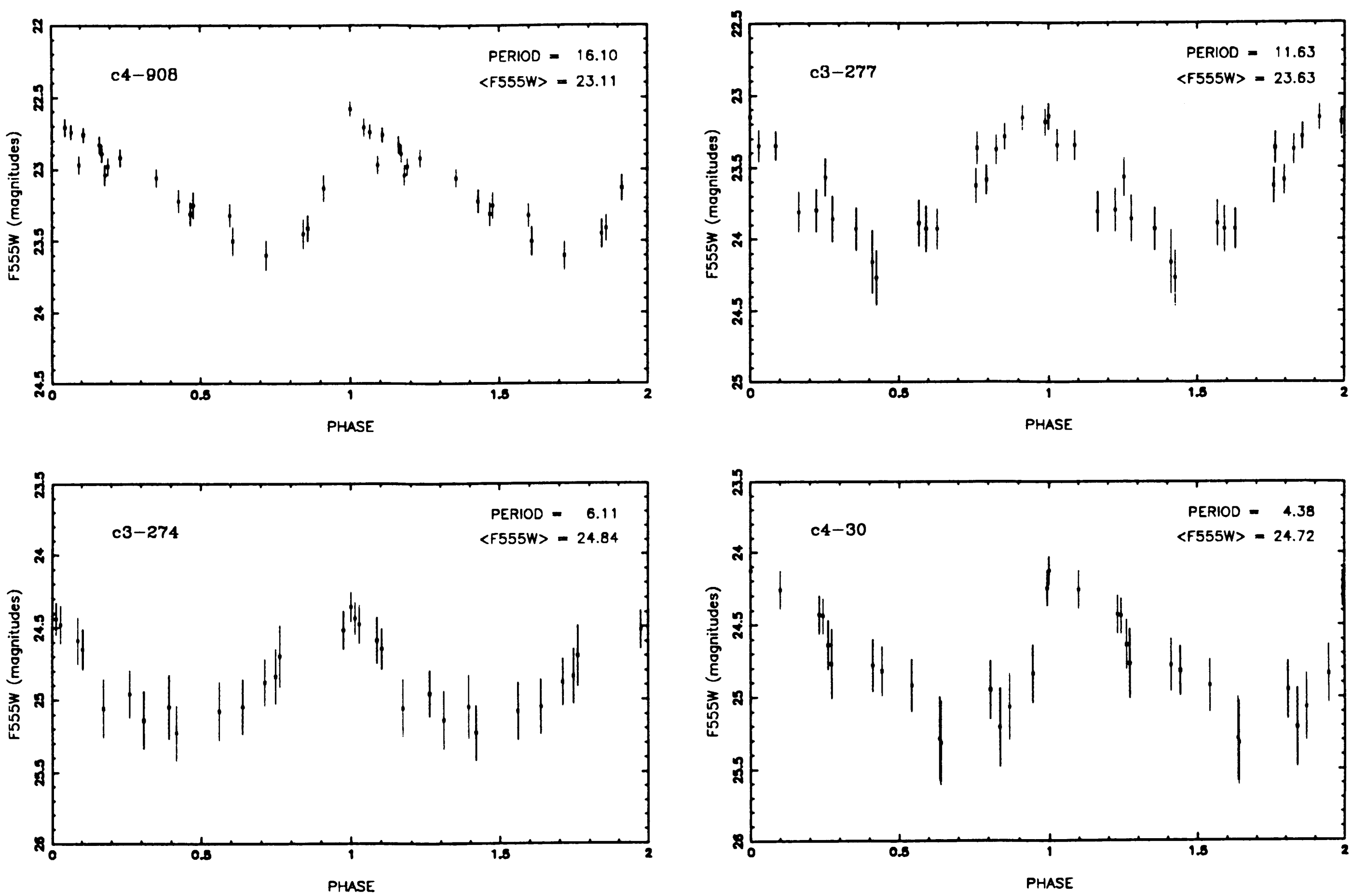

FIG. 2.—Light curves of four of the 12 definitive Cepheids found in NGC 5253

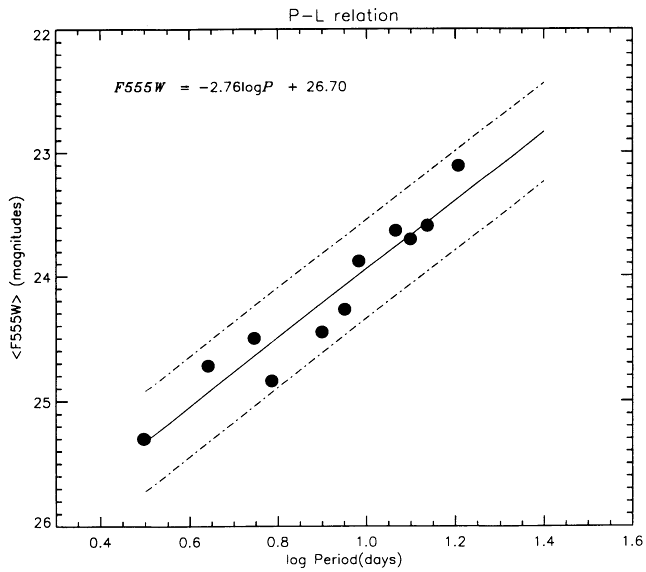

FIG. 3.—The $P-L$ relation in F555W magnitudes for the 11 Cepheids with definitive periods.

tic Cepheids and on Cepheids in the LMC. The dashed lines in Figure 3 are drawn ± 0.4 mag from the ridge line. This is the expected intrinsic scatter due to the finite width of the Cepheid instability strip (Sandage & Tammann 1968).

5. THE DISTANCE TO NGC 5253

Consistency with the $P-L$ relation in F785W, whose calibration is given only by Madore & Freeman (1991, hereafter MF), requires that we use the MF calibration for the F555W data as well. This zero point is 0.04 mag brighter than that given by Sandage & Tammann (1968, Table 4) in the period range of the NGC 5253 variables.

The equation of the ridge line in Figure 3 is $\langle \mathrm{F555W} \rangle = -2.76 \log P + 26.70$ which is a fit to the 11 Cepheids that have no aliases in the period. The individual Cepheids scatter about this line by rms = 0.19 mag, implying that the mean ordinate of the ridge line is determined to ± 0.06 mag. Using the MF (1991) calibration of $M_V = -2.76 \log P - 1.40$, the apparent modulus in V, after applying a color correction of -0.04 needed to convert F555W to V (Harris et al. 1991), is $(m - M)_{AV} = 28.06 \pm 0.06$. The quoted error is internal, no account taken of any uncertainty in the absolute magnitude zero point of the Cepheid $P-L$ relation.

The F785LP data are not so straightforward. Only five epochs were observed, and the sensitivity in I is 1.5 mag poorer at the same S/N as in F555W. Furthermore, the fluctuation amplitude of the background is higher in I than in V, and is higher in I than for our previous data in IC 4182, affecting the reliability to which magnitudes can be obtained for the faintest Cepheids here. If the eight Cepheids for which it is possible to obtain believable magnitudes are used, and adding a color correction of 0.08 mag to transform F785LP to I (Harris et al. 1991 at colors appropriate for Cepheids), then the best-fit $P-L$ relation is $\langle I \rangle = -3.06 \log P + 26.14 \pm 0.11$. Using the calibration of the Cepheid absolute calibration in I (MF 1991) gives an apparent distance modulus of $(m - M)_{\mathrm{AI}} = 28.03 \pm 0.14$. Hence, formally, $E(V-I) = 0.03 \pm 0.15$. The uncertainty in this estimate makes it less useful than other available methods to determine the reddening that are discussed in § 7.

6. APPARENT MAGNITUDES OF SNs 1972E AND 1895B

Fitting of an adopted standard template light curve to the photoelectric data for SN 1972E, gives $V(\max) = 8.60$, and $B(\max) = 8.58$ (Leibundgut et al. 1991) after we change the tabulated magnitudes in the Basel Atlas back to the *observed* system, that is, by removing their correction for the Galactic absorption of 0.10 mag in V and 0.13 mag in B. The observed magnitudes have an accuracy at the 0.10 mag level. They have a strong photoelectric basis in the observations by Ardeberg & de Groot (1973), begun only 2 days after Kowal's (1972) discovery.

Data, reduced to the modern B system, are also available for SN 1895B. Leibundgut et al. list $m_{\mathrm{pg}}(\max) = 7.0$ on the basis of initial estimates by Fleming & Pickering (1895) and by Cannon (1916) on the discovery plate. Later measurements of the same plate by Walker (1923), based on comparison stars whose magnitudes were freshly determined by Walker, show beyond doubt that the initial estimate of $m_{\mathrm{pg}}(\max) = 7.0$ is not correct. We agree with Branch et al. (1994) that the correct value is $m_{\mathrm{pg}} = 8.0$ based on Walker's measurement of the discovery plate. Reduction by the known color equation between the old international m_{pg} and the B system (Arp 1961) gives $B(\max) = 8.3$. A further correction of 0.1 mag is required to correct Walker's comparison stars to known modern photoelectric B and V values, found by comparing the Walker magnitudes with B (photoelectric) listings in the modern catalog literature for the same stars (Saha et al. 1994b). Therefore $B(\max) = 8.4$ for SN 1895B. Based on our analysis of the magnitude scale (Saha et al. 1994b), we assign an estimated error of ± 0.2 mag. The SN is so much brighter at maximum than the background light of the galaxy that it is clear that Walker's measurements are not appreciably affected by the background light of NGC 5253 at maximum (see the chart in Caldwell & Phillips 1989).

7. LIMITS ON THE DIFFERENTIAL EXTINCTION BETWEEN THE CEPHEIDS AND THE TWO SUPERNOVAE IN NGC 5253

As shown in § 5, the determination of the $P-L$ relations in V and I are consistent, but constrain $E(V-I)$ poorly. We seek more accurate ways to determine the differential absorption between the Cepheids and the two SNs in NGC 5253. Four different methods exist for showing that the differential extinction between the Cepheids and the two SN is smaller than we can measure.

1. The ionized gas within the central 20" of NGC 5253 has an emission-line spectrum whose $\mathrm{H}\alpha/\mathrm{H}\beta$ ratio is 2.7 (Welch 1970; Osmer, Smith, & Weedman 1974), which is the *reddening-free* value. This evidence alone excludes very strong reddening but has sometimes been taken to be puzzling because a few prominent dust lanes exist within 10" of the center, providing an ambiguous interpretation.

Clarification has come from study of *IUE* archive spectra of 39 "starburst" galaxies (Calzetti, Kinney, & Storchi-Bergmann 1993), including NGC 5253. They find that NGC 5253 has the bluest nucleus in both F(1250 Å) and F(1700 Å) and in the $\mathrm{H}\alpha/\mathrm{H}\beta$ ratio. NGC 5253 defines the blue edge of their absorption/reddening distribution, indicating negligible reddening within the 10" × 20" aperture of *IUE*. Yet the 8–13 μm spectrophotometry by Aitken et al. (1992) shows a compact nucleus that is so highly obscured to be undetected at optical and UV wavelengths. We conclude that the nucleus itself is the only region with significant differential absorption.

2. The apparent magnitude of the "Baade Population II sheet" is present in NGC 5253 at $V = 25.5$, found by stacking the 20 V frames (Saha et al. 1994b). The very steep rise of the luminosity function is identical with the same phenomenon in IC 4182 (Saha et al. 1994a, Fig. 12), but the magnitude of the top of the Baade sheet occurs 0.3 mag brighter in NGC 5253 than in IC 4182. This is just the difference in the moduli between NGC 5253 and IC 4182 obtained from the Cepheids. The sheet in NGC 5253 is not absorbed because the stars are in the E-like part of the outer galaxy, far from the center. The fact that the difference in the distance modulus of 0.3 mag determined from the Cepheids in the two galaxies is the same as determined from the Baade sheets shows that the Cepheids in NGC 5253 are not absorbed relative to those in IC 4182 where we know the reddening is smaller than we can measure, based on its color-magnitude diagram (Saha et al. 1994a).

3. The color-magnitude diagram (not shown here but shown in Saha et al. 1994b) of the stars in the central region of NGC 5253 (incorrectly identified as "clusters" by van den Bergh 1972, 1980, and carried as such by Caldwell & Phillips 1989) shows a main sequence whose blue color of the vertical rise (corrected for foreground Galactic reddening) is $(V-I)_0 = -0.20$. This is identical with the $(V-I)$ CM diagram of IC 4182 where the internal reddening is known to be zero (Saha et al. 1994a). We have also plotted separate CM diagrams for the inner 30″, for the annulus from 30″ to 60″, and for the region outside 60″ in NGC 5253. These CM diagrams at different radial distances are identical in the color of the vertical rise of the main sequence at $M_V = -6$ (Saha et al. 1994b), proving that no *differential reddening* exists between the inner and outer regions of NGC 5253.

4. The two strongest proofs that no detected differential *absorption* exists between the Cepheids and the positions of the two SNs at the level of $A_V < 0.1$ mag are (a) the observed scatter in the Cepheid $P-L$ relation is no larger than expected from the intrinsic width of the Cepheid instability strip, and (b) the zero points of the individual $P-L$ data are independent of distance from the center of NGC 5253. Point (a) constrains any additional scatter due to differential absorption among the Cepheids to less than half the observed scatter in the $P-L$ relation simply by the statistics of Poisson distributions, giving $A_V < 0.1$ mag. Proof (b) is made by plotting the apparent distance modulus from each Cepheid against its distance from the center, ranging from 22″ to 78″. The distribution shows no gradient of apparent modulus with distance (details are set out in the archive paper, Saha et al. 1994b) at the level of $A_V = 0.1$ mag over the entire radial range of Cepheid distances, which includes the positions of the two SNs.

8. THE ABSOLUTE MAGNITUDES OF SN 1972E AND SN 1895B AT MAXIMUM AND THE VALUE OF THE HUBBLE CONSTANT

We have adopted the apparent V modulus of NGC 5253 to be $(m - N)_{AV} = 28.06 \pm 0.06$ mag (internal error). The apparent blue modulus consistent with our precepts is $(m - M)_{AB} = 28.09$ [i.e., using a Galactic reddening of $E(B-V) = 0.03$ mag].

Using the values in § 6 for the adopted apparent magnitudes at maximum, noting zero differential reddening between the Cepheids and the SN, gives $M_B(\text{max}) = -19.53 \pm 0.12$, and $M_V(\text{max}) = -19.46 \pm 0.12$ for SN 1972E.

In the same way, the data for SN 1895B give $M_B(\text{max}) = -19.69 \pm 0.21$. There are no V(max) magnitudes for SN 1895B.

Recall the values obtained for SN 1937C (Saha et al. 1994a) are $M_B(\text{max}) = -19.51 \pm 0.14$, and $M_V(\text{max}) = -19.72 \pm 0.15$, which are the same as obtained here for the NGC 5253 SNs to within the combined errors.

Combining the data for IC 4182 and NGC 5253, using weights as the inverse square of the quoted errors, gives

$$\langle M_B(\text{max}) \rangle = -19.55 \pm 0.08 , \quad (1)$$

from three independent SNs, and

$$\langle M_V(\text{max}) \rangle = -19.58 \pm 0.09 , \quad (2)$$

from two SNs.

Using the equations of the Hubble diagrams in B and in V given by Sandage & Tammann (1993) which are $\log v_{220} = 0.2B + 0.630 \pm 0.016$, and $\log v_{220} = 0.2V + 0.653 \pm 0.012$, and using equations (1) and (2) here, gives

$$H_0(V) = 55 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1} , \quad (3)$$

and

$$H_0(B) = 52 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1} , \quad (4)$$

where the quoted errors are external uncertainties based on an assumed true intrinsic dispersion of SNs about the Hubble diagram of $\sigma = 0.3$ mag.

Of course, the purpose of this program is to determine the intrinsic dispersion by repeating the Cepheid experiment on many different galaxies. With NGC 5253 we have exhausted the targets that can be reached before the repair of *HST*. The first two postrepair galaxies on the program are NGC 4496 and NGC 4536 which are the parent galaxies for SN 1960F and SN 1981B, respectively.

We are indebted to John Tonry for providing his magnitudes for selected field stars in the WFC frames with which we tested our final F555W and F785LP magnitude scales. It is a pleasure to thank Anne Kinney for her discussion of the reddening data for NGC 5253 which she and her coauthors have produced. We also thank the many individuals at the STScI who have worked behind the scenes to make this program possible. G. A. T., L. L., and H. S. also thank the Swiss National Science Foundation for support. We thank a referee for a most detailed report from which several points could be clarified.

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