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G. Fritz Benedict

B. E. McArthur

L. W. Fredrick

T. E. Harrison

J. Lee

See next page for additional authors

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ASTROMETRY WITH THE *HUBBLE SPACE TELESCOPE*: A PARALLAX OF THE FUNDAMENTAL DISTANCE CALIBRATOR RR LYRAE[1]

G. Fritz Benedict,[2] B. E. McArthur,[2] L. W. Fredrick,[3] T. E. Harrison,[4] J. Lee,[5] C. L. Slesnick,[3] J. Rhee,[3] R. J. Patterson,[3] E. Nelan,[6] W. H. Jefferys,[7] W. van Altena,[5] P. J. Shelus,[2] O. G. Franz,[8] L. H. Wasserman,[8] P. D. Hemenway,[9] R. L. Duncombe,[10] D. Story,[11] A. L. Whipple,[11] and A. J. Bradley[12]
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ABSTRACT

We present an absolute parallax and relative proper motion for the fundamental distance scale calibrator, RR Lyrae. We obtain these with astrometric data from FGS 3, a white-light interferometer on the *Hubble Space Telescope*. We find $\pi_{\rm abs} = 3.82 \pm 0.2$ mas. Spectral classifications and $VRIJHKT_2M$ and DDO 51 photometry of the astrometric reference frame surrounding RR Lyr indicate that field extinction is low along this line of sight. We estimate $\langle A_V \rangle = 0.07 \pm 0.03$ for these reference stars. The extinction suffered by RR Lyr becomes one of the dominant contributors to the uncertainty in its absolute magnitude. Adopting the average field absorption $\langle A_V \rangle = 0.07 \pm 0.03$, we obtain $M_V^{\rm RR} = 0.61^{-0.11}_{+0.10}$. This provides a distance modulus for the Large Magellanic Cloud (LMC) of $m - M = 18.38$–$18.53^{-0.11}_{+0.10}$, with the average extinction-corrected magnitude of RR Lyrae variables in the LMC, $\langle V({\rm RR}) \rangle$, remaining a significant uncertainty. We compare this result with more than 80 other determinations of the distance modulus of the LMC.

Key words: astrometry — distance scale — stars: distances — stars: individual (RR Lyrae) — techniques: interferometric

On-line material: color figure

1. INTRODUCTION

The various methods used to determine the distances to remote galaxies, and ultimately the size, age, and shape of the universe itself all depend on our knowledge of the distances to local objects. Among the most important of these are the RR Lyrae variable stars. Considerable effort has gone into determining the absolute magnitudes, M_V, of these objects through statistical methods (see, e.g., Popowski & Gould 1998, 1999; Tsujimoto, Miyamoto, & Yoshii 1998; Fernley et al. 1998; Layden et al. 1996). For RR Lyrae variables, this determination is complicated by dependence on metallicity, rendering the calibration uncertain (compare Fernley et al. 1998; McNamara 1997; Udalski 2000a; Popowski 2001). Only recently has a relatively high-precision trigonometric parallax been available for RR Lyr from *Hipparcos* (RR Lyr = HIP 95497; Perryman et al. 1997). We have redetermined the parallax of RR Lyr with FGS 3 on *Hubble Space Telescope* (*HST*) with higher precision. We hope to reduce zero-point errors due to the spatially correlated errors in the *Hipparcos* Catalogue, discussed by Narayanan & Gould (1999). Additionally, our extensive investigation of the astrometric reference stars provides an independent estimation of the line-of-sight extinction to RR Lyr, a significant contributor to the uncertainty in its absolute magnitude, $M_V^{\rm RR}$.

In this paper, we describe the calibration, allowing us to use a neutral density filter to relate astrometry of very bright targets to faint reference stars; present the results of extensive spectrophotometry of the astrometric reference stars, required to correct our relative parallax to absolute; briefly discuss data acquisition and analysis; and derive an absolute parallax for RR Lyr. Finally, we calculate an absolute magnitude for RR Lyr and apply it to derive a distance modulus for the Large Magellanic Cloud (LMC). We briefly review the present status of LMC distance moduli.

Bradley et al. (1991) provide an overview of the FGS 3 instrument, and Benedict et al. (1999) describe the fringe-tracking (position or POS) mode astrometric capabilities of FGS 3, along with the data acquisition and reduction strategies used in the present study. We time tag our data with a Modified Julian Date, MJD = JD − 2,444,000.5.

2. CROSS FILTER CALIBRATION

The filter wheel in each FGS contains a neutral density filter with a 1% transmission (Nelan 2001). These filters, designated FND5, provide 5 mag of attenuation. This reduction of signal is required to obtain astrometry for stars that are brighter than $V = 8.5$, for which the count rate for the FGS photomultiplier tubes would exceed the electronics capacity (Bradley et al. 1991). No filter has perfectly plane-parallel

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[2] McDonald Observatory, University of Texas, Austin, TX 78712.
[3] Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903.
[4] Department of Astronomy, New Mexico State University, Las Cruces, NM 88003.
[5] Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520.
[6] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[7] Department of Astronomy, University of Texas, Austin, TX 78712.
[8] Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001.
[9] Department of Oceanography, University of Rhode Island, Kingston, RI 02881.
[10] Department of Aerospace Engineering, University of Texas, Austin, TX 78712.
[11] Aerospace Engineering Division, Jackson and Tull, 7375 Executive Place, Suite 200, Seabrook, MD 20706.
[12] Spacecraft System Engineering Services, P.O. Box 91, Annapolis Junction, MD 20706.

faces, an effect called filter wedge. Filter wedge introduces a slight shift in position when comparing an observation with the standard astrometry filter, F583W, with the FND5 filter. We require this latter filter to perform astrometry on our primary science target, RR Lyr, $V \sim 7.2$. To obtain milliarcsecond astrometry requires knowledge of the filter wedge effect to that precision or better. Hemenway et al. (1997) describe an early version of this calibration but provide no explicit numbers nor an estimate of the precision with which the calibration can be determined. Motivated by these difficulties, we obtained a second calibration in 1998.

2.1. *Cross Filter Calibration Observations*

Conceptually, the calibration observations are simple. Observe in POS (fringe-tracking) mode the same star with and without the FND5 filter and compare the positions. The shift so determined is then applied when comparing faint reference stars with bright science targets. The standard astrometry filter is F583W. As a consequence, we will actually measure differential filter wedge because F583W is also a filter with nonparallel faces. Note that each filter is a refractive element. Thus, a star position will depend on the color of the star. This is an element of the lateral color effect discussed in Benedict et al. (1999).

We carried out this calibration with two different stars at two different epochs. Our target in 1995 was HD 41940 in M35. Our target in 1998 was Upgren 69 in the cluster NGC 188, a star used often as a template for fringe scanning with FGS 3 (Franz et al. 1998). We obtained eight to 10 observations with F583W and seven observations with FND5 over 30 minutes on 1995 March 14 and 1998 January 1. The 1998 measurements along each axis, X and Y, with 1 σ errors are plotted in Figure 1. The errors associated with FND5 are larger because the signal from Upgren 69 is reduced by 99%. These observations clearly show the offset due to differential filter wedge and a typical amount of intraorbit positional drift.

2.2. *Cross Filter Calibration Results*

We remove the effect of drift by fitting each set of measures with a line (see Fig. 1) and adopt the offset between the lines at the midpoint of the sequence as the amount of differential filter wedge for X and Y, ΔXF_x and ΔXF_y. These corrections with associated error estimates, the cross filter calibration, are collected in Table 1, along with the actual attenuation in signal, Δm, due to the FND5 filter. Note that the differential filter wedge is different, comparing 1995 with 1998. This is due the lateral color effect discussed in Benedict et al. (1999). As can be seen in Table 1, the two calibration stars differ in color.

3. OBSERVATIONS AND DATA REDUCTION

Figure 2 shows the distribution in R.A. and decl. of the five reference stars and RR Lyr. Nine sets of data were acquired, spanning 2.09 yr for a total of 120 measurements of RR Lyr and reference stars. Each data set required approximately 40 minutes of spacecraft time. The data were reduced and calibrated as detailed in Benedict et al. (1999) and McArthur et al. (2001). At each epoch, we measured reference stars and the target RR Lyr multiple times to correct for intraorbit drift of the type seen in the cross filter calibration data (Fig. 1).

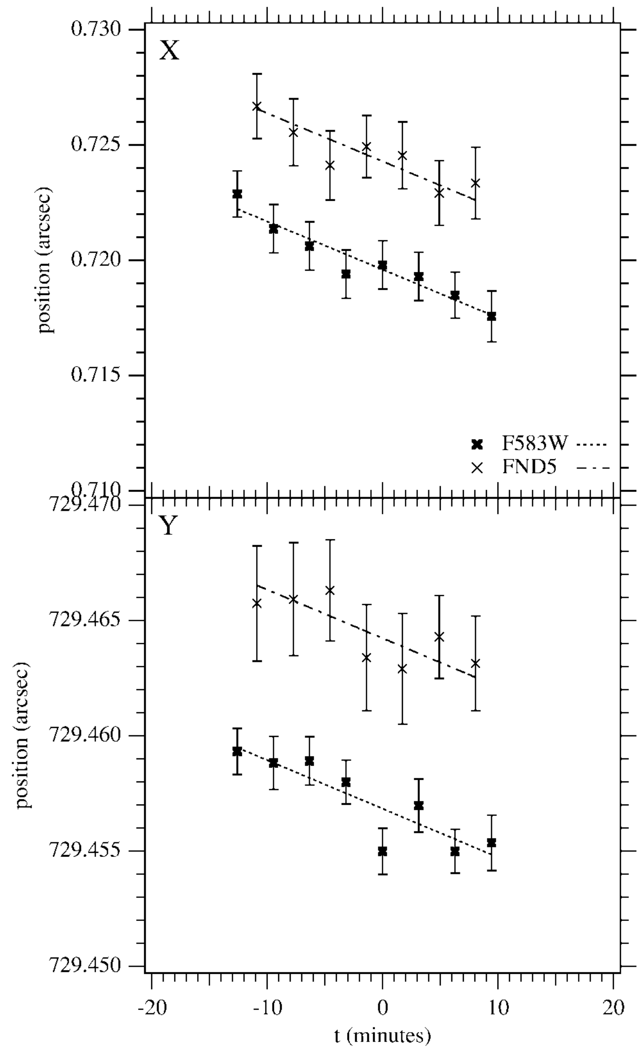

Fig. 1.—Cross filter calibration observations in 1998. Target is Upgren 69 in NGC 188. The plots show the shift in position between F583W and FND5 and typical intraorbit drift in FGS 3.

4. SPECTROPHOTOMETRIC ABSOLUTE PARALLAXES OF THE ASTROMETRIC REFERENCE STARS

Because the parallax determined for RR Lyr will be measured with respect to reference-frame stars that have their own parallaxes, we must either apply a statistically derived correction from relative to absolute parallax (Van Altena, Lee, & Hofleit 1997, hereafter YPC95) or estimate the absolute parallaxes of the reference-frame stars listed in Table 2. In principle, the colors, spectral type, and luminosity class of a star can be used to estimate the absolute magnitude, M_V, and V-band absorption, A_V. The absolute parallax is then simply,

$$\pi_{\rm abs} = 10^{(V-M_V+5-A_V)/5}. \qquad (1)$$

The luminosity class is generally more difficult to estimate than the spectral type (temperature class). However, the derived absolute magnitudes are critically dependent on the luminosity class. As a consequence, we obtained additional photometry in an attempt to confirm the luminosity classes. Specifically, we employ the technique used by Majewski et

TABLE 1
CROSS FILTER CALIBRATIONS

Year	MJD	Star	V	$B-V$	ΔXF_x (mas)	ΔXF_y	Δm
1995	49,790.762	HD 41940	8.14	0.05	-3.5 ± 0.7	-6.9 ± 0.8	5.29
1998	50,814.813	Upgren 69	9.58	0.50	-4.5 ± 0.3	-7.2 ± 0.5	5.21

TABLE 2
RR LYR AND REFERENCE-STAR DATA

ID	ξ[a]	η[a]	μ_x[b]	μ_y[b]
RR Lyr	48.5557 ± 0.0002	-36.1748 ± 0.0003	-0.1061 ± 0.0002	-0.1973 ± 0.0003
RR-2.........	12.9877 ± 0.0001	-122.0915 ± 0.0002	...	...
RR-4[c]........	0.0000 ± 0.0002	0.0000 ± 0.0002	...	...
RR-5.........	70.6893 ± 0.0002	-7.2290 ± 0.0003	0.0045 ± 0.0003	-0.0123 ± 0.0003
RR-6.........	72.4101 ± 0.0002	60.4006 ± 0.0004	...	...
RR-8.........	83.8194 ± 0.0002	-88.7945 ± 0.0002	...	...

[a] ξ and η are relative positions in arcseconds.
[b] μ_x and μ_y are relative motions in arcseconds per year.
[c] R.A. = $19^h25^m23^s.56$, decl. = $42°47'40''.7$ (J2000.0), and epoch = MJD 50,201.05711.

al. (2000) to discriminate between giants and dwarfs for stars later than ~G5, an approach also discussed by Paltoglou & Bell (1994).

4.1. *Photometry*

Our bandpasses for reference-star photometry include: *BVRI*, *JHK* (from the second incremental release of the Two Micron All Sky Survey [2MASS]),[13] and Washington-DDO filters *M*, 51, and T_2 (obtained at McDonald Observatory with the 0.8 m prime-focus camera). The 2MASS *JHK* have been transformed to the Bessell & Brett (1988) system using the transformations provided in Carpenter (2001). Tables 3 and 4 list the visible, infrared, and Washington-DDO photometry for the RR Lyr reference stars, RR-2 through RR-8.

[13] The Two Micron All Sky Survey is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center.

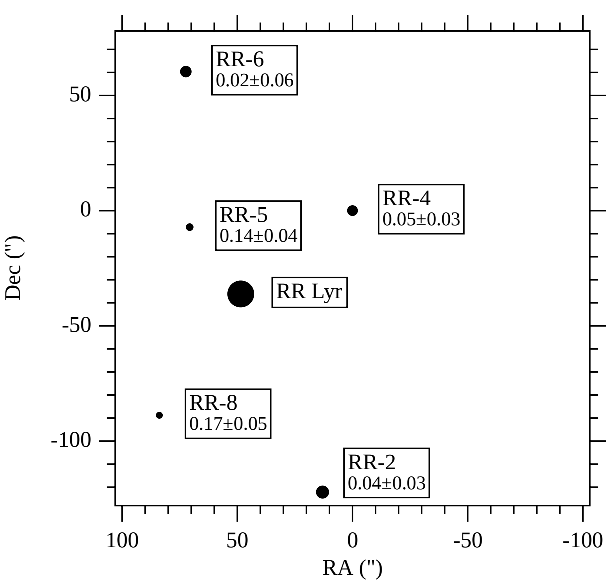

FIG. 2.—RR Lyr and astrometric reference stars. Symbol size is indicative of *V* magnitude (Table 3). The numbers within each identification box are the $\langle A_V \rangle$ from Table 5, § 4.3.

4.2. *Spectroscopy*

The spectra from which we estimated spectral type and luminosity class come from WIYN[14] and New Mexico State University (NMSU) Apache Peak Observatory.[15] Classifications used a combination of template matching and line ratios. For this field, we have two sets of spectral types and luminosity class for four out of five stars. Table 6 lists the spectral types and luminosity classes for our reference stars. The differences between the WIYN and NMSU spectral types provide an estimate of σ_{M_V}. In those instances where the spectral types differ, we adopt the classification closest to that suggested by a $J-H$ versus $H-K$ color-color diagram, the spectral type–color mapping least affected by reddening. These colors are listed in Table 4.

The Washington-DDO photometry provides a possible confirmation of the estimated luminosity class. In Figure 3,

[14] The WIYN Observatory is a joint facility of the University of Wisconsin–Madison, Indiana University, Yale University, and the National Optical Astronomy Observatory.
[15] The Apache Point Observatory 3.5 m telescope is owned and operated by the Astrophysical Research Consortium.

TABLE 3
ASTROMETRIC REFERENCE STARS: VISIBLE PHOTOMETRY

RR	V	$V-R$	$V-I$	$V-K$
2.......	12.68 ± 0.02	0.51 ± 0.03	0.68 ± 0.03	1.429 ± 0.06
4.......	13.47 ± 0.02	0.48 ± 0.04	0.61 ± 0.04	1.325 ± 0.06
5.......	14.50 ± 0.02	0.67 ± 0.05	0.94 ± 0.05	2.199 ± 0.06
6.......	13.15 ± 0.02	0.49 ± 0.03	0.70 ± 0.03	1.467 ± 0.06
8.......	14.94 ± 0.02	0.56 ± 0.06	0.76 ± 0.06	1.633 ± 0.08

TABLE 4
ASTROMETRIC REFERENCE STARS: NEAR-IR AND WASHINGTON-DDO PHOTOMETRY

RR	K	$J-H$	$H-K$	$M-T_2$	$M-51$
2.......	11.21 ± 0.03	0.31 ± 0.02	0.07 ± 0.02	0.86 ± 0.01	0.02 ± 0.01
4.......	12.11 ± 0.03	0.29 ± 0.02	0.06 ± 0.02	0.81 ± 0.01	0.06 ± 0.01
5.......	12.26 ± 0.03	0.53 ± 0.02	0.09 ± 0.02	1.22 ± 0.02	0.00 ± 0.02
6.......	11.64 ± 0.03	0.33 ± 0.02	0.07 ± 0.02	0.86 ± 0.01	0.04 ± 0.01
8.......	13.27 ± 0.04	0.37 ± 0.02	0.04 ± 0.02	0.96 ± 0.02	0.04 ± 0.02

we plot the Washington-DDO photometry, along with a dividing line between dwarfs and giants (Paltoglou & Bell 1994). The boundary between giants and dwarfs is actually far "fuzzier" than suggested by the solid line in Figure 3 and complicated by the photometric transition from dwarfs to giants through subgiants. This soft boundary is readily apparent in Figure 14 of Majewski et al. (2000). Objects just above the heavy line are statistically more likely to be giants than objects just below the line. All but one of our reference stars lies on the dividing line to the left, where giant/dwarf discrimination is poorest. The remaining star, RR-5, moves closer to the other stars on the dividing line by correcting for the $\langle A_V \rangle = 0.14$ indicated in Table 5. Except for this one measurement, all the photometry is consistent with a dwarf classification for each reference star.

4.3. *Interstellar Extinction*

To determine interstellar extinction, we first plot these stars on several color-color diagrams. A comparison of the relationships between spectral type and intrinsic color against those we measured provides an estimate of reddening. Figure 4 contains $V-R$ versus $V-K$ and $V-I$ versus $V-K$ color-color diagrams and total Galactic reddening vectors determined by Schlegel, Finkbeiner, & Davis (1998) along this line of sight. Also plotted are mappings between spectral type and luminosity class V and III from Bessell & Brett (1988) and Cox (2000, hereafter AQ00). Again with maximum reddening vectors and the loci of luminosity class V and III stars. Figure 4, along with the estimated spectral

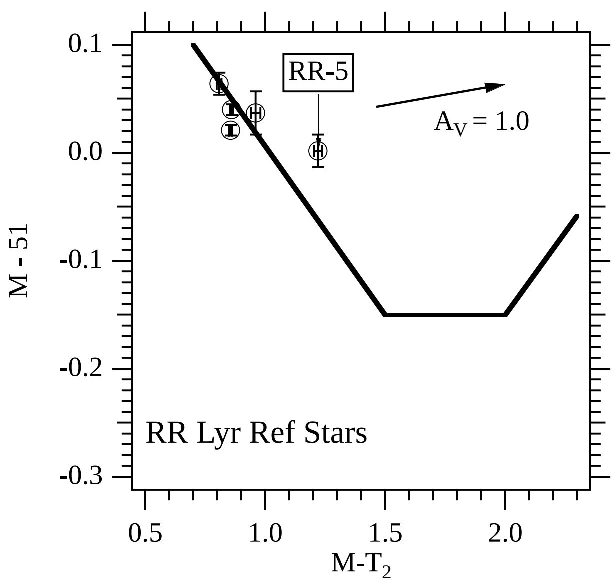

FIG. 3.—$M-$DDO 51 ($M-51$) vs. $M-T_2$ color-color diagram. The solid line is the division between luminosity class V and luminosity class III stars. Giants are above the line, dwarfs below. The reddening vector is for $A_V = 1.0$. Dereddening star RR-5 by the $\langle A_V \rangle = 0.14$ value from Table 5 would move it nearer to the dividing line between giants and dwarfs.

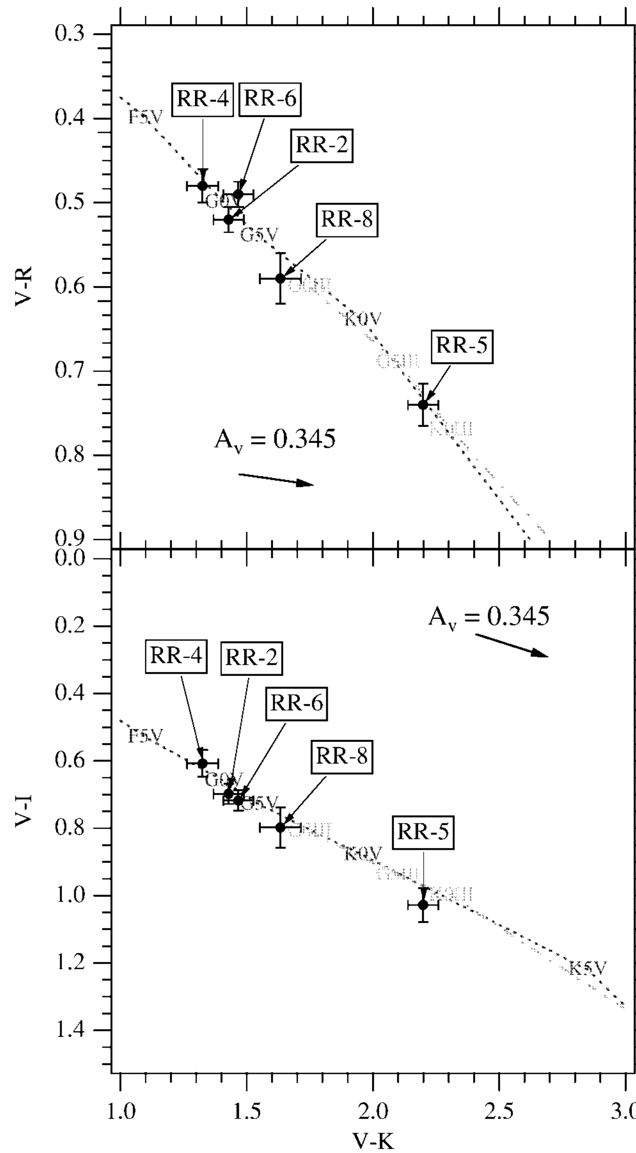

FIG. 4.—$V-R$ vs. $V-K$ and $V-I$ vs. $V-K$ color-color diagrams. The dashed line is the locus of dwarf (luminosity class V) stars of various spectral types; the dot-dashed line is for giants (luminosity class III). The reddening vector is the total Galactic reddening determined by Schlegel et al. (1998).

TABLE 5
REFERENCE STAR A_V FROM SPECTROPHOTOMETRY

RR	$A_V(V-I)$	$A_V(V-R)$	$A_V(V-K)$	$\langle A_V\rangle$
2	0.07	0.05	−0.01	0.04 ± 0.03
4	0.00	0.10	0.04	0.05 ± 0.03
5	0.19	0.15	0.06	0.14 ± 0.04
6	0.12	−0.10	0.03	0.02 ± 0.06
8	0.17	0.26	0.09	0.17 ± 0.05
$\langle A_V\rangle$	0.09	0.08	0.04	0.07 ± 0.03

types, provides measures of the reddening for each reference star.

Assuming an $R = 3.1$ galactic reddening law (Savage & Mathis 1979), we derive A_V values by comparing the measured colors (Table 3) with intrinsic $V-R$, $V-I$, and $V-K$ colors from Bessell & Brett (1988) and AQ00. Specifically, we estimate A_V from three different ratios, each derived from the Savage & Mathis (1979) reddening law: $A_V/E(V-R) = 5.1$; $A_V/E(V-K) = 1.1$; and $A_V/E(V-I) = 2.4$. These A_V are collected in Table 5. For the RR Lyr field, colors and spectral types are consistent with a field-wide average $\langle A_V\rangle = 0.07 \pm 0.03$, far less than the maximum reddening, $A_V < 0.35$ determined by Schlegel et al. (1998). The spatial distribution of the average reddening for each star is shown in Figure 2. We can only weakly assert that reddening is patchy, given the scatter in and uncertainty associated with these A_V values. If we accept the variation in A_V across the field, a two-dimensional linear interpolation in A_V between the four nearest astrometric reference stars (Fig. 2) yields $A_V = 0.11 \pm 0.10$ at the location of RR Lyr.

4.4. *Adopted Reference-Frame Absolute Parallaxes*

We derive absolute parallaxes with M_V values from AQ00 and the $\langle A_V\rangle$ derived from the photometry. Our parallax values are listed in Table 6. Individually, no reference-star parallax is better determined than $\sigma_\pi/\pi = 18\%$. The average absolute parallax for the reference frame is $\langle\pi_{\rm abs}\rangle = 1.9$ mas. As a check, we compare this with the correction to absolute parallax discussed and presented in the Yale Parallax Catalog (YPC95, § 3.2, Fig. 2). Entering YPC95, Fig. 2, with the RR Lyr galactic latitude, $l = 12\overset{\circ}{.}5$, and average magnitude for the reference frame, $\langle V_{\rm ref}\rangle = 13.75$, we obtain a correction to absolute of 1.1 mas. We will use the 1.9 mas correction derived from spectrophotometry because the use of spectrophotometric parallaxes offers a more direct way of determining the reference-star absolute parallaxes when such data are available.

5. ABSOLUTE PARALLAX OF RR LYR

5.1. *Astrometric Model*

With the positions measured by FGS 3, we determine the scale, rotation, and offset "plate constants" relative to an arbitrarily adopted constraint epoch (the so-called master plate) for each observation set (the data acquired at each epoch). The MJD of each observation set is listed in Table 7, along with a measured magnitude, a phase (based on $P = 0.5668$ days (Kukarin et al. 1971, rephased using the more recent photometry of Schoeneich & Lange 1979), and a $B-V$ estimated by comparison with the *UBV* photometry of Hardie (1955). The RR Lyr reference frame contains five stars. We employ the six-parameter model discussed in McArthur et al. (2001) for those observations. For the RR Lyr field, all the reference stars are redder than the science target. Hence, we apply the corrections for lateral color discussed in Benedict et al. (1999).

As for all our previous astrometric analyses, we employ GaussFit (Jefferys, Fitzpatrick, & McArthur 1987) to minimize χ^2. The solved equations of condition for RR Lyr are

$$x' = x + {\rm lc}_x(B-V) - \Delta{\rm XF}_x, \quad (2)$$

$$y' = y + {\rm lc}_y(B-V) - \Delta{\rm XF}_y, \quad (3)$$

$$\xi = Ax' + By' + C + R_x(x'^2 + y'^2) - \mu_x\Delta t - P_\alpha\pi_x, \quad (4)$$

$$\eta = -Bx' + Ay' + F + R_y(x'^2 + y'^2) - \mu_y\Delta t - P_\delta\pi_y, \quad (5)$$

where x and y are the measured coordinates from *HST*; ${\rm lc}_x$ and ${\rm lc}_y$ are the lateral color corrections from Benedict et al. 1999; and $B-V$ are the $B-V$ colors of each star, including the variable $B-V$ of RR Lyr (Table 7). Here $\Delta{\rm XF}_x$ and $\Delta{\rm XF}_y$ are the cross filter corrections in X and Y, applied only to the observations of RR Lyr. RR Lyr has a full range of $0.2 < B-V < 0.6$. For this analysis we linearly interpolate between the 1995 and 1998 cross filter calibrations (Table 1) as a function of RR Lyr color. A and B are scale and rotation plate constants, C and F are offsets, R_x and R_y are radial terms, μ_x and μ_y are proper motions, Δt is the epoch difference from the mean epoch, P_α and P_δ are parallax factors, and π_x and π_y are the parallaxes in x and y. We obtain the parallax factors from a JPL Earth orbit predictor (Standish 1990), upgraded to version DE405. Orientation to the sky is obtained from ground-based astrometry (USNO-A2.0 catalog, Monet 1998) with uncertainties in the field orientation of $\pm0\overset{\circ}{.}05$.

Solutions carried out constraining four reference stars to have no proper motion, but allowing proper motion for the remaining reference star, indicate a statistically significant proper motion for reference star RR-5. Estimating the

TABLE 6
ASTROMETRIC REFERENCE-STAR SPECTRAL CLASSIFICATIONS AND SPECTROPHOTOMETRIC PARALLAXES

RR	WIYN	NMSU	Adopted	V	M_V	A_V	$\pi_{\rm abs}$	σ_π/π (%)
2	G1 V	G3 V	G1 V	12.68	4.6 ± 0.4	0.07	2.4 ± 0.4	18
4	G0 V	F8 V	F8 V	13.47	4.6 ± 0.4	0.07	1.7 ± 0.3	28
5	...	K1 V	K1 V	14.50	5.5 ± 0.6	0.07	1.9 ± 0.6	18
6	G1 V	G0 V	G1 V	13.15	4.6 ± 0.4	0.07	1.9 ± 0.4	18
8	G2 V	G5 V	G5 V	14.94	5.1 ± 0.4	0.07	1.1 ± 0.2	25

TABLE 7

RR LYR LOG OF OBSERVATIONS

Set	MJD	Phase[a]	V[b]	$B-V$[c]
1......	49,984.76525	0.36	7.99	0.3
2......	50,047.5617	0.24	7.70	0.3
3......	50,173.4915	0.34	7.96	0.3
4......	50,201.57787	0.65	8.19	0.44
5......	50,229.3208	0.62	8.24	0.44
6......	50,563.39767	0.29	7.86	0.3
7......	50,568.10532	0.46	8.08	0.4
8......	50,745.70698	0.65	8.26	0.44
9......	50,749.74358	0.16	7.39	0.2

[a] Phase based on $P = 0.5668$ days (Kukarkin et al. 1971).

[b] From FGS photometry. See Benedict et al. 1998 for transformation details.

[c] Estimated from phase using UBV photometry from Hardie 1955.

proper motion of that star imposed an 8% decrease in number of degrees of freedom but resulted in a 15% decrease in χ^2.

5.2. *Assessing Reference-Frame Residuals*

The optical field angle distortion calibration (McArthur et al. 1997) reduces as-built *HST* and FGS 3 distortions with magnitude $\sim 1''$ to below 2 mas over much of the FGS 3 field of regard. From histograms of the astrometric residuals (Fig. 5), we conclude that we have obtained correction at the $\sim$1 mas level in the region available at all *HST* rolls (an inscribed circle centered on the pickle-shaped FGS field of regard). The resulting reference-frame "catalog" in ξ and η standard coordinates (Table 2) was determined with $\langle \sigma_\xi \rangle = 0.2$ and $\langle \sigma_\eta \rangle = 0.3$ mas.

To determine if there might be unmodeled—but possibly correctable—systematic effects at the 1 mas level, we plotted the RR Lyr reference-frame X and Y residuals against a number of spacecraft, instrumental, and astronomical parameters. These included (X, Y)-position within the pickle, radial distance from the pickle center, reference-star V magnitude and $B-V$ color, and epoch of observation. We saw no obvious trends other than an expected increase in positional uncertainty with reference-star magnitude.

5.3. *Absolute Parallax of RR Lyr*

In a quasi-Bayesian approach, the calibration values were entered into the model as observations with associated errors. The reference-star spectrophotometric absolute parallaxes also were input as observations with associated errors not as hardwired quantities known to infinite precision.

We obtain for RR Lyr an absolute parallax of $\pi_{\rm abs} = 3.82 \pm 0.11$ mas thus $\sigma_\pi/\pi = 3\%$. This parallax differs by $\sim 1\ \sigma_{\rm HIP}$ and by $\sim 4\ \sigma_{\rm HST}$ from that measured by *Hipparcos*, $\pi_{\rm abs} = 4.38 \pm 0.59$ mas. Comparing our various solutions with and without reference-star proper motion, we find some sensitivity in the resulting parallax, with a full range of variation of 0.2 mas. We feel this range represents a more likely error in our determination and adopt as the *HST* absolute parallax of RR Lyr $\pi_{\rm abs} = 3.82 \pm 0.2$ mas ($\sigma_\pi/\pi = 4.6\%$), an error one-third that of *Hipparcos*. Figure 6 compares the *HST*, *Hipparcos*, and YPC95 (a weighted

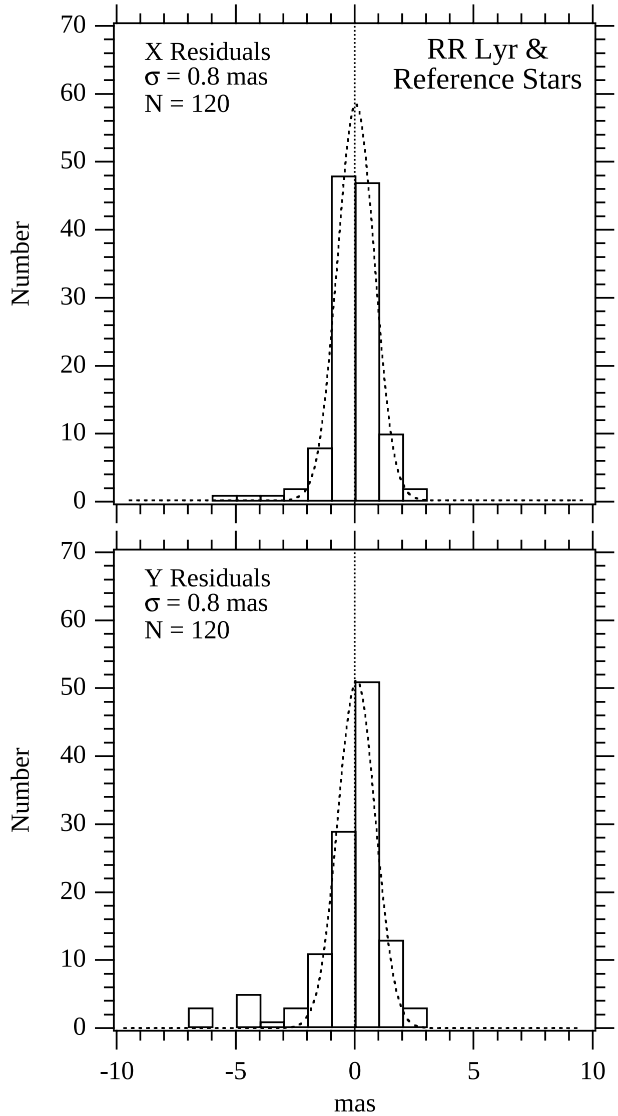

FIG. 5.—Histograms of x and y residuals obtained from modeling RR Lyr and the astrometric reference stars with equations (4) and (5). Distributions are fitted with Gaussians whose σ values are noted in the plots.

average of past ground-based results) determinations. The horizontal line is a weighted average of all three sources, $\langle \pi_{\rm abs} \rangle = 3.87 \pm 0.19$ mas. Parallax and proper-motion results from *HST*, *Hipparcos*, and YPC95 are collected in Table 8.

6. DISCUSSION AND SUMMARY

6.1. *HST Parallax Accuracy*

Our parallax precision, an indication of our internal, random error, is often less than 0.5 mas. To assess our accuracy, or external error, we must compare our parallaxes with results from independent measurements. Following Gatewood, Kiewiet de Jonge, & Persinger (1998), we plot all parallaxes obtained by the HST Astrometry Science Team with FGS 3 against those obtained by *Hipparcos*. These data are collected in Table 9 and are shown in Figure 7. We have not considered four Hyades stars whose parallaxes are considered preliminary (van Altena et al. 1997). The dashed

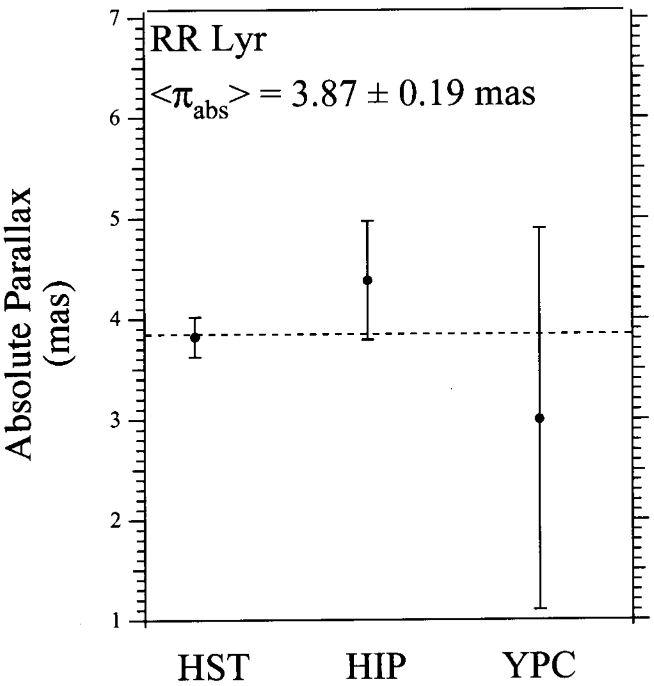

FIG. 6.—Absolute parallax determinations for RR Lyr. We compare *HST*, *Hipparcos*, and YPC95. The horizontal dashed line gives the weighted average absolute parallax, $\langle\pi_{abs}\rangle$.

line is a weighted regression that takes into account errors in both input data sets. The regression demonstrates the lack of scale and zero-point differences between *Hipparcos* and *HST* FGS results. The rms *Hipparcos* residual to the regression line is 1.02 mas.

6.2. *Lutz-Kelker Bias*

When using a trigonometric parallax to estimate the absolute magnitude of a star, a correction should be made for the Lutz-Kelker (LK) bias (Lutz & Kelker 1973). Because of the galactic latitude and distance of RR Lyr and the scale height of the stellar population of which it is a member, we use a uniform space density for calculating the LK bias. An LK algorithm modified by Hanson (1979) (H) that includes the power law of the parent population is used. A correction of -0.02 ± 0.01 mag is derived for the LKH bias for RR Lyr. The LKH bias is small because $\sigma_\pi/\pi = 4.6\%$ is small.

TABLE 8
RR LYR PARALLAX AND PROPER MOTION

Parameter	Value
HST study duration (yr)	2.09
Number of observation sets	10
Reference stars $\langle V\rangle$	13.75
Reference stars $\langle B-V\rangle$	0.71
HST absolute parallax (mas)	3.82 ± 0.20
Hipparcos absolute parallax (mas)	4.38 ± 0.59
YPC95 absolute parallax (mas)	3.0 ± 1.9
Weighted-average absolute parallax (mas)	3.87 ± 0.19
HST proper motion (mas yr^{-1})	224.0 ± 0.5
In position angle (deg)	208.3 ± 0.5
Hipparcos proper motion (mas yr^{-1})	224.2 ± 1.4
In position angle (deg)	209.3 ± 1.3
YPC95 proper motion (mas yr^{-1})	207.4
In position angle (deg)	210.7

TABLE 9
HST AND *Hipparcos* ABSOLUTE PARALLAXES

ID	*HST*	*Hipparcos*	*HST* Reference
Prox Cen	769.7 ± 0.3	772.33 ± 2.42	Benedict et al. 1999
Barnard's star	545.5 ± 0.3	549.3 ± 1.58	Benedict et al. 1999
Feige 24	14.6 ± 0.4	13.44 ± 3.62	Benedict et al. 2000
Gl 748 AB	98.0 ± 0.4	98.56 ± 2.66	Benedict et al. 2001
RR Lyr	3.82 ± 0.20	4.38 ± 0.59	This paper

6.3. *Absolute Magnitudes of RR Lyr*

Adopting for RR Lyr an intensity weighted average of $\langle V\rangle = 7.76$ (Fernley et al. 1998) and the absolute parallax weighted average from § 5.3, we determine that *in the absence of reddening* $M_V^{RR} = 0.68^{-0.10}_{+0.10}$, including the LKH correction and uncertainty. We derived (§ 4.3) an average $\langle A_V\rangle = 0.07 \pm 0.03$ from the astrometric reference stars that surround RR Lyr. Fernley et al. (1998) obtain for RR Lyr $A_V = 0.06 \pm 0.03$ from a log P–$(V-K)$ relation. If there is no patchy extinction with angular scale less than 1′, it seems reasonable to conclude that RR Lyr, less distant than any reference star, has $A_V \leq 0.07$ and, hence, $M_V^{RR} \leq 0.61$. Including this 0.03 mag uncertainty in $\langle A_V\rangle$ in quadrature, we obtain $M_V^{RR} = 0.61^{-0.11}_{+0.10}$. Alternatively, we could accept the A_V variations seen in Figure 2 as real and correct for a

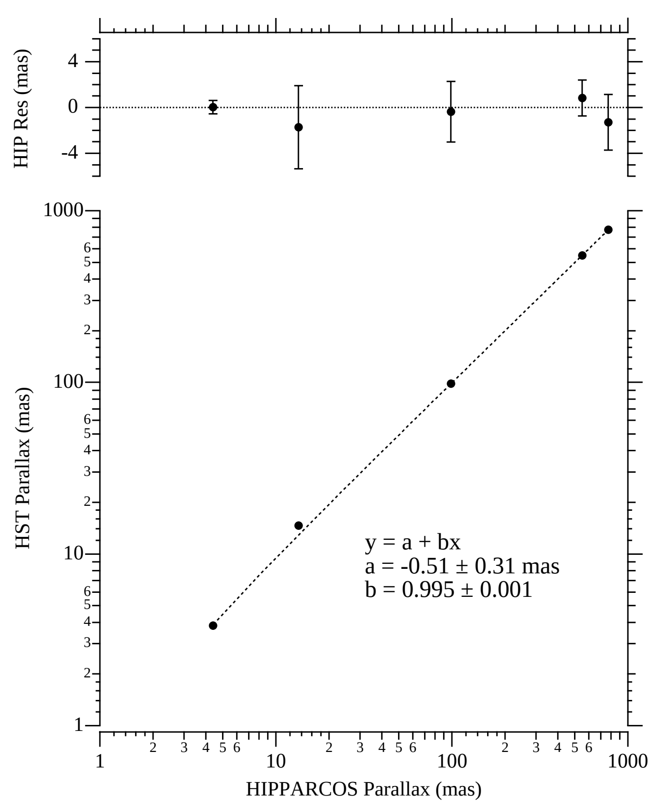

FIG. 7.—*Bottom*: *HST* absolute parallax determinations compared with *Hipparcos* for the five targets listed in Table 9. *Top*: The *Hipparcos* residuals to the error-weighted regression line. The error bars on the residuals are *Hipparcos* 1 σ errors.

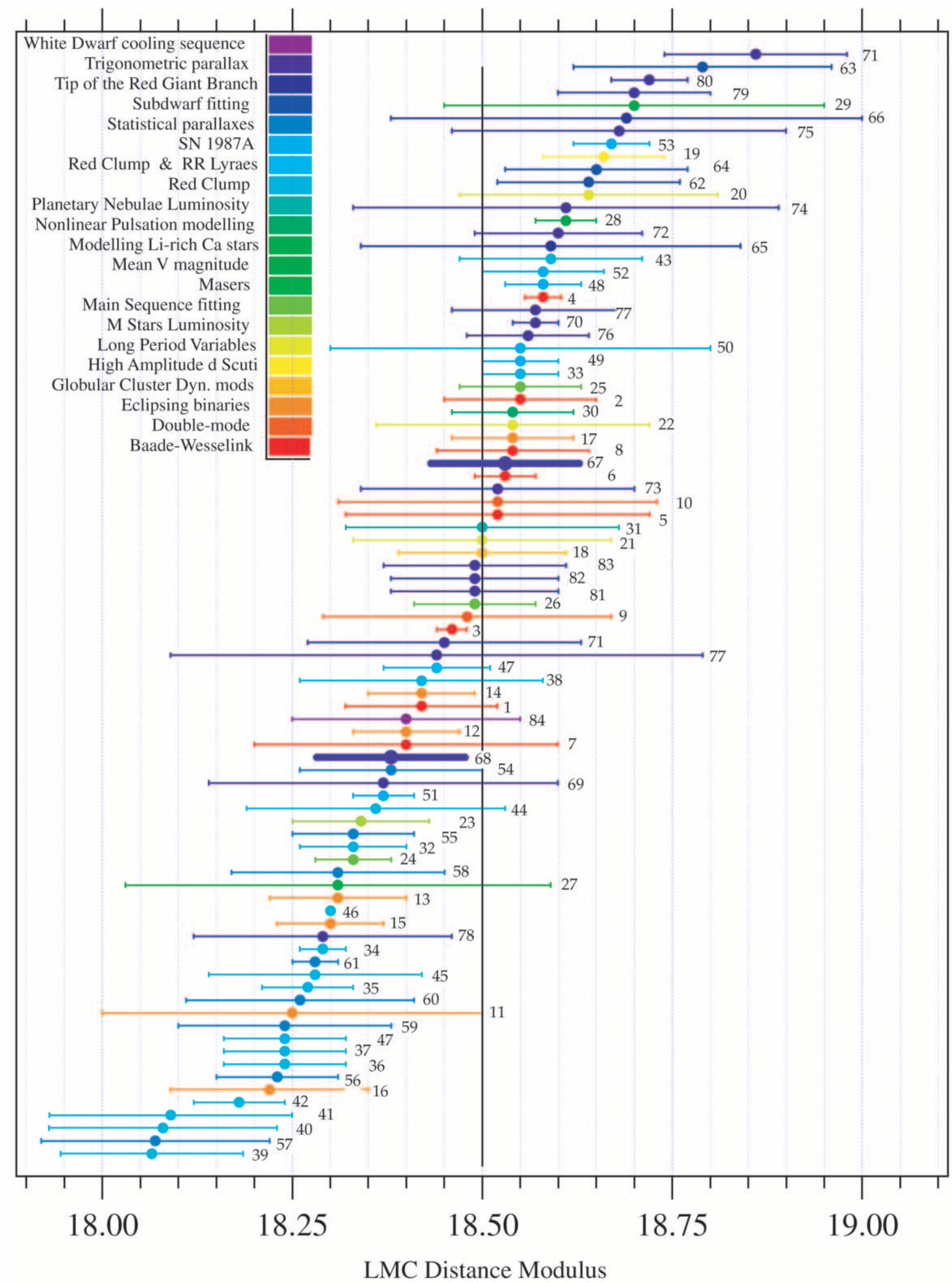

FIG. 8.—Recent determinations of the distance modulus of the LMC, an expansion of the plot found in Gibson (1999). Colors represent the various methods listed in column (2) of Table 10, while the numbers refer to the individual investigations (col. [1]). Results from this paper are in bold. The thick vertical line denotes the distance modulus adopted by the *HST* Distance Scale Key Project (Freedman et al. 2001) and the Type Ia Supernovae Calibration Team (Saha et al. 1999).

linearly interpolated $A_V = 0.11 \pm 0.10$, local to RR Lyr. Including that uncertainty in quadrature, we obtain $M_V^{\rm RR} = 0.57^{-0.15}_{+0.14}$. Our range of values for $M_V^{\rm RR}$ is remarkably close to that determined by Tsujimoto et al. (1998) from the *Hipparcos* parallax. We ascribe this similarity to differing LKH bias corrections and different A_V corrections.

Beers et al. (2000) cite an [Fe/H]-M_V relation from Chaboyer (1999),

$$M_V^{\rm RR} = 0.23([{\rm Fe/H}] + 1.6) + 0.56. \qquad (6)$$

An [Fe/H] = −1.39 value for RR Lyr (also from Beers et al.

TABLE 10

Recent Distance Moduli to the LMC

No. (1)	Method (2)	Object (3)	Author (4)	$m - M$ (5)
1.......	Baade-Wesselink	Cepheids	Gieren et al. 2000	18.42 ± 0.10
2.......	...	Cepheids	Carretta et al. 2000a	18.55 ± 0.10
3.......	...	Cepheid	Gieren, Fouqué, & Gómez 1998	18.46 ± 0.02
4.......	...	Cepheid	Di Benedetto 1997	18.58 ± 0.024
5.......	...	RR Lyraes	Carretta et al. 2000b	18.52 ± 0.20
6.......	...	RR Lyraes	Feast 1997	18.53 ± 0.04
7.......	...	RR Lyraes	Cacciari, Clementini, & Fernley 1992,	18.40 ± 0.20
8.......	...	RR Lyraes	McNamara 1997	18.54 ± 0.10
9.......	Double mode	RR Lyraes	Alcock et al. 1997	18.48 ± 0.19
10.....	...	RR Lyraes	Kovacs 2000	18.52 ± 0.21
11.....	Eclipsing binaries	EROS 1044	Maloney et al. 2001	18.25 ± 0.25
12.....	...	HV 2274	Nelson et al. 2000	18.40 ± 0.07
13.....	...	HV 982	Fitzpatrick et al. 2001	18.31 ± 0.09
14.....	...	HV 2274	Guinan et al. 1998a	18.42 ± 0.07
15.....	...	HV 2274	Guinan et al. 1998b	18.30 ± 0.07
16.....	...	HV 2274	Udalski 1998a	18.22 ± 0.13
17.....	...	HV 2274	Guinan et al. 1997	18.54 ± 0.08
18.....	Globular cluster dyn. mods	...	Chaboyer et al. 1998	18.50 ± 0.11
19.....	High amplitude δ Scuti	δ Scuti	McNamara 2001	18.66 ± 0.08
20.....	Long-period variables	Mira	Whitelock & Feast 2000	18.64 ± 0.17
21.....	...	Ca Stars	Bergeat, Knapik, & Rutily 1998	18.50 ± 0.17
22.....	...	Mira	Van Leeuwen et al. 1997	18.54 ± 0.18
23.....	M stars luminosity	...	Schmidt-Kaler & Oestreicher 1998	18.34 ± 0.09
24.....	Main-sequence fitting	NGC 1866	Walker et al. 2001	18.33 ± 0.05
25.....	...	Cepheids	Carretta et al. 2000a	$18.55 \pm 0.04 \pm 0.04$
26.....	...	Cepheids	Laney & Stobie 1994	$18.49 \pm 0.04 \pm 0.04$
27.....	Masers	NGC 4258	Newman et al. 2001	$18.31 \pm 0.11 \pm 0.17$
28.....	Mean V magnitude	LMC RR Lyraes	McNamara 2001	18.61 ± 0.04
29.....	Modeling Li-rich Ca stars	...	Ventura, D'Antona, & Mazzitelli 1999	18.70 ± 0.25
30.....	Nonlinear pulsation modeling	Cepheids	Wood 1998	18.54 ± 0.08
31.....	Planetary nebulae luminosity	M31	Walker 1999	18.50 ± 0.18
32.....	Red clump	...	Popowski 2001	18.33 ± 0.07[a]
33.....	...	...	Girardi & Salaris 2001	18.55 ± 0.05
34.....	...	...	Sakai, Zaritsky, & Kennicutt 2000	18.29 ± 0.03
35.....	...	...	Popowski 2000	18.27 ± 0.06[b]
36.....	...	...	Stanek et al. 2000	18.24 ± 0.08
37.....	...	...	Udalski 2000a	18.24 ± 0.08
38.....	...	...	Twarog, Anthony-Twarog, & Bricker 1999	18.42 ± 0.16
39.....	...	...	Stanek, Zaritsky, & Harris 1998	18.065 ± 0.12
40.....	...	...	Udalski et al. 1998b	18.08 ± 0.15
41.....	...	...	Udalski et al. 1998a	18.09 ± 0.16
42.....	...	...	Udalski 1998b	18.18 ± 0.06
43.....	...	...	Romaniello et al. 2000	$18.59 \pm 0.04 \pm 0.08$
44.....	...	...	Cole 1998	18.36 ± 0.17
45.....	...	...	Girardi et al. 1998	18.28 ± 0.14
46.....	...	...	Beaulieu & Sackett 1998	18.3
47.....	Red clump and RR Lyraes	...	Popowski 2001	18.24 ± 0.08 to 18.44 ± 0.07
48.....	SN 1987A	...	Carretta et al. 2000	18.58 ± 0.05
49.....	...	...	Romaniello et al. 2000	18.55 ± 0.05
50.....	...	...	Walker 1999	$18.55 \pm 0.07 \pm 0.16$
51.....	...	...	Gould & Uza 1998	18.37 ± 0.04
52.....	...	...	Panagia, Gilmozzi, & Kirchner 1998	18.58 ± 0.08
53.....	...	...	Lundqvist & Sonneborn 1998	18.67 ± 0.05
54.....	Statistical parallaxes	RR Lyraes	Carretta et al. 2000a	18.38 ± 0.12
55.....	...	RR Lyraes	Popowski & Gould 1999	18.33 ± 0.08[a]
56.....	...	RR Lyraes	Popowski & Gould 1999	18.23 ± 0.08[b]
57.....	...	RR Lyraes	Popowski & Gould 1998	18.07 ± 0.15[a]
58.....	...	RR Lyraes	Popowski & Gould 1998	18.31 ± 0.14[b]
59.....	...	RR Lyraes	Gould & Popowski 1998	18.24 ± 0.14
60.....	...	RR Lyraes	Fernley et al. 1998	18.26 ± 0.15
61.....	...	RR Lyraes	Layden et. al 1996	18.28 ± 0.03
62.....	Subdwarf fitting	...	Carretta et al. 2000a	18.64 ± 0.12
63.....	...	...	Reid 1998	18.79 ± 0.17
64.....	...	...	Reid 1997	18.65 ± 0.12

TABLE 10—*Continued*

No. (1)	Method (2)	Object (3)	Author (4)	$m - M$ (5)
65.....	Tip of the red giant branch	...	Sakai et al. 2000	18.59 ± 0.09± 0.16
66.....	...	...	Romaniello et al. 2000	18.69 ± 0.25 ± 0.06
67.....	Trigonometric parallax	RR Lyrae	This paper	18.53 ± 0.10[c]
68.....	...	RR Lyrae	This paper	18.38 ± 0.10[d]
69.....	...	RR Lyrae	Luri et al. 1998	18.37 ± 0.23
70.....	...	RR Lyrae	McNamara 1997	18.57 ± 0.03
71.....	...	Cepheids	Groenewegen & Oudmaijer 2000	18.45 ± 0.18 to 18.86 ± 0.12
72.....	...	Cepheids	Groenewegen & Oudmaijer 2000	18.60 ± 0.11[e]
73.....	...	Cepheids	Groenewegen & Oudmaijer 2000	18.52 ± 0.18[f]
74.....	...	Cepheids	Groenewegen & Salaris 1999	18.61 ± 0.28
75.....	...	Cepheids	Feast 1999	18.68 ± 0.22[g]
76.....	...	Cepheids	Oudmaijer, Groenewegen, & Schrijver 1998	18.56 ± 0.08
77.....	...	Cepheids	Madore & Freedman 1998	18.44 ± 0.35 to 18.57 ± 0.11
78.....	...	Cepheids	Luri et al. 1998	18.29 ± 0.17
79.....	...	Cepheids	Feast & Catchpole 1997	18.70 ± 0.10
80.....	...	Cepheids	Paturel et al. 1997	18.72 ± 0.05
81.....	...	HB	Carretta et al. 2000a	18.49 ± 0.11
82.....	...	HB	Gratton 1998	18.49 ± 0.11
83.....	...	HB	Koen & Laney 1998	18.49 ± 0.12
84.....	White dwarf cooling sequence	...	Carretta et al. 2000a	18.40 ± 0.15

[a] Walker 1992 photometry.
[b] Udalski et al. 1999 photometry.
[c] Carretta et al. 2000 $\langle V \rangle = 19.11$ (+0.03, $\langle$[FeH]$\rangle$ correction) = 19.14.
[d] Udalski et al. 1999 $\langle V \rangle = 18.94$ (+0.05, $\langle$[FeH]$\rangle$ correction) = 18.99.
[e] Based on the period-luminosity relation in V and I and the Wesenheit index.
[f] Based on the period-luminosity relation in K.
[g] Data from Koen & Laney 1998.

2000) implies $M_V^{\rm RR} = 0.61$, in agreement with either our $M_V^{\rm RR}$ value derived from a variable A_V or the $M_V^{\rm RR}$ value derived from the average $\langle A_V \rangle$.

6.4. *Distance Modulus of the LMC*

The distance to the LMC is a critical link in determining the scale of the universe. This distance uncertainty contributes a substantial fraction of the uncertainty in the Hubble constant (Mould et al. 2000). The *HST* Key Project on the extragalactic distance scale (Freedman et al. 2001; Mould et al. 2000) and the Type Ia Supernovae Calibration Team (Saha et al. 1999) have adopted the distance modulus value $m - M = 18.5$. Values from 18.1 to 18.8 are reported in the current literature, with those less than 18.5 supporting the short distance scale, and those greater than 18.5, the long distance scale. Comprehensive reviews of the methods can be found in Carretta et al. (2000a), Gibson (1999), and Cole (1998). A representative sample of opinion about the "best method" can be found in Paczynski (2001), Popowski (2001), Udalski (2000b), and Gould (2000).

Let us proceed with the constant $\langle A_V \rangle$ result $M_V^{\rm RR} = 0.61^{-0.11}_{+0.10}$. Because of our two results for absolute magnitude, it has smaller formal errors. We adopt (from Carretta et al. 2000a) $\langle V \rangle = 19.11$ for the RR Lyrae variables in the bar of the LMC and their assumed $\langle[\rm Fe/H]\rangle = -1.5$. Correcting for the differential variation of M_V with [Fe/H] (using the slope from Chaboyer 1999), we compute $\langle V \rangle = 19.14$, correcting from $\langle[\rm Fe/H]\rangle = -1.50$ to $[\rm Fe/H] = -1.39$. We obtain an LMC distance modulus of $m - M = 18.53 \pm 0.12$. Carretta, Gratton, & Clementini (2000b) address possible luminosity differences between horizontal-branch stars in globular clusters and in the field and conclude that there is little difference, unless the masses are very different. There is another source of uncertainty in the LMC distance modulus, the measured apparent magnitude of the RR Lyr population in the LMC corrected for extinction local to the LMC. For example, adopting (Udalski et al. 1999) $\langle V \rangle = 18.94$ and $\langle[\rm Fe/H]\rangle = -1.6$ for the RR Lyrae variables in the LMC, we obtain an LMC distance modulus of $m - M = 18.38 \pm 0.12$, once again correcting $\langle V \rangle$ to $[\rm Fe/H] = -1.39$.

These two estimates, which agree within their respective errors, are included in Figure 8, a summary of the current LMC distance modulus situation, displaying over 80 determinations, based on 21 independent methods. These are listed in Table 10. The weighted average of these is $\langle m - M \rangle = 18.47 \pm 0.04$, where the error is derived as the standard deviation of the mean with $N = 21$.

6.5. *Summary*

HST astrometry yields an absolute trigonometric parallax for RR Lyrae, $\pi_{\rm abs} = 3.82 \pm 0.2$ mas. A weighted average of *HST*, *Hipparcos*, and YPC95 absolute parallaxes is $\langle \pi_{\rm abs} \rangle = 3.87 \pm 0.19$ mas. This high-precision result requires an extremely small LK bias correction of -0.02 ± 0.01 mag. Spectrophotometry of the astrometric reference stars local to RR Lyr suggest a low extinction, $\langle A_V \rangle = 0.07 \pm 0.03$. The dominant error terms in the resulting absolute magnitude, $M_V^{\rm RR} = 0.61^{-0.11}_{+0.10}$ ($[\rm Fe/H] = -1.39$), are the parallax and the uncertainty in the amount of extinction for RR Lyr itself. Depending on metallicity determinations and extinction corrections for RR Lyr variables in the LMC, we find a distance modulus range on the low end of $m - M = (18.38\text{–}18.53) \pm 0.12$, marginally supporting the "short scale" and an H_0 at the higher end of the present range.

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