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MAP–BASED TRIGONOMETRIC PARALLAXES OF OPEN CLUSTERS: THE PLEIADES

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ABSTRACT

The multichannel astrometric photometer and Thaw refractor of the University of Pittsburgh's Allegheny Observatory have been used to determine the trigonometric parallax of the Pleiades star cluster. The distance determined, 150 with a standard error of 18 parsecs (a distance modulus of 5.9 ± 0.26 magnitudes) places the cluster slightly farther away than generally accepted. This suggests that the basis of many estimations of the cosmic distance scale is approximately 20% short. The accuracy of the determination is limited by the number and choice of reference stars. With careful attention to the selection of reference stars in several Pleiades regions, it should be possible to examine differences in the photometric and trigonometric modulus at a precision of 0.1 magnitudes.

Subject headings: astrometry — clusters: open — stars: luminosities

I. BACKGROUND

Cosmic scale is based largely upon the trigonometric determination of stellar distance. Since astrometric precision has not been sufficient to directly determine the distances of intrinsically bright luminosity standards, a process sometimes referred to as main-sequence fitting has been used to bridge the gap (Rowan-Robinson 1985), for example, to determine the distance of star clusters containing Cepheid variables (e.g., Balona and Shobbrook 1984). The algorithm matches a composite H-R diagram to that of much more distant systems. The composite itself is the result of fitting nearby clusters to the H-R diagram of the Hyades; the distance estimate of which is partially dependent upon a fit to the trigonometric distances of local dwarfs. This process assumes intrinsic similarity, with some adjustment for age and composition. While this process is fundamental to our understanding of cosmic scale, it is littered with potential pitfalls. With sufficient precision, astrometrists could enhance the reliability of the algorithm by measuring the direct trigonometric parallax of each of the clusters used in the composite H-R diagram.

The recently developed multichannel astrometric photometer (MAP) and new optical system of the Thaw refractor (Gatewood 1987) of the University of Pittsburgh's Allegheny Observatory combine to give that instrument a precision sufficient to determine significant trigonometric parallaxes of objects within several hundred parsecs (Gatewood 1989). Thus we have instituted an observing effort to measure the distances of the Hyades, the Pleiades, the Praesepe, and the Coma open star clusters.

II. METHOD, PHOTOMETRY, AND SPECTRAL CLASSIFICATIONS

Both the instrumentation and the reduction of the photometric-phase measurements of the MAP to astrometric positions have been described by Gatewood (1987). The transformation of these to the star constants listed below is known as the central overlap technique (e.g., Gatewood and Russell 1974; Eichhorn 1988). The reduction of the derived relative parallaxes to absolute distances includes the estimation of the intrinsic luminosities of the reference stars. This need is the basis of our two calibration efforts, one by Stephenson using the 10° objective prism on the Case 24 inch (61 cm) Schmidt telescope as discussed by Bidelman (1966), and the other involving intermediate-band photometry by Castelaz and Persinger (1989).

III. ASTROMETRIC RESULTS AND THE ADJUSTMENT TO ABSOLUTE

The MAP region chosen for this study is near the apparent center of the cluster. Only one MAP region was chosen in the cluster, it being assumed that the European astrometric satellite *HIPPARCOS* (Perryman 1985) would soon yield the parallaxes of a number of Pleiades stars with a standard error, for each star, of approximately 0″002 (2 mas). Our study, with an expected standard error of 1 mas per star but for far fewer stars, was set up more as a calibration and a check than an effort to find an independent distance. It was for this reason that five of the nine stars studied in detail are cluster members, and this is the primary limitation of the precision of our derived parallax. As discussed below, for the Thaw/MAP the ideal ratio of reference to cluster stars is approximately 2:1. To estimate the cluster's distance, the other four stars were chosen from bright background objects with proper motions significantly different than that of the cluster (Hertzsprung *et al.* 1947). Preference was given to objects that appeared, from a comparison of apparent magnitudes derived from plates taken with the Thaw 0.76 m red and blue objective lenses, to lie off of the cluster's main sequence.

Table 1 is a continuation of a series of parallaxes now under observation with the Thaw/MAP and reduced via the central overlap technique. In that series each star is subject to a full analysis of its motion, including parallactic reflex motion. This approach has the double advantage of finding previously unsuspected nearby stars and providing the information neces-

TABLE 1

STAR PARAMETERS IN THE REGION OF THE PLEIADES

AO No.	d	V mag	$B-V$	abs Par. (mas)	R.A.(2000)	PM(R.A.)	Decl.(2000)	PM(Decl.)
826	2	10.88	1.33	1.5	$3^h45^m49^s.56057$	$-0^s.000308$	$24^\circ25'35''.5460$	$-0''.00391$
				1.7	0.00009	0.000074	0.0012	0.00092
827	2	6.43	−0.02	7.0*	3 46 2.85635	0.001218	24 31 40.1108	−0.04977
				0.8	0.00004	0.000033	0.0005	0.00042
828	2	7.69	1.23	4.6	3 46 13.71107	0.001226	24 11 47.8205	−0.00914
				0.8	0.00004	0.000037	0.0006	0.00046
829	2	9.31	0.47	6.7*	3 46 39.30290	0.001476	24 6 11.5900	−0.05034
				1.1	0.00006	0.000050	0.0008	0.00062
830	2	6.82	0.02	6.6*	3 46 59.35251	0.000956	24 31 12.2141	−0.04837
				0.9	0.00005	0.000039	0.0006	0.00050
831	2	10.35	1.35	...	3 47 3.52296	−0.001295	24 38 13.3592	0.00182
					0.00072	0.000415	0.0091	0.00527
832	2	10.52	1.85	0.1	3 47 28.79821	−0.000266	24 33 24.6583	−0.01161
				1.2	0.00006	0.000053	0.0008	0.00065
833	2	6.81	0.06	6.5*	3 47 29.42391	0.001446	24 17 17.9923	−0.04953
				1.1	0.00006	0.000047	0.0008	0.00060
834	2	10.55	0.65	...	3 47 40.41568	0.001602	24 21 52.3112	−0.05016
					0.00037	0.000204	0.0040	0.00233
835	2	10.02	0.64	1.4	3 47 59.29486	−0.000407	24 5 57.1274	−0.01740
				2.5	0.00013	0.000103	0.0016	0.00126
836	2	8.27	0.36	6.5*	3 48 13.52966	0.001595	24 19 61.2685	−0.05051
				1.1	0.00006	0.000045	0.0007	0.00058

AO numbers are part of a continuing series beginning with the use of the central overlap technique. The 2 in column "d" notes that the device used to gather the astrometric data was the Thaw/MAP. The absolute parallaxes listed above were obtained by adding a correction to absolute of 5.3 mas. An * denotes that the star is a Pleiades cluster member. All standard errors (second row of each entry), for example those of the positions, are strictly internal and do not allow for the zero-point errors of the reference system. The precession for +50 yr, at the target object, is 2.980 minutes of time in R.A. and 9.22 arcmin in Decl.

sary for the reduction (and future improvement in that reduction) of the relative parallaxes to absolute distances. The positions and motions resulting from the current study are listed in the last four columns of Table 1, over their standard errors. The system of the positions and motions is that of the AGK3 (Heckmann and Dieckvoss 1975) but the data are listed for the epoch and equinox J2000 (Fricke 1977). The standard errors are given in units of the last digit of the parameter to which they pertain and are strictly internal at the central epoch, here 1988.0. Note that they do not include allowance for the zero-point, scale, orientation, or proper motion uncertainties of the reference system. AO 831 and AO 834 were observed only during the last year, and a reliable relative parallax could not be derived. They were not used as reference stars and are included in the table only for completeness. Photometric values for the three brightest stars are from Johnson and Mitchell (1958), while the rest are from Castelaz and Persinger (1990).

While parallaxes are included in the last several iterations of the reduction algorithm, no constraints were placed on their weighted mean. Thus the system of equations converged on relative, not absolute, parallaxes. The most reliable way to determine the difference between the relative and the absolute parallaxes is to determine the spectroscopic parallax of as many reference stars as possible and find the weighted mean of the difference. This adjustment is then applied to all of the relative parallaxes.

As noted by Gatewood (1987), reference stars should be bright enough that photon statistics play a relatively small part in the error of their positions, but they should also be as distant as possible. As pointed out by Castelaz and Persinger (1989), the standard error of a spectroscopic parallax is a function of the parallax. Thus a 25% random error in the estimate of the luminosity of a reference star with a parallax of 1 mas contributes only a 0.1 mas error to the estimate of the correction-to-absolute based upon that star.

Likewise, transferal of systematic errors in the positions of various luminosity classes on the H-R diagram, to that of the target parallax is a function of the relative distance of the reference and target objects. For example, if the reference star distances averaged 5 times that of the target, a 10% error in the calibration of their luminosities would be reduced to a 1% systematic error in the luminosities of the newly measured stars. Thus the process of using the spectroscopic parallaxes of distant stars to adjust the relative parallax of target objects to absolute parallax, and then using the newly determined parallaxes of the nearby stars to improve our knowledge of the H-R diagram *is convergent on an error-free system.*

Listed in Table 2 are the AO catalog (stars observed at the Allegheny Observatory and reduced by the central overlap technique) number, the Hertzsprung number from his second list (Hertzsprung *et al.* 1947) (HII), the apparent visual magnitude, and the adopted spectral classification and luminosity type of the four noncluster members for which a precise trigonometric study was possible. Spectral classifications result from a comparison of 10 band photometry given by Castelaz and Persinger (1990) with classifications determined by Stephenson using two plates acquired with the Case

TABLE 2

ADJUSTMENT TO ABSOLUTE IN THE REGION OF THE PLEIADES

AO No.	Hertzsprung No.	m_v	Adopted Spectral	Spectral Parallax	σ Spectroscopic Parallax	Relative Parallax	Adjustment to Absolute	Weight	Weighted Residuals (mas)
826...........	784	10.88	K1 III	1.2	0.38	−3.8	5.0	0.74	−0.27
828...........	938	7.69	K2 III	3.9	1.32	−0.7	4.6	1.42	−1.08
832...........	1426	10.52	M2 II	0.4	0.13	−5.2	5.6	1.54	+0.52
835...........	1666	10.02	G2 IV	4.1	1.60	−3.9	8.0	0.31	−0.82

Average adjustment to absolute = 5.32 mas.
Standard error of mean adjustment = 0.75.

61 cm Schmidt. This is followed by the implied spectroscopic parallax, an estimate of its standard error, the relative parallax, and the adjustment found by comparing the latter two values, and an estimate of the statistical weight of that adjustment. The weighted residuals to this adjustment are listed in the last column. The average weighted correction and its standard error are listed at the bottom of the table. The adjustment found here is applied in Table 1.

With interstellar absorption variable in the direction of the Pleiades, varying over the cluster with $E(B-V)$ ranging from 0.00 to 0.58 magnitudes (C'ernis 1987), we expected to find considerable variation in the absorption of the light from background stars. In each case $A_v/E(B-V)$ was assumed to be 3.6 in accordance with C'ernis who finds 3.6 ± 0.2 in this region. The first of the four noncluster stars, AO 826 (HII 784), is too faint for the Case plates of the region. Binnendijk (1946) estimated the temperature class as G5. The DDO and *UBVRI* photometry of this star (Castelaz and Persinger 1990) indicates a K1 III star with $E(B-V) = 0.23$. The *UBVRI* magnitudes are in good agreement with those given in Table 1 of Johnson (1966) and the DDO 45–48, 42–45, 41–42 colors, after correction for reddening (Janes 1975), indicate a K1–2 III giant. The 38–42 index is also in accordance with this luminosity classification (McClure and Forrester 1981). The spectrum of AO 828 (HII 398) was classified by Stephenson as a K2 II. With only a slight amount of reddening $[E(B-V) = 0.07]$ the *UBVRI* data fit a K2 III closely. The DDO photometry suggests a K3 III with the 45–48/42–45 ratios indicating an object with a III–IV luminosity. AO 832 (HII 1426) was too faint for the Case objective prism plate; Binnendijk listed its temperature class as K7. *UBVRI* photometry is suggestive of a reddened $[E(B-V) = 0.25]$ M2 supergiant, $U-V$ being too large for a class III. The DDO photometry indicates an M2.5 giant in the 41–42/42–45 chart of Dawson (1977) and falls at the crossover point from M2.5 and K5 giants on the 45–48/42–45 chart. The 38–42/45–48 ratio is suggestive of a class II luminosity. Unfortunately, M temperature classes were not calibrated for supergiants in any DDO source we could find. AO 835 (HII 1666 + HII 1667) was classified by Stephenson as a G2 IV, but he notes that the image was underexposed and therefore the classification is uncertain. Binnendijk notes that the object is double with a combined spectrum of G and a difference in blue magnitude of 2.2. Aitken (1932) lists a separation of 2″1 and gives the visual magnitudes as 10 and 11. This and the value listed by Binnendijk suggest that the companion is relatively bright and red. Altogether, AO 835 is not a very good reference star and had the largest set of positional residuals of any star in the field. The presences of a possible red companion exacerbates the calibration of the interstellar reddening. The $U-V$ color is close to that of a G2 temperature star, but the redder colors indicate successive later class stars rising to approximately a G6 in the $V-I$ index. If we adopt a reddening $[E(B-V)]$ of 0.1, the DDO photometry agrees with the G2 temperature and the 41–42/42–45 ratio agrees with the IV luminosity class. However the 45–48/42–45 ratio suggests a class V. We added the light of the companion ($\Delta M_v = 1.0$) in our adopted luminosity for the star. Adopted values are given in Table 2.

The weights applied in determining the mean correction are estimated from the standard error of the correction to absolute

$$\sigma_C = (\sigma_T^2 + \sigma_S^2)^{1/2} , \quad (1)$$

where σ_T is the standard error of the relative parallax and σ_S is the standard error, as estimated by the precepts of Castelaz and Persinger (1989) and Stein (1990), of the spectroscopic parallax. For the latter we have adopted the value suggested by past experience: $\sigma_S = 0.25$ times the parallax (Gatewood 1989).

A weighted mean adjustment from relative to absolute parallax of 5.3 + 0.7 mas was determined using (1) the luminosity classifications listed in Table 2, (2) the absolute magnitudes given by Allen (1973), and (3) the individual interstellar absorptions noted above. Adding the adjustment to absolute found above to the mean relative parallax of the five cluster stars (1.3 ± 0.2 mas), and including the estimated standard error of their mean, we find a parallax of $0''0066 \pm 0''0008$ (the dispersion due to the depth of the cluster is several percent of the parallax and is therefore not a significant factor). This yields a distance of 150 ± 18 parsecs or a distance modulus of 5.9 ± 0.26 magnitudes.

IV. DISCUSSION

Eggen (1986) (see also summary in C'ernis) finds a distance modulus of the Pleiades equal to 5.65 ± 0.1 magnitudes, within one standard deviation of the value found here. Given the uncertainties in both studies (e.g., C'ernis 1987), and the radically different approaches, the agreement is reassuring. In view of the difference we have examined our assumptions to determine what changes might bring the values closer together. In the red giant sequences, luminosity is not very sensitive to the temperature class. Thus errors in this estimate are relatively unimportant. The luminosity classes, however, are well separated and are therefore important. The most uncertain of the luminosity calibrations is that of AO 826. Fortunately, any reasonable interpretation of the photometric data yields a very distant star and therefore little change in the correction to absolute. For example, reclassification to type III would change the derived distance of the cluster by only 2%. Other likely scenarios also resulted in insignificant changes in our conclusion; thus we conclude that the result of this particular study is, with a certainty of one standard deviation, that distances based upon this cluster's main sequence are short by ~20%.

Obviously, with sufficient weight, results that impact cosmic scale directly are very important. As noted earlier, the greatest weakness in this study is the small number of reference stars. However, having more than one cluster star allows the astrometrists to derive a mean relative parallax with a higher precision. With the recent installation of three additional channels on the MAP, a partial solution is at hand. A balance in the allocation of these is suggested by the relative precisions of the cluster and reference star parallaxes, the latter tending to average somewhat fainter (the apparent lack of magnitude associated errors is attested to by the slope in Figure 1 of Gatewood 1989). The precision of an observation of a relatively bright star is 3.3 mas per 20 minutes or, since two observations are made per night, approximately 2.3 mas per night (similar to the precision planned for the entire *HIPPARCOS* mission). The standard error of an observation of an 11th magnitude star is ~20% higher. Allowing for the additional uncertainty in the correction to absolute, this suggests a ratio of four cluster stars to eight reference stars for a 12 channel MAP. Assuming a parallax precision of 0.9 mas per cluster star parallax, we predict that the MAP can achieve a precision of 0.6 mas per region in cluster studies. For the Hyades open clusters, this is equivalent to an error 0.06 magnitudes in the distance modulus. Multiple regions per cluster will reduce this error further.

We note that the proposed astrometric reflector, the ATT (Gatewood, Meinel, and Meinel 1989), a mountaintop variant of the proposed space borne AIT (Levy *et al.* 1986), would have 3–4 times the precision of the Thaw, allowing the calibration of the distances of these clusters to a precision similar to that of the photoelectric photometry of the individual member stars and bringing a number of Cepheids within range of direct trigonometric calibration.

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