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CONFIRMATION OF ERRORS IN *HIPPARCOS* PARALLAXES FROM *HUBBLE SPACE TELESCOPE* FINE GUIDANCE SENSOR ASTROMETRY OF THE PLEIADES[1]

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ABSTRACT

We present absolute trigonometric parallaxes and relative proper motions for three members of the Pleiades, obtained with the *Hubble Space Telescope*'s Fine Guidance Sensor 1r, a white-light interferometer. We estimate spectral types and luminosity classes of the stars comprising the astrometric reference frame from $R \approx 2000$ spectra, *VJHK* photometry, and reduced proper motions. From these we derive estimates of absolute parallaxes and introduce them into our model as observations with error. We constrain the three cluster members to have a 1 σ dispersion in distance less than 6.4 pc and find an average $\pi_{\rm abs} = 7.43 \pm 0.17 \pm 0.20$ mas, where the second error is systematic due to member placement within the cluster. This parallax corresponds to a distance of 134.6 ± 3.1 pc or a distance modulus of $m - M = 5.65 \pm 0.05$ for these three Pleiades stars, presuming a central location. This result agrees with three other independent determinations of the Pleiades distance. Presuming that the cluster depth systematic error can be significantly reduced because of the random placement of these many members within the cluster, these four independent measures yield a best-estimate Pleiades distance of $\pi_{\rm abs} = 7.49 \pm 0.07$ mas, corresponding to a distance of 133.5 ± 1.2 pc or a distance modulus of $m - M = 5.63 \pm 0.02$. This resolves the dispute between the main-sequence fitting and the *Hipparcos* distance moduli in favor of main-sequence fitting.

Key words: astrometry — distance scale — open clusters and associations: general — stars: distances — techniques: interferometric

1. THE PROBLEM

Our knowledge of the life histories of stars relies on models whose fidelity is ultimately tested by appeal to real stars. The Sun provides the most basic calibration of these models, of course, because it is only for the Sun that an accurate age exists and for which the mass, temperature, composition, and structure are known with precision, accuracy, and completeness. Clusters of stars are also fundamental for constructing models because we can assume that all the cluster's members are of the same age and composition, even if other parameters are more loosely constrained.

Preeminent among clusters is the Pleiades, and much effort has gone into determining the absolute parallax of this cluster. ESA's *Hipparcos* mission brought the benefits of space observing to astrometry to produce precise positions, proper motions, and parallaxes for nearly all stars brighter than $V \approx 9$. Before *Hipparcos*, the distance to the Pleiades was too large for ground-based parallaxes to yield a good distance, so the best estimates were derived by comparing the main sequence of the Pleiades with a main sequence constructed from nearby stars with large parallaxes. A small correction for evolution is necessary (the Pleiades is about 100 Myr old [Pinsonneault et al. 1998], whereas the nearby field stars are typically as old as the Sun), but the Pleiades appears to have essentially the same elemental abundances as the Sun (Boesgaard & Friel 1990), obviating a need for a metallicity correction such as is needed, for example, for the Hyades.

In addition to its primary program, *Hipparcos* included stars in several of the nearest open clusters in order to resolve the "Hyades distance problem" once and for all and to similarly calibrate other clusters. The result obtained by *Hipparcos* for the Pleiades (van Leeuwen 1999) was a complete surprise, yielding a distance modulus of $m - M = 5.37 \pm 0.06$ mag to be compared with a modulus of 5.60 ± 0.04 from main-sequence fitting (Pinsonneault et al. 1998). Taken at face value, the *Hipparcos* result means that stars in the Pleiades are about 0.23 mag fainter than otherwise similar stars of the solar neighborhood. This large discrepancy has forced a careful reexamination of the assumptions and input parameters of the stellar models, as well as a thorough study of the *Hipparcos* data itself and potential errors in it. The controversy has not been fully resolved in that builders of star models find that the changes in physics or input parameters needed to account for the *Hipparcos* distance are too radical to be reasonable, whereas the *Hipparcos* team has resolutely defended the *Hipparcos* result. With no clear reconciliation of these divergent views, we felt it worthwhile to reobserve some stars in the Pleiades in the traditional method of parallax astrometry—highly precise measurements of stellar positions relative to nearby reference stars—by taking advantage of the extraordinary precision achievable with Fine Guidance Sensor (FGS) 1r on the *Hubble Space Telescope* (*HST*).

[1] Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555.

TABLE 1
PLEIADES LOG OF OBSERVATIONS AND MEMBER PHOTOMETRY

Set	MJD	Roll[a] (deg)	V[b] 3030	3063	3179
1......................	51,770.65507	284.046	14.03	13.54	10.05
2......................	51,783.6811	284.046	14.00	13.56	10.06
3......................	51,957.17546	103.014	14.00	13.47	10.08
4......................	51,968.37565	103.014	14.01	13.57	10.09
5......................	52,128.77383	284.046	13.97	13.58	10.07
6......................	53,053.24519	113.021	14.00	13.44	10.08
$\langle V \rangle$			14.00	13.53	10.07
σ_V....................			0.02	0.06	0.01

[a] Spacecraft roll, as defined in Chapter 2 of the FGS Instrument Handbook (Nelan & Makidon 2001).
[b] Average of 2–5 observations at each epoch. Internal errors are on the order of 0.005 mag per observation set.

This project began as an effort to resolve known Pleiades spectroscopic binaries into visual binaries so that we could both obtain an accurate distance and calibrate the zero-age main sequence with known masses. We did not succeed in resolving the spectroscopic binaries, nor would our measurement of the Pleiades parallax by itself resolve the problem raised by *Hipparcos*, but our measurement in concert with other recent independent measurements of the Pleiades distance clearly and unambiguously shows that the *Hipparcos* parallax is wrong and that traditional main-sequence fitting results in reliable estimates. To avoid repetition, we discuss the work to date in detail in our discussion.

2. OBSERVATIONS AND DATA REDUCTION

Six sets of astrometric data were acquired with *HST*, spanning 3.51 yr, for a total of 135 measurements of three Pleiades stars and nine reference stars. The three Pleiades targets were HII 3030, 3063, and 3179 in Hertzsprung (1947), identified hereafter by their numbers alone. Table 1 lists the epochs of observation and measured FGS V-band photometry of the three Pleiades stars. Each data set required approximately 33 minutes of spacecraft time. The reductions and calibrations are detailed in Benedict et al. (2002a, 2002b) and McArthur et al. (2001). At each epoch we measured both the reference stars and the target multiple times in order to correct for intraorbit drift of the type seen in the cross filter calibration data shown in Figure 1 of Benedict et al. (2002a). Figure 1 shows the distribution of the reference stars (4–14) and the presumed Pleiades stars (3030, 3063, and 3179) on a second-generation R-band image obtained from the Digital Sky Survey.[2]

[2] Available from http://stdatu.stsci.edu/dss/.

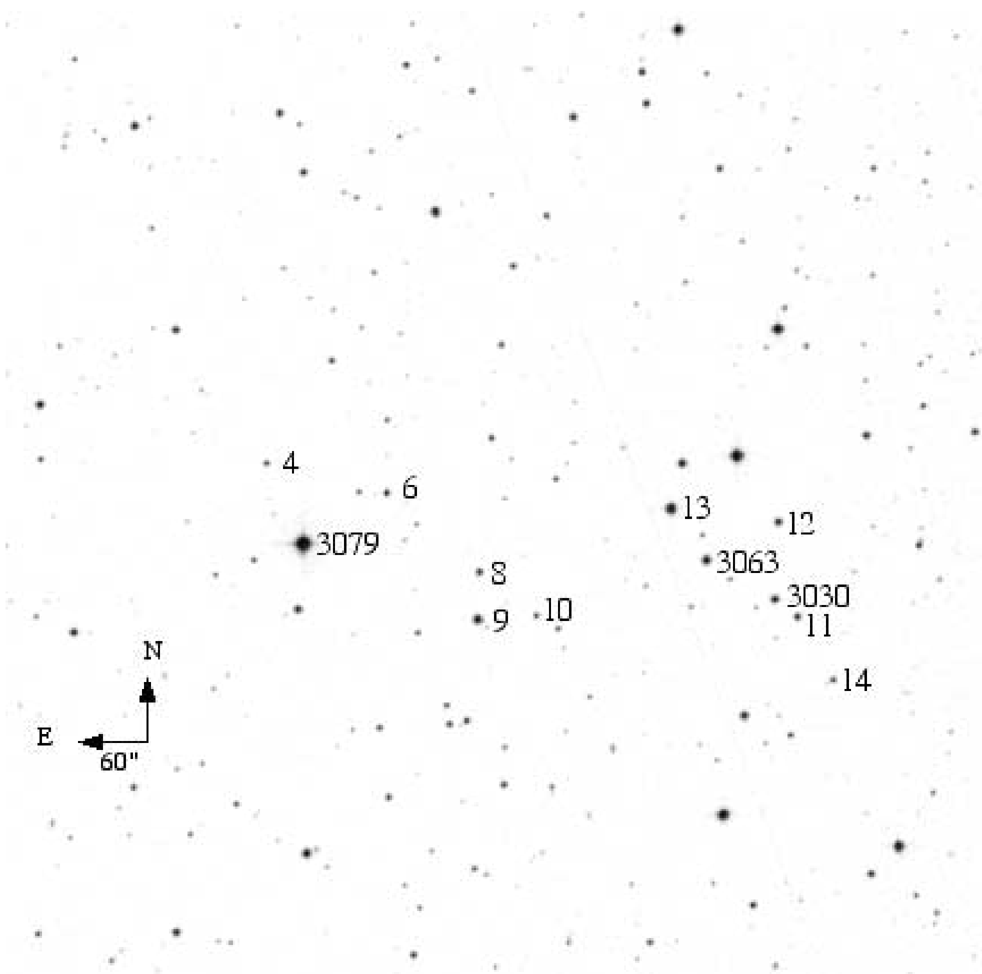

FIG. 1.—Plot of the Pleiades, its members, and the astrometric reference stars observed.

TABLE 2
Fine Guidance Sensor and Near-Infrared Photometry

ID	V	K	$J-H$	$J-K$	$V-K$
3179	10.07	8.68 ± 0.02	0.32 ± 0.02	0.37 ± 0.02	1.40 ± 0.10
3063	13.54	10.34 ± 0.02	0.67 ± 0.03	0.84 ± 0.03	3.20 ± 0.10
3030	14.00	10.63 ± 0.02	0.71 ± 0.03	0.85 ± 0.03	3.37 ± 0.10
Ref-4	15.66	13.98 ± 0.05	0.43 ± 0.05	0.49 ± 0.06	1.70 ± 0.11
Ref-6	14.56	12.03 ± 0.02	0.56 ± 0.02	0.68 ± 0.03	2.54 ± 0.10
Ref-8	14.48	12.91 ± 0.03	0.29 ± 0.03	0.37 ± 0.04	1.57 ± 0.10
Ref-9	13.60	10.64 ± 0.02	0.68 ± 0.02	0.79 ± 0.03	2.97 ± 0.10
Ref-10	15.85	13.40 ± 0.04	0.55 ± 0.04	0.67 ± 0.05	2.45 ± 0.11
Ref-11	14.63	12.75 ± 0.02	0.43 ± 0.03	0.49 ± 0.04	1.88 ± 0.10
Ref-12	14.23	12.15 ± 0.03	0.48 ± 0.04	0.51 ± 0.04	2.10 ± 0.10
Ref-13	13.15	10.57 ± 0.02	0.34 ± 0.03	0.42 ± 0.03	1.57 ± 0.10
Ref-14	15.48	13.78 ± 0.03	0.42 ± 0.05	0.44 ± 0.05	1.70 ± 0.11

Bradley et al. (1991) and Nelan & Makidon (2001) provide an overview of *HST*'s Fine Guidance Sensors, and Benedict et al. (2002b) describe the fringe-tracking mode astrometric capabilities of an FGS, along with data acquisition and reduction strategies also used in the present study. Times of observation use a modified Julian Date, MJD = JD − 2,444,000.5.

We obtained observations at each of the two maximum parallax factors. This leads to the two distinct spacecraft roll angles shown, which result from the requirement to keep *HST*'s solar panels fully illuminated throughout the year. This roll constraint generally imposes alternate orientations at each time of maximum positive or negative parallax factor over a typical 2.5 yr parallax campaign, allowing a clean separation of parallax and proper-motion signatures. As noted, our original intent was to determine orbital parameters for some known spectroscopic binaries, but once resolution of the binary did not work out, we changed this dynamical parallax experiment to a standard parallax program. The most recent data set extended our time span by 2.5 yr, significantly improving the accuracy of our final parallaxes and the precision of our final proper-motion values.

3. ABSOLUTE PARALLAXES FOR THE REFERENCE STARS

Because the parallax determined for the three Pleiades members is measured with respect to reference frame stars, which have their own parallaxes, we must either apply a statistically derived correction from relative to absolute parallax (van Altena et al. 1995, hereafter YPC95) or estimate the absolute parallaxes of the reference frame stars. 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), yet the derived absolute magnitudes are critically dependent on the assumed luminosity. As a consequence, we use as much additional information as possible in an attempt to confirm the luminosity classes. Specifically, we obtained Two Micron All Sky Survey (2MASS[3]) photometry and proper motions from the second United States Naval Observatory's CCD Astrograph Catalog (UCAC2) for a 1 deg^2 field containing Figure 1 and then iteratively employ the technique of reduced proper motion (Yong & Lambert 2003; Gould & Morgan 2003) in an effort to discriminate between giants and dwarfs.

3.1. *Reference Star Photometry*

Our bandpasses for reference star photometry include V (from FGS 1r) and JHK (from 2MASS). The 2MASS JHK values have been transformed to the Bessell & Brett (1988) system using the transformations provided in Carpenter (2001). Table 2 lists $VJHK$ photometry for the target and reference stars indicated in Figure 1.

3.2. *Reference Star Spectroscopy*

The spectra from which we estimated spectral type and luminosity class come from Lick Observatory.[4] The resolution was approximately 2000, with coverage from 3900 to 6700 Å. Classifications used a combination of template matching and line ratios. Spectral types for the stars are good to about two subclasses. Table 3 lists the spectral types and luminosity classes for our reference stars. The estimated classification uncertainties are used to generate the σ_{M_V} values in that table.

3.3. *Interstellar Extinction*

To determine interstellar extinction, we first plot these stars in a $J-K$ versus $V-K$ diagram. A comparison of the relationships between spectral type and intrinsic color against those we measured provides an estimate of reddening. Figure 2 shows this color-color diagram and a reddening vector for $A_V = 1.0$. Also plotted are mappings between spectral type and luminosity classes V and III from Bessell & Brett (1988) and Cox (2000, hereafter AQ2000). Figure 2, along with the estimated spectral types, provides an indication 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 2) with intrinsic $(V-K)_0$ colors from Bessell & Brett (1988) and AQ2000. Specifically, we estimate A_V from $A_V/E(V-K) = 1.1$, derived from the Savage & Mathis (1979) reddening law. The resulting A_V values are collected in Table 4. Colors and spectral types of these reference stars are consistent with a field-wide average $\langle A_V \rangle = 0.17 \pm 0.06$, far less than the maximum reddening, $A_V < 0.72$, determined by Schlegel et al.

[3] The Two Micron All Sky Survey is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology.

[4] Lick Observatory is owned and operated by the University of California.

TABLE 3

Astrometric Reference Star Spectral Classifications and Spectrophotometric Parallaxes

ID	Spectral Type	V	M_V	A_V	$m - M$	$\pi_{\rm abs}$ (mas)
Ref-4.............	G5 V	15.68	5.1	0.14	10.6 ± 0.7	0.8 ± 0.3
Ref-6.............	K1 IV	14.5	3.4	0.23	11.2 ± 2	0.06 ± 0.6
Ref-8.............	G3 V	14.48	4.8	0.14	9.7 ± 0.7	1.2 ± 0.4
Ref-9.............	K2 III	13.61	0.5	0.23	13.1 ± 0.7	0.3 ± 0.1
Ref-10...........	K1 IV	15.85	3.4	0.23	12.5 ± 2	0.4 ± 0.3
Ref-11...........	G8 V	14.63	5.6	0.14	9.1 ± 0.7	1.7 ± 0.5
Ref-12...........	K0 V	14.24	5.9	0.14	8.3 ± 0.7	2.3 ± 0.7
Ref-13...........	G3 V	12.14	4.8	0.14	7.3 ± 0.7	3.66 ± 1.2
Ref-14...........	G5 V	15.48	5.1	0.14	10.4 ± 0.7	0.9 ± 0.3

(1998). For the stars classified as dwarfs, $\langle A_V \rangle = 0.14 \pm 0.03$, in good agreement with a recent determination of $A_V = 0.12$ for the Pleiades (Hainline et al. 2001). The more distant nondwarfs have $\langle A_V \rangle = 0.23 \pm 0.08$.

The technique of reduced proper motions can confirm the reference stars' estimated luminosity classes, but the precision of existing proper motions for all the reference stars was so low that only suggestive discrimination between giants and dwarfs was possible. Typical uncertainties for H_K, a parameter equivalent to absolute magnitude, M_V, were about a magnitude. Nonetheless, a reduced proper motion diagram does suggest that ref-6, ref-9, and ref-10 are not dwarf stars, since they are considerably redder in $J - K$ than the other stars classified as dwarfs. Giants are typically redder in $J - K$ than dwarfs for a given spectral type (AQ2000). Our luminosity class uncertainty is reflected in their input spectrophotometric parallax errors (Table 3). We revisit this additional test in § 4.1, once we have solved for higher precision proper motions.

3.4. *Adopted Reference Frame Absolute Parallaxes*

We derive absolute parallaxes with M_V values from AQ2000 and the $\langle A_V \rangle$ derived from the photometry. Our adopted errors for $(m - M)_0$ are 0.7 mag for the dwarfs and from 0.7 to 2 mag for the nondwarf reference stars. These are somewhat larger than we have used in the past (Benedict et al. 2002a, 2002b; McArthur et al. 2002) but are justified given our far smaller set of spectrophotometric data. Our parallax values are listed in Table 3. Individually, no reference star absolute parallax is better determined than $\sigma_\pi/\pi = 32\%$. The average absolute parallax for the reference frame is $\langle \pi_{\rm abs} \rangle = 1.3$ mas. As a check, we compare this with the correction to absolute parallax discussed and presented in YPC95 (§ 3.2, Fig. 2). Entering YPC95, Figure 2, with the Pleiades Galactic latitude, $b = -23\overset{\circ}{.}0$, and average magnitude for the reference frame, $\langle V_{\rm ref} \rangle = 14.5$, we obtain a correction to absolute of 1.0 mas. We prefer to introduce into our reduction model our spectrophotometrically estimated reference star parallaxes as observations with error. When such data are available, the use of spectrophotometric parallaxes offers a more direct (i.e., less Galaxy model–dependent) way of determining the reference star absolute parallaxes.

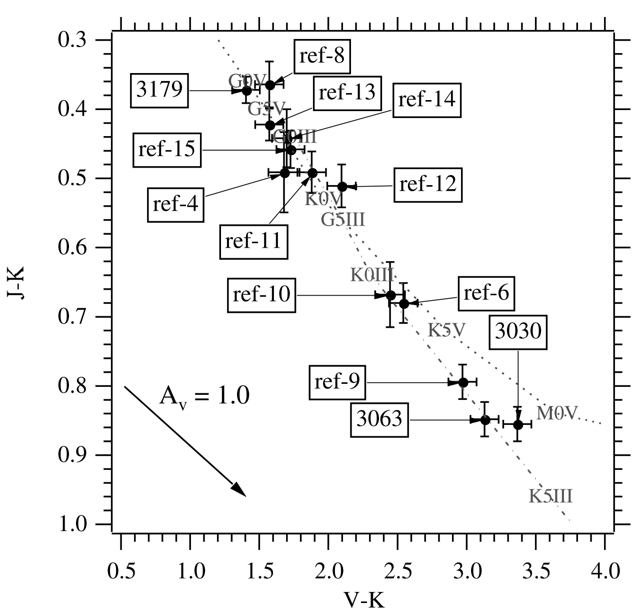

Fig. 2.—Plot of a $J - K$ vs. $V - K$ color-color diagram. The dotted line is the locus of dwarf (luminosity class V) stars of various spectral types; the dashed line is for giants (luminosity class III). The reddening vector indicates $A_V = 1.0$ for the plotted color systems.

4. THE ABSOLUTE PARALLAX OF THE PLEIADES

4.1. *The Astrometric Model*

Using the positions measured by FGS 1r, 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 1, along with a measured magnitude transformed from the FGS instrumental system as per Benedict et al. (1998). Our Pleiades reference frame contains nine stars. We employ the six-parameter model discussed in Benedict et al. (1999) for those observations. In this case, we determined the plate parameters from target and reference star data. In addition, we apply corrections for lateral color discussed in Benedict et al. (1999), using values specific to FGS 1r as determined from observations with that FGS.

As for all our previous astrometric analyses, we employ GaussFit (Jefferys et al. 1987) to minimize χ^2. The solved equations of condition for the Pleiades field are

$$x' = x + lcx(B - V), \quad (2)$$

$$y' = y + lcy(B - V), \quad (3)$$

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

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

where x and y are the measured coordinates from *HST*; lcx and lcy are the lateral color corrections; and $(B - V)$ represents the $B - V$ color of each star, estimated from its spectral type, A_V,

TABLE 4
REFERENCE STAR A_V VALUES FROM SPECTROPHOTOMETRY

ID	Spectral Type	$(V-K)_0$	$V-K$	$E(V-K)$	A_V[a]
Ref-4........	G5 V	1.55	1.68	0.13	0.14
Ref-6........	K1 IV	2.32	2.54	0.22	0.24
Ref-8........	G3 V	1.45	1.57	0.12	0.13
Ref-9........	K2 III	2.70	2.97	0.27	0.30
Ref-10......	K1 IV	2.32	2.45	0.13	0.14
Ref-11......	G8 V	1.80	1.88	0.08	0.09
Ref-12......	K0 V	1.96	2.10	0.13	0.15
Ref-13......	G3 V	1.45	1.57	0.12	0.13
Ref-14......	G5 V	1.55	1.70	0.15	0.16

[a] The quantity $A_V = 1.1E(V-K)$.

and $J-K$ color listed in Table 2. The quantities A and B are scale and rotation plate constants, C and F are offset plate constants, 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 (2MASS) with uncertainties in the field orientation of 0°.05.

4.2. *Modeling Constraints from Prior Knowledge*

In addition to introducing our estimated reference star parallaxes as observations with error, we also introduce proper-motion data from UCAC2 (Zacharias et al. 2003) and Schilbach et al. (1995). Initial values are listed in Table 5. Typical input errors are 5–6 mas for each coordinate. The lateral color calibrations and the $B-V$ color indexes are also treated as observations with error. As a final constraining observation, we solve for a line-of-sight dispersion in the parallaxes of the three Pleiades members with the "observation" derived from the 1 σ angular extent of the Pleiades (1°; Adams et al. 2001) and an assumption of spherical symmetry. From this, we infer that the 1 σ dispersion in distance in this group is $1°/1$ radian $= 1.7\%$. Hence, the 1 σ dispersion in the parallax difference between Pleiades members is

$$\Delta\pi = (1.7\%)\left(\sqrt{2}\right)(7.7 \text{ mas}) = 0.20 \text{ mas}, \tag{6}$$

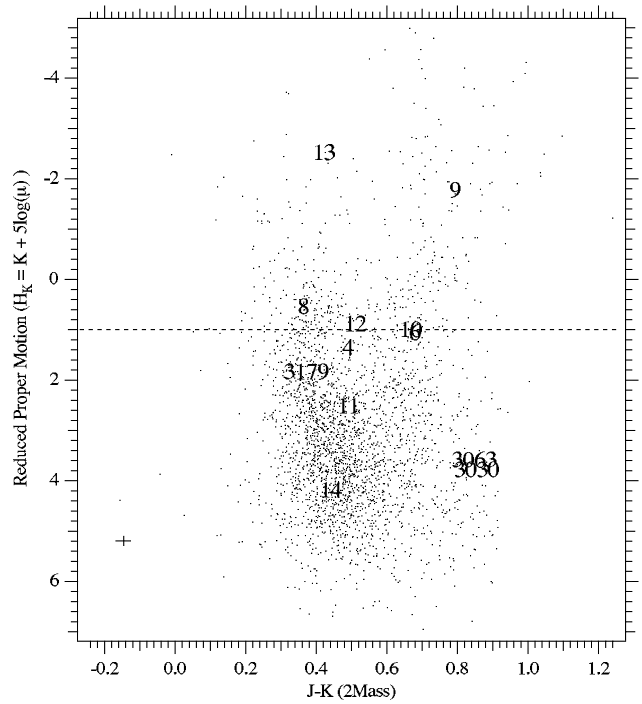

FIG. 3.—Reduced proper motion diagram for 5542 stars in a 1° field centered on the Pleiades. Star identifications are shown for our Pleiades targets (3030, 3063, and 3179) and our astrometric reference stars. For a given spectral type, giants and subgiants have more negative H_K values and are redder than dwarfs in $J-K$. Stars ref-6 and ref-10 are coincident. Values of H_K are derived from "final" proper motions in Table 5. The small cross at the bottom left represents a typical $J-K$ error of 0.04 mag and H_K error of 0.17 mag. The horizontal dashed line is a giant-dwarf demarcation derived from a statistical analysis of the Tycho input catalog (D. Ciardi 2004, private communication).

where we have here temporarily adopted a parallax of the Pleiades, $\langle\pi\rangle = 7.7$ mas. The parallax dispersion among targets 3030, 3179, and 3063 becomes an observation with associated error fed to our model, an observation used to estimate the parallax dispersion among the three stars while solving for their parallaxes. Loosening the cluster 1 σ dispersion to 2° (i.e., $\Delta\pi = 0.38$ mas) had no effect on the final weighted average parallax. Again, note that $\Delta\pi = 0.2$ mas is not an error associated with the *distance* to the Pleiades. It serves to constrain the dispersion in distances measured for Pleiades members.

TABLE 5
PLEIADES AND REFERENCE STAR PROPER MOTIONS

		INPUT (UCAC2)		FINAL (*HST*)	
ID	V	μ_x[a]	μ_y[a]	μ_x[a]	μ_y[a]
3179.....................	10.08	+0.0192 ± 0.0006	−0.0465 ± 0.0006	+0.0192 ± 0.0003	−0.0465 ± 0.0002
3063[b]...................	13.47	+0.0164 ± 0.0011	−0.0418 ± 0.0011	+0.0168 ± 0.0003	−0.0421 ± 0.0005
3030[b]...................	14.00	+0.0154 ± 0.0004	−0.0408 ± 0.0004	+0.0155 ± 0.0004	−0.0403 ± 0.0002
Ref-4...................	15.68	+0.0035 ± 0.0056	−0.0034 ± 0.0056	+0.0024 ± 0.0026	−0.0019 ± 0.0024
Ref-6...................	14.57	+0.0054 ± 0.0056	−0.0094 ± 0.0056	+0.0044 ± 0.0010	−0.0049 ± 0.0010
Ref-8...................	14.47	+0.0052 ± 0.0056	−0.0119 ± 0.0056	+0.0030 ± 0.0005	−0.0016 ± 0.0005
Ref-9...................	13.61	+0.0117 ± 0.0056	+0.0033 ± 0.0056	−0.0014 ± 0.0015	+0.0031 ± 0.0019
Ref-10.................	15.85	−0.0016 ± 0.0069	−0.0092 ± 0.0069	−0.0016 ± 0.0022	−0.0091 ± 0.0026
Ref-11.................	14.63	+0.0030 ± 0.0056	−0.0131 ± 0.0056	−0.0043 ± 0.0007	−0.0039 ± 0.0006
Ref-12.................	14.24	+0.0058 ± 0.0056	−0.0096 ± 0.0056	−0.0008 ± 0.0010	+0.0024 ± 0.0012
Ref-13.................	12.14	−0.0074 ± 0.0019	−0.0129 ± 0.0019	−0.0093 ± 0.0010	−0.0083 ± 0.0011
Ref-14.................	15.48	0.0000 ± 0.0058	−0.0053 ± 0.0058	−0.0056 ± 0.0024	−0.0051 ± 0.0032

[a] The quantities μ_x and μ_y are relative motions in arcsec yr^{-1}.
[b] The quantities μ_x and μ_y are from Schilbach et al. (1995).

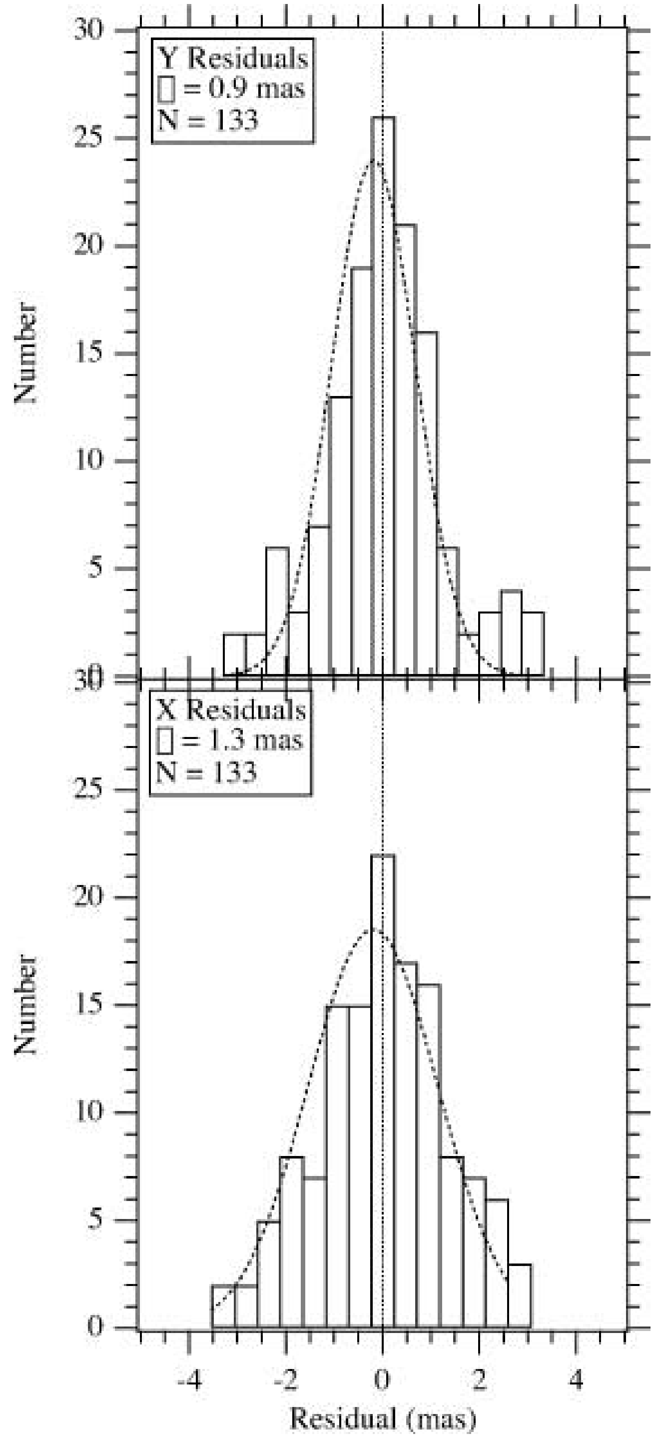

FIG. 4.—Histograms of x and y residuals obtained from modeling the Pleiades members and astrometric reference stars with eqs. (4) and (5). Distributions are fitted with Gaussians whose 1 σ dispersions are noted in the plots.

Proper-motion values obtained from our modeling of *HST* data are listed in Table 5 as "Final." We now employ the technique of reduced proper motions to provide a confirmation of the reference star estimated luminosity class listed in Table 3. We obtain proper motion and J and K photometry from UCAC2 and 2MASS for a 1 deg^2 field centered on the Pleiades. Figure 3 shows $H_K = K + 5\log(\mu)$ versus $J - K$ color index for 5542 stars. If all stars had the same transverse velocities, Figure 3 would be equivalent to an H-R diagram. Target Pleiades stars and reference stars are plotted as identification numbers from Table 5. Errors in H_K are now $\sim$0.3 mag. Reference stars 6, 9, and 10 are clearly separated from the others, supporting their classification as nondwarfs. Ref-6 and ref-10 remain below ref-9, confirming their subgiant nature.

TABLE 6

PLEIADES AND REFERENCE STAR POSITIONS

ID	V	ξ[a]	η[a]
3179	10.08	+163.1991 ± 0.0002	−13.1667 ± 0.0002
3063	13.47	−198.8822 ± 0.0003	+59.7779 ± 0.0003
3030	14.00	−268.2952 ± 0.0003	+39.2897 ± 0.0003
Ref-4	15.68	+213.0875 ± 0.0012	+51.9487 ± 0.0010
Ref-6	14.57	+99.5992 ± 0.0003	+51.2020 ± 0.0006
Ref-8[b]	14.47	0.0000 ± 0.0005	0.0000 ± 0.0006
Ref-9	13.61	−8.4395 ± 0.0003	−42.3189 ± 0.0003
Ref-10	15.85	−60.3818 ± 0.0009	−26.3444 ± 0.0008
Ref-11	14.63	−292.6740 ± 0.0003	+28.8663 ± 0.0004
Ref-12	14.24	−254.6792 ± 0.0004	+109.6633 ± 0.0005
Ref-13	12.14	−156.6322 ± 0.0003	+97.8026 ± 0.0003
Ref-14	15.48	−338.2213 ± 0.0006	−19.8165 ± 0.0007

[a] The quantities ξ and η are relative positions in arcseconds.
[b] R.A. = $03^h51^m45\overset{s}{.}050$, decl. = $+23°53'43\overset{''}{.}43$, J2000.

4.3. *Assessing Reference Frame Residuals*

Our initial modeling attempts indicated that three of the original 12 reference stars exhibited significantly larger residuals than average. These reference stars were near the top and bottom edges of the FGS 1r field of regard. The optical field angle distortion calibration (McArthur et al. 2002) reduces as-built *HST* telescope and FGS 1r distortions with amplitude $\sim 1''$ to below 2 mas over much of the FGS 1r field of regard. However, because the fidelity of correction drops precipitously near the edge of the field of regard, we removed these three stars from the solution. From histograms of the remaining reference star astrometric residuals (Fig. 4) we conclude that we have obtained satisfactory correction. The resulting reference frame "catalog" in ξ and η standard coordinates (Table 6) was determined with $\langle\sigma_\xi\rangle = 0.5$ and $\langle\sigma_\eta\rangle = 0.5$ mas.

To determine if there might be unmodeled but possibly correctable systematic effects at the 1 mas level, we plotted the Pleiades reference frame x and y residuals against a number of

TABLE 7

PLEIADES AND REFERENCE STAR PARALLAXES AND TRANSVERSE VELOCITIES

ID	μ[a] (mas yr^{-1})	π_{abs}[b] (mas)	V_t[c] (km s^{-1})
3179	50.36 ± 0.40	7.45 ± 0.16	32
3063	45.30 ± 0.53	7.43 ± 0.16	29
3030	43.20 ± 0.48	7.41 ± 0.18	28
Ref-4	3.07 ± 3.54	0.82 ± 0.09	18
Ref-6	6.63 ± 1.39	0.84 ± 0.25	38
Ref-8	3.40 ± 0.76	1.21 ± 0.13	13
Ref-9	3.42 ± 2.43	0.26 ± 0.03	61
Ref-10	9.28 ± 3.39	0.36 ± 0.11	122
Ref-11	5.79 ± 0.98	1.66 ± 0.16	17
Ref-12	2.50 ± 1.52	2.25 ± 0.23	5
Ref-13	12.50 ± 1.46	1.64 ± 0.32	36
Ref-14	7.58 ± 4.04	0.92 ± 0.10	39

[a] The quantity $\mu = (\mu_x^2 + \mu_y^2)^{1/2}$ is from "Final" in Table 5.
[b] Final π_{abs} from modeling *HST* data with eqs. (2)–(5), employing the constraints summarized in § 4.2.
[c] The quantity $V_t = 4.74\mu/\pi_{abs}$.

TABLE 8
PLEIADES PARALLAX AND PROPER MOTION

Parameter	Value
HST study duration (yr)	3.51
Number of observation sets	6
Reference star $\langle V \rangle$	14.63
Reference star $\langle (B-V) \rangle$	0.9[a]
HST absolute parallax (mas)[b]	7.43 ± 0.17
HST relative proper motion (mas yr^{-1})[c]	46.3 ± 3.7
HST relative proper motion in position angle (deg)	158 ± 1

[a] Estimated from *VJHK* photometry and spectral types, with $A_V = 0.14$ for dwarfs and $A_V = 0.23$ for giants.
[b] Average of 3030, 3063, and 3179 from Table 7.
[c] Average of 3030, 3063, and 3179 from Table 5, "Final" data. Proper-motion error is the standard deviation of the individual measures.

spacecraft, instrumental, and astronomical parameters. These included x and y position within the FGS "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.

4.4. *The Absolute Parallax of the Pleiades*

Note that we do not measure the parallax of these Pleiades stars relative to a reference frame with unknown parallax and then apply a correction to absolute parallax, assuming some model of the Galaxy. In a quasi-Bayesian approach, the reference star spectrophotometric absolute parallaxes, UCAC2 and Schilbach et al. (1995) proper motions, and an estimated cluster depth were input as observations with associated errors, not as hard-wired quantities known to infinite precision. Parallaxes and relative proper motion results from *HST* are collected in Tables 5 and 7. We obtain for the Pleiades members an average absolute parallax $\pi_{abs} = 7.43 \pm 0.17$ mas (Table 8). Because we employ a cluster depth constraint, the three Pleiades member parallaxes are not independent measurements. Hence, we cannot use the standard deviation of the mean to reduce our final error by $\sqrt{2}$. Along with our result, other recent Pleiades parallaxes are listed in Table 9 and compared in Figure 5. The most discrepant of these is clearly and only the *Hipparcos* result.

Our absolute parallax for the Pleiades contains one last systematic uncertainty: where in the cluster do our three Pleiades members lie? In § 4.2 we estimated a "depth" in parallax of $\sim$0.20 mas. Our final parallax result should be stated as $\pi_{abs} = 7.43 \pm 0.17 \pm 0.20$ mas, with the error having both a random and systematic component. We point out that each of the astrometric results in Figure 5 suffers from the same systematic error. In the next section we reduce that error by averaging those results. Inspecting Tables 5 and 7, we note that ref-14, identified as Cl* Melotte 22 CALAR 7, is in fact not a Pleiades star, disagreeing in parallax and proper motion with the first three stars in these tables, all identified members.

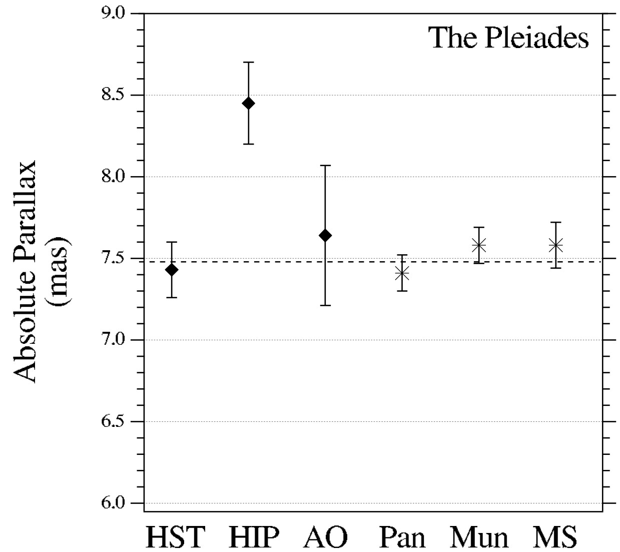

FIG. 5.—Absolute parallax determinations for the Pleiades. We compare astrometric parallax results (*filled diamonds*) from *HST* ("HST"), *Hipparcos* ("HIP"), and recent determinations from Allegheny Observatory ("AO"; Gatewood et al. 2000). Pan et al. (2004) ("Pan") have derived a dynamical parallax from long-baseline interferometry and radial velocity measurements of the binary star Atlas. Munari et al. (2004) ("Mun") have performed a similar dynamical determination on another Pleiades binary. "MS" denotes a parallax derived from main-sequence fitting (Pinsonneault et al. 1998). The horizontal dashed line is the weighted average of the HST, Pan, Mun, and AO measures.

5. DISCUSSION AND SUMMARY

5.1. *HST Parallax Accuracy*

Our parallax precision, an indication of our internal, random error, is often less than 0.3 mas. To assess our accuracy, or external error, we must compare our parallaxes with results from independent measurements. Following Gatewood et al. (1998) and extending the analysis presented in Benedict et al. (2002b) with the addition of a recent parallax for Gl 876 (Benedict et al. 2002c), we plot eight parallaxes obtained by the *HST* Astrometry Science Team with FGS 3 and now FGS 1r against those obtained by *Hipparcos*. Data for these objects are collected in Table 10 and shown in Figure 6. The dashed line is a weighted regression that takes into account errors in both input data sets and excludes the Pleiades. Figure 6 indicates no statistically

TABLE 9
PREVIOUS AND PRESENT PLEIADES PARALLAXES

Method	Abbreviation	π_{abs}	d (pc)	$m-M$	Ref.
HST FGS parallax	HST	7.43 ± 0.17	134.6 ± 3.1	5.65 ± 0.05	1
Hipparcos all-sky	HIP	8.45 ± 0.25	118.3 ± 3.5	5.37 ± 0.06	2
Allegheny Observatory	AO	7.64 ± 0.43	130.9 ± 7.4	5.59 ± 0.11	3
Interferometric orbit	Pan	7.41 ± 0.11	135.0 ± 2.0	5.65 ± 0.03	4
Dynamical parallax	Mun	7.58 ± 0.11	131.9 ± 3.0	5.60 ± 0.05	5
Main-sequence fitting	MS	7.58 ± 0.14	131.9 ± 2.4	5.60 ± 0.04	6

REFERENCES.—(1) This paper; (2) van Leeuwen 1999; (3) Gatewood et al. 2000; (4) Pan et al. 2004; (5) Munari et al. 2004; (6) Pinsonneault et al. 1998.

TABLE 10
HST and *Hipparcos* Absolute Parallaxes

Object	π_{HST} (mas)	π_{Hip} (mas)	*HST* Reference
Proxima Cen	769.7 ± 0.3	772.33 ± 2.42	1
Barnard's Star	545.5 ± 0.3	549.3 ± 1.58	1
Gliese 876	214.6 ± 0.2	212.7 ± 2.1	2
Feige 24	14.6 ± 0.4	13.44 ± 3.62	3
Wolf 1062	98.0 ± 0.4	98.56 ± 2.66	4
Pleiades	7.43 ± 0.17	8.45 ± 0.25	5
RR Lyrae.............	3.60 ± 0.20	4.38 ± 0.59	6
δ Cephei	3.66 ± 0.15	3.32 ± 0.58	7
HD 213307	3.65 ± 0.15	3.43 ± 0.64	7

References.—(1) Benedict et al. 1999; (2) Benedict et al. 2002c; (3) Benedict et al. 2000; (4) Benedict et al. 2001; (5) this paper; (6) Benedict et al. 2002a; (7) Benedict et al. 2002b.

significant scale difference compared with *Hipparcos*. However, for this fit, which excludes the Pleiades, we obtain a reduced $\chi^2 = 0.265$. Including the Pleiades, we obtain a significantly poorer fit with reduced $\chi^2 = 0.551$, again suggesting a problem with the *Hipparcos* Pleiades parallax.

Our result, in and of itself, does not lead to the conclusion that the *Hipparcos* parallax for the Pleiades is wrong, but that conclusion cannot be avoided once all the results are examined together. Especially important for making this case are the two recent determinations of visual binary orbits for Pleiades members. Pan et al. (2004) used the Palomar Testbed Interferometer to determine very precise relative positions of the two stars comprising Atlas, one of the Seven Sisters. Without having a radial velocity orbit they could not determine all the parameters, but a solution is possible by assuming masses for the stars, and the masses enter in the cube root. By doing this they concluded that the distance to the Pleiades cannot be less than 127 pc and that the most likely distance lies between 133 and 137 pc. Munari et al. (2004) analyzed light curves and radial velocity curves for HD 23642, an eclipsing binary in the Pleiades, and determined a distance of 132 ± 2 pc. [This would decrease to 130.6 ± 3.7 if the assumed reddening were increased to as much as $E(B-V) = 0.035$ mag.]

5.2. *The Distance to the Pleiades*

There now exist three completely independent determinations of the Pleiades distance that use completely independent techniques and data, and they all yield the same answer to within their errors. Our traditional parallax determination leads to $d = 134.6 \pm 3.1$ pc, a visual binary orbit leads to $d = 135 \pm 2$, and an eclipsing binary orbit results in $d = 132 \pm 2$. For comparison, recent estimates from main-sequence fitting include 132 ± 4 (Stello & Nissen 2001) and 132 ± 2 (Pinsonneault et al. 1998), and Gatewood et al. (2000) have determined 131 ± 7 at Allegheny Observatory. Narayanan & Gould (1999) derived 131 ± 24 pc from the gradient in the radial velocities of Pleiades members in the direction of the cluster's proper motion.

Clearly the *Hipparcos* result, 118 ± 4, is discrepant. This can be seen graphically in Figure 6, and a summary of these distance determinations is given in Table 9. Understanding this discrepancy is crucial. Astrometry is arguably the one branch of astronomy in which accurate and precise knowledge of uncertainties cannot be overlooked. The *Hipparcos* team has been well aware of this and has put considerable effort into examining potential sources of systematic error. Their most recent

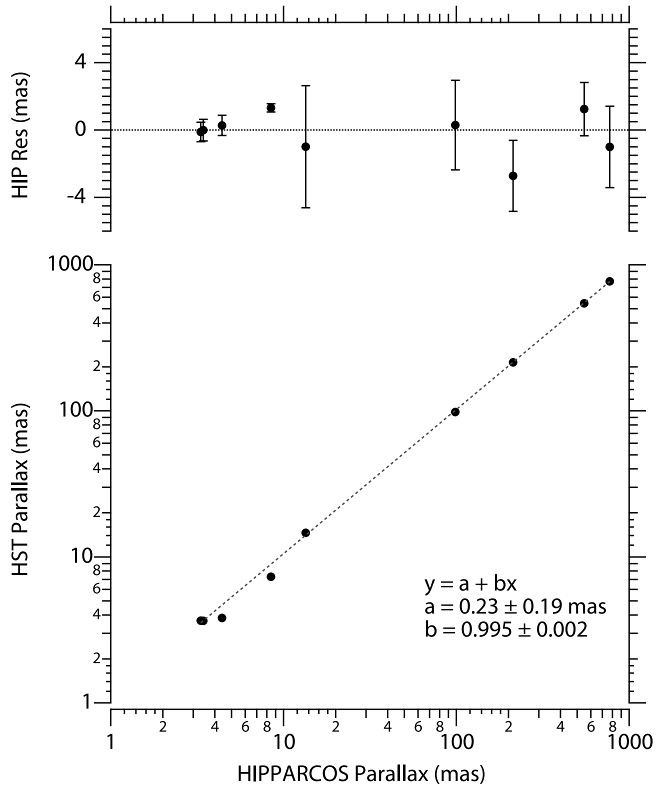

Fig. 6.—*Bottom*: *HST* absolute parallax determinations compared with *Hipparcos* for all targets listed in Table 10. *Top*: *Hipparcos* residuals to the dotted error-weighted impartial regression line that excludes the Pleiades. The error bars on the residuals are *Hipparcos* Catalogue 1 σ errors.

papers (van Leeuwen & Fantino 2003a, 2003b; Dalla Torre & van Leeuwen 2003; van Leeuwen & Penston 2003; Fantino & van Leeuwen 2003) show, for instance, that noise in the along-scan attitude dominates for $H_p < 4.5$ (where H_p is the apparent magnitude as directly measured by *Hipparcos*) and that this may be especially important for the Pleiades, inter alia (van Leeuwen & Fantino 2003b). This possibility was examined by Makarov (2002), who reanalyzed *Hipparcos* data to derive $d = 129 \pm 3$, a value that is substantially less discrepant than that reported by van Leeuwen (1999) and Robichon et al. (1999).

The answer certainly does not lie in an unusual shape or physical properties for the Pleiades. Stello & Nissen (2001) suggested that the *Hipparcos* distance could be reconciled with traditional measures if the bright stars—the Seven Sisters—that dominate the *Hipparcos* result happen to lie at the near end of an elongated cluster. This is disproved by the fact that Pan et al. (2004) find Atlas itself to lie at the traditional distance. Grenon (2001) suggested that the luminosities of Pleiades stars could be accounted for by a low cluster metallicity of -0.112 ± 0.025, determined from Geneva photometry. The exact metallicity of the Pleiades remains uncertain, but it is unlikely to be as low as that since analyses from high-resolution spectra yield values that are essentially solar (e.g., Boesgaard & Friel [1990] get $[\mathrm{Fe/H}] = -0.034 \pm 0.024$). Hainline et al. (2001) have likewise refuted the Grenon (2001) metallicity on several grounds.

To summarize, *HST* astrometry yields an absolute trigonometric parallax for three members of the Pleiades of $\pi_{\rm abs} = 7.43 \pm 0.17$ mas with a 0.20 mas systematic error due to cluster depth. A weighted average with previous ground-based astrometric determinations (*HST*, AO, Pan, and Munari; Table 9) provides $\pi_{\rm abs} = 7.49 \pm 0.07$ mas. This average result should reduce the contribution of the cluster depth systematic error, presuming that the stars measured by these techniques are randomly distributed within the cluster. With $\sigma_\pi/\pi \sim 1\%$, any Lutz-Kelker-Hanson bias correction (Lutz & Kelker 1973; Hanson 1979) to an absolute magnitude would be less than 0.01 mag (e.g., Benedict et al. 2002b). This net parallax of 7.49 ± 0.07 mas corresponds to $d = 133.5 \pm 1.2$ pc, or $m - M = 5.63 \pm 0.02$ mag. This is likely to be the best available distance for the Pleiades until observations of substantially better precision can be made with a mission such as *SIM* or *GAIA*.

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