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MAP-BASED TRIGONOMETRIC PARALLAXES OF OPEN CLUSTERS.
II. THE HYADES: 51 TAURI

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ABSTRACT

The Multichannel Astrometric Photometer (MAP) and Thaw Refractor of the University of Pittsburgh's Allegheny Observatory have been used to determine the trigonometric parallax, mass, and mass ratio of 51 Tauri, a binary member of the Hyades star cluster. The parallax solution, 19.4 mas ($0\rlap{.}''0194$) with a standard error of 1.1 mas is slightly greater than its generally accepted value and yields a cluster distance of 43.0 ± 2.0 pc or a distance modulus equivalent of 3.16 ± 0.10 mag, in excellent agreement with recent photographic parallax results. The weighted mean of all trigonometric parallax determinations of the cluster is now 22.9 ± 0.6 mas or a modulus of 3.20 ± 0.06 mag. The total mass of the 51 Tauri system was found to be $2.56 \pm 0.44\ M_\odot$. Adopting a magnitude difference in line with the spectral types of the components yields individual masses of 1.61 ± 0.28 and 0.95 ± 0.18 solar masses. This result places the mass of both the A8 V primary and the G0 secondary stars within the errors of the measurement of the mass-luminosity relation established for solar-neighborhood main-sequence stars. The derived absolute magnitudes for the A and B components, 2.3 and 4.3, respectively, are both 0.1 mag less than, but within their standard errors of, those listed by Allen for luminosity class V stars. A reference star, AO 870, an early M dwarf, is found to be passing either just in front of or through the near side of the Hyades cluster.

Subject headings: open clusters and associations: individual (Hyades) — stars: fundamental parameters — stars: individual (51 Tau)

1. BACKGROUND

The cosmic distance scale is based largely upon a process sometimes referred to as main-sequence fitting (Rowan-Robinson 1985). The algorithm matches a composite HR diagram to that of much more distant systems. The composite itself is the result of fitting nearby open clusters to the HR diagram of the Hyades cluster, the distance estimate of which is partially dependent upon a fit to the trigonometric distances of local main-sequence (MS) stars. This process assumes intrinsic similarity, with some adjustment for age and composition between local MS stars and members of the several star clusters. While this procedure is fundamental to our understanding of the cosmic scale, it is obviously littered with potential pitfalls. Ideally the composite HR diagram would result from the direct measurement of the trigonometric parallaxes of each of the component clusters. The recently developed Multichannel Astrometric Photometer (MAP) and the new optical system of the Thaw Refractor (Gatwood 1987) at Allegheny Observatory provide the basis for the requisite astrometric precision called for in that approach (Gatewood 1989). This presentation is the second in a series detailing the direct trigonometric measurement of the distances to the Hyades, Pleiades, Praesepe, and Coma open star clusters (Gatewood et al. 1990).

Both the instrumentation and the reduction of the MAP-generated photometric-phase values to astrometric positions have been described by Gatewood (1987). The algorithm used to transform the latter to the star constants listed below is known as the central overlap technique (e.g., Gatewood & 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 for a parallel series of reports detailing intermediate band photometry results (e.g., Persinger & Castelaz 1990) and a second program by Stephenson based on the 10° objective prism on the Warner Swasey Observatory's 24 inch (61 cm) Schmidt telescope.

Observation of this Hyades region with the MAP was started in the fall of 1986, shortly after the installation of the new Thaw objective lens, with the most recent observation dating from 1991 October. Altogether 46 MAP observations were obtained in somewhat less than five-and-one-third years. The 51 Tauri system is one of the few bright stars not covered by the Allegheny Observatory photographic parallax program; only one photographic observation of the region has been taken with the Thaw Refractor's 76 cm new red-light objective lens. Thus, unlike previous studies (e.g., Gatewood et al. 1989a), this orbital motion study relies entirely upon MAP observations.

The 51 Tauri (A0 998) system is a spectroscopic-interferometric binary consisting of a rapidly rotating A8 V star and a G0 star (Deutsch, Lowen, & Wallerstein 1971; McAlister 1976). It was added to the MAP observing program in order to determine the individual masses of the component stars, a McAlister (1976) gauntlet. The analysis of the astrometric motion of 51 Tauri, using instrumentation and reduction techniques not previously employed in distance studies of the Hyades cluster, yields a parallax of a single-member star system with unprecedented precision. A way to

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transfer this information to other member stars is examined, as is a simple cross check of the distance and observed motion of the cluster.

2. THE ADJUSTMENT TO ABSOLUTE PARALLAX

Table 1 is an example of a broad series of ongoing parallax observation now being undertaken with the Thaw/MAP instrumentation and reduced via the central overlap technique. In this series each star is subjected to a comprehensive motion study including parallactic reflex motion. This approach has the double advantage of finding previously unsuspected nearby stars, for example, A0 870 in the region here under study, and providing the information necessary 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 above their corresponding standard errors. The system of the positions and motions is that of the PPM catalog (Röser & Bastian 1991). The standard errors are given in units of the last shown digits of the parameter to which they pertain and are strictly internal at J2000. We note that they do not include an allowance for the zero-point, scale, orientation, or proper motion uncertainties of the reference system. Thus, for example, the proper motion of the target star is best obtained from studies of the FK5 (e.g., Schwan 1991). Photometric values for the three brightest stars are from the SIMBAD data base, while the rest are from Persinger & Castelaz (1990) and Castelaz & Persinger (1991).

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 compute the spectroscopic parallax of as many reference stars as possible and to find the weighted mean of the difference. This adjustment is then applied to all of the relative parallaxes. This approach is fundamentally different from that underlying previous trigonometric parallax programs and has been described most recently by Stein (1991).

Listed in Table 2 are the AO catalog number and the adopted spectral classification-luminosity type of the eight noncluster member reference stars for which trigonometric and spectrophotometric studies were meaningful. With the exception noted below, the spectral classifications result from an evaluation of catalog-listed spectral types and the 10 band photometry of this region given by Persinger & Castelaz (1990) and Castelaz et al. (1991). This is followed by the implied spectroscopic parallax, an estimate of its standard error (e.g., Stein 1991), the relative parallax, its estimated standard error, the adjustment found by subtracting the relative parallax from the spectroscopic parallax, and an adopted weight for that individual estimate of the mean adjustment. The weighted residuals to this adjustment are listed in the last column. The mean adjustment and its standard error are listed at the bottom of the table. The adjustment found here is applied in Table 1 and throughout this paper.

Interstellar visual absorption in the direction of the Hyades cluster would seem to be only moderately variable (Persinger & Castelaz 1990). In each case the ratio $A_v/E(B-V)$ was assumed to be 3.1. The Castelaz & Persinger $U-B$, $B-V$, $V-R$, and $R-I$ photometry of the star AO 870 falls between Johnson's (1966) profiles for an unreddened M0 and M1 dwarf. Persinger & Castelaz's photometry indicates that the star AO 875 has a smaller $U-B$ value than expected for a MS star. Their values also place it above the MS, near the giants, in the Hβ-C1 plot of Reglero et al. (1988). Stephenson, noting enhanced strontium II lines on a plate acquired with the

TABLE 1

STAR PARAMETERS IN THE REGION OF 51 TAURI

AO Number	d	V (mag)	$B-V$	Absolute Parallax (mas)	R.A.(2000)	PM(R.A.)	Decl.(2000)	PM(Decl.)
869	2	10.18	0.40	2.0	$4^{h}17^{m}17^{s}.03317$	$0^{s}.000676$	21°52′19″.8904	−0″.00839
				0.6	0.00019	0.000018	0.0025	0.00023
870	2	12.35	1.40	25.1	4 17 53.91664	0.023867	21 32 11.7422	−0.10909
				2.8	0.00092	0.000094	0.0118	0.00121
871	2	11.77	1.22	1.1	4 18 9.13387	−0.000283	21 33 24.7883	0.00100
				1.4	0.00043	0.000041	0.0051	0.00048
998[a]	2	5.65	0.28	19.4	4 18 23.21824	0.006932	21 34 45.4053	−0.03600
				1.1	0.00055	0.000051	0.0042	0.00038
872	2	11.28	1.59	5.8	4 18 32.10095	−0.001058	21 21 35.6660	0.00129
				1.8	0.00055	0.000053	0.0071	0.00068
873	2	11.66	0.83	5.5	4 18 32.52700	0.000052	21 40 4.8902	−0.02938
				1.4	0.00042	0.000041	0.0055	0.00053
874	2	10.49	0.56	0.4	4 18 56.58823	0.000727	21 43 7.6633	−0.01207
				1.1	0.00033	0.000031	0.0043	0.00041
875	2	8.17	0.46	2.5	4 19 1.19704	0.002668	21 17 57.5167	−0.03994
				0.4	0.00012	0.000012	0.0017	0.00016
876	2	11.40	1.76	1.3	4 19 28.91516	−0.000181	21 52 45.0953	−0.01821
				1.9	0.00057	0.000055	0.0071	0.00069
999	2	5.38	−0.14	1.9	4 19 36.73288	0.002138	21 46 24.3106	−0.05118
				0.6	0.00020	0.000019	0.0026	0.00025

NOTES.—The absolute parallaxes listed above were obtained by adding an adjustment to absolute of 1.7 milli-arcseconds (mas). All standard errors, for example those of the positions, are strictly internal and do not allow for the zero point errors of the reference system. Colum "d" denotes the device used to gather the astrometric data. A "2" indicates that the data was obtained with the Multichannel Astrometric Photometer (MAP).

[a] The 51 Tauri system.

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TABLE 2

ADJUSTMENT TO ABSOLUTE IN THE REGION OF 51 TAURI

AO Number	Adopted Spectral Type	Spectroscopic Parallax	Estimated Error	Relative Parallax	Calculated Error	Adjustment to Absolute	Weight	Observed Parallax	Spectroscopic-Observed Parallax
869..........	B9.5 V	2.1	0.8	0.3	0.6	1.8	1.0	2.0	0.1
870..........	M0.5 V	26.5	11.0	23.4	2.8	3.1	0.1	25.1	1.4
871..........	G2 III	1.4	0.8	−0.6	1.4	2.0	0.6	1.1	0.3
872..........	K1 III	1.6	1.0	4.1	1.8	−2.5	0.5	5.8	−4.2
873..........	G0 V	4.9	1.6	3.8	1.4	1.1	0.5	5.5	−0.6
874..........	A1 V	2.6	1.8	−1.3	1.1	3.9	0.5	0.4	2.2
875..........	F4 III	5.4	3.2	0.8	0.4	4.6	0.3	2.5	2.9
876..........	K4 III	1.0	0.6	−0.4	1.9	1.4	0.5	1.3	−0.3

NOTES.—Weighted mean adjustment to absolute = 1.7 mas. Standard error of weighted mean adjustment = 0.6 mas.

Warner Swasey Schmidt and objective prism, assigns a spectral classification F4 III to this star.

The intrinsic luminosity of the star AO 999,[1] a variable A p star, is difficult to assign, and so it was not used as a standard in the determination of the adjustment to absolute parallax. We note also that the object is placed at the edge of the MAP field. Thus we do not consider the parallax derived here to be definitive. The relatively low weight of AO 870, the faintest star in the field and the last one to be assigned a channel on the still developing MAP, results from the relatively small number of MAP observations of this object rather than from its magnitude. At 39.8 ± 4.4 pc, this early M dwarf star lies near the line of sight to 51 Tauri, a bit closer than the mean distance of the cluster.

Given the luminosity classifications listed in Table 2, the absolute magnitudes given by Allen (1973), and the individual interstellar absorption corrections, we find a weighted mean value of 1.66 ± 0.63 mas for the adjustment of the relative parallaxes to absolute. This value is applied in all following discussions and in Table 1. An alternate estimate for this adjustment is found in galactic dynamics (e.g., Van Altena 1974), and its value has been applied to all but one, as noted below, of the photographic parallax studies of the Hyades cluster.

Excluding star AO 870, the average distance of the reference stars is more than 17 times that of the cluster. Thus any systematic errors in the Allen tables are reduced by more than an order of magnitude in their application to the distance of the Hyades cluster.

3. BINARY MOTION AND PARALLAX OF 51 TAURI

Since its discovery by Deutsch, 51 Tauri has been the subject of both spectroscopic and speckle interferometry observations. Unfortunately the high rotation rate of the primary conceals its radial velocity variations. Thus the spectroscopic orbit is derived entirely from the motion of the secondary, and it is not possible to derive the parallax from these two types of observation alone. There have been several orbital studies. Deutsch et al. is basically a spectroscopic study, while Peterson & Solensky (1988) combine spectroscoic and speckle interferometry observations. Most recently Dombrowski (1990), from speckle interferometry observations covering two revolutions, finds an orbital period of 11.295 ± 0.001 yr and a semimajor axis of 133.7 ± 0.3 mas in general agreement with Baize (1989).

Figure 1 is a plot of the residuals from a combined two-axis adjustment of the MAP observations allowing for (1) position, (2) proper motion, and (3) parallax. Each point represents the mean of a season's observations. The adjustment did not include a term for the photocentric semimajor axis. Because of the current direction of the orbital motion, almost all of the nonlinear motion is in declination. Figure 2 is a plot of the MAP residuals from a two-axis adjustment allowing for the above motions plus (4) the semimajor axis of the photocentric orbit suggested by the Dombrowski parameters. The standard deviation of the normal points about a straight line is 1.1 mas, indicating that the agreement between this orbit and the MAP data is excellent.

The parallax of 51 Tauri improved with the allowance for orbital motion and adjusted to absolute as noted above is 19.4 ± 1.1 mas. Based on 5.4 yr of consecutive observation during the 11.3 yr orbital period, the preliminary value of the photometric semimajor axis is 31.4 ± 2.2 mas. Adopting the Dombrowski orbit, we find a total mass of 2.57 ± 0.44 $M_{\odot}$. Unfortunately, although it is occulted by the Moon, there are no direct measurements of the magnitude difference of the components of 51 Tauri. Adoption of a magnitude difference of 2.0 ± 0.2, in line with the spectral types, yields a mass function

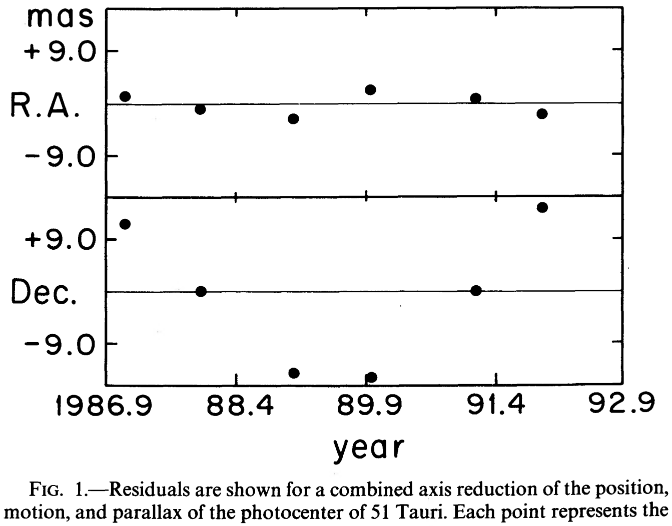

FIG. 1.—Residuals are shown for a combined axis reduction of the position, motion, and parallax of the photocenter of 51 Tauri. Each point represents the mean of one season's observations.

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[1] AO numbers are assigned as measurements for each star are published. Persinger & Castelaz published their photometric data for all but two of these stars in 1990.

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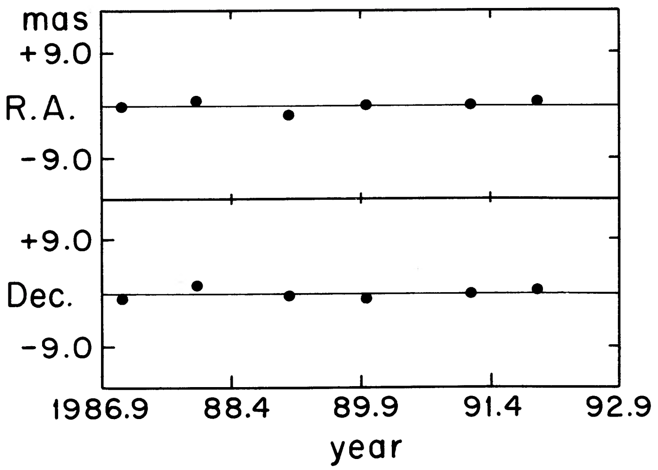

FIG. 2.—Residuals as in Fig. 2 after the inclusion of a term for the photocentric semimajor axis of the orbit. The standard deviation of the residuals is 1.1 mas.

of 0.372 ± 0.027. The resulting masses of the primary and secondary components of 51 Tauri are estimated at 1.61 ± 0.28 and 0.95 ± 0.18 $M_\odot$, respectively. The derived absolute magnitudes for the A and B components, 2.3 and 4.3, respectively, are both 0.1 mag less than, but within their standard errors of, those listed by Allen for luminosity class V stars.

The only other estimate of the magnitude difference is a preliminary value from the speckle-interferometric study of Dombrowski, namely 0.72 ± 0.15 mag. This value is difficult to reconcile with statements that the secondary star is at the limit of observation in both the speckle and spectroscopic measurements (Deutsch et al. 1971; McAlister 1976). This value also leads to a mass function of 0.575 ± 0.035, resulting in a secondary component more massive than the preliminary, which in turn is not easy to reconcile with the measured radial velocity of the secondary star and the substantial photocentric orbit.

4. TRIGONOMETRIC PARALLAXES AND THE MOVING CLUSTER METHOD

The precision of the parallax derived here for 51 Tauri is unique for a member of the Hyades cluster and is several times more than required to resolve the depth of the cluster. As such it gives a full closure of the terms in the simple relationship between the motion and distance of a moving cluster-member star:

$$\pi = 4.74 \frac{\mu}{V_r} \cot \lambda \,. \qquad (1)$$

Here π is the star's annual parallax, μ is its total proper motion, V_r is its radial velocity, and λ is the angle to the convergent point. Thus any of the observed values may be checked against the others. Solving for the angle to the convergent point, for example, and propagating the error, yields $\lambda = 34\overset{\circ}{.}8 \pm 1\overset{\circ}{.}5$ (the value derived from Schawn's 1991 paper is $36\overset{\circ}{.}5 \pm 0\overset{\circ}{.}4$). While the derived value of λ only yields a radius, several such parallax studies will result in intersecting small circles that could, much as in terrestrial navigation, pinpoint the right ascension and declination of the convergent point.

Knowing the parallax of one member star and assuming a common space velocity also allows us to estimate that of other member stars or of the cluster as a whole. From equation (1) it can be shown that the parallax of any other member star is simply that of the studied star divided by factor[2] f:

$$f = \frac{\pi_p}{\pi_i} = \frac{\mu_p}{\mu_i} \frac{\sin \lambda_i}{\sin \lambda_p} \,, \qquad (2)$$

where the subscript p denotes the parallax star and i denotes any other member star. Since the convergent point is usually several cluster diameters away from the center, it is evident that the ratio of the sines of the angles λ_i and λ_p are relatively insensitive to small errors in the convergent point. Indeed the geometry suggests that, at least to the first order, we may consider one angle as an increment on the other. Thus writing $\lambda_i = \lambda_p + \Delta\lambda$ have

$$f = \frac{\mu_p}{\mu_i} (\cot \lambda_p \times \sin \Delta\lambda + \cos \Delta\lambda) \,. \qquad (3)$$

This form of equation (2) is useful when considering the uncertainty in the derived distance to the cluster center. Assuming that the cluster center is defined by the properties of the set of or a subset of the member stars, the errors in that distance associated with μ_i and $\Delta\lambda$ will decrease approximately as the square root of the number of comparison stars (members of the set defining the center). The error contributed to the derived cluster distance by the estimates for the parallax star will only decrease as the square root of the number of individual stars for which the trigonometric parallax is derived directly. The error associated with the uncertainty of the convergent point will decrease as more precise values for this quantity are derived, perhaps as indicated above.

Following Schwan, using his subset of 50 stars, his proper motions for these stars, and his value for the convergent point, we find a mean cluster parallax of 23.3 ± 1.1 mas (modulus 3.16 ± 0.10 mag). The result is surprisingly insensitive to small changes in the assumed convergent point, increasing approximately 0.1 mas per degree decrease in its longitude and increasing approximately 0.05 mas per degree decrease in its latitude. Adopting the conergent point of Schwan's (1990) first paper, for example, increases the cluster parallax derived here by 0.04 mas. Thus the error associated with the parallax of 51 Tauri dominates the error propagation, the errors associated with the 50 comparisons and that of the assumed tangent point adding insignificantly to the result.

5. DISCUSSION

Table 3 summarizes previous trigonometric parallax studies of members of the Hyades cluster. The weighted mean trigonometric parallax (using the precisions quoted in the respective studies) of the Hyades cluster is 22.9 ± 0.6 mas (modulus 3.20 ± 0.06 mag). Their internal agreement, ±0.5 mas (standard error), belies the notion that the cluster is beyond the reach of this technique. With the exception of the present study, each of these efforts include the results from multiple regions and plate series. The value listed for the Yale Catalog is from Van Altena (1974) who reports a mean distance modulus of 3.23 ± 0.19 mag. The Lick result is from Klemola et al. (1975), while the Van Vleck result is from the remeasurement, on the Yale PDS comparator, of the plates used in an earlier

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[2] We chose to derive this factor in terms of proper motion because, at this epoch, it has a smaller percentage error than the measured radial velocities of the same stars.

TABLE 3

TRIGONOMETRIC MEASUREMENTS OF THE PARALLAX OF THE HYADES

Observatory	Parallax	Standard Error	Weight	Residual
Yale Catalog	22.6	2.0	0.5	−0.3
Lick	23.0	1.5	0.9	0.1
Van Vleck	22.0	1.2	1.4	−0.9
McCormick	23.2	1.0	2.0	0.3
Allegheny[a]	23.3	1.1	1.6	0.4
Mean	22.9	0.6	6.4	0.5
Distance Modulus = 3.20 ± 0.06				

[a] Photoelectric determination not including previous photographic contributions to the Yale Catalog.

study (Upgren et al. 1990). To ensure statistical independence, only the value obtained from the most recent measurement of those plates is reported. The McCormick result is that of Patterson & Ianna (1991). The latter reported two values differing in their method of adjustment to absolute. The one adopted here, and preferred[3] by Patterson & Ianna, is based upon an adjustment similar to that used in MAP parallax series. Unfortunately the data available for the McCormick study did not include the luminosity class of each reference star. Thus this assignment was sometimes based upon the relative parallax of the star. Since a reference star was assumed to be a MS star unless otherwise indicated, this approach may have led to too large a value for the adjustment. The McCormick value based upon a statistical adjustment to absolute (van Altena 1992) was 21.8 ± 1.0 mas which, if used, would lower the mean of all trigonometric parallaxes by 0.4 mas. In this case, the best value may lie between the two methods of adjustment. A significant contribution to the study of the Hyades cluster would be the determination of the luminosity classes of the reference stars in that study and/or the determination of the magnitude difference of the components of 51 Tauri.

The mass derived here for the 51 Tauri system is only slightly less than the sum of the masses of two MS stars of given estimated spectral type as derived from the mass-luminosity relation based upon local MS stars (Harris, Strand, & Worley 1963). It is interesting to note that the updated mean trigonometric parallax of the Hyades cluster suggests that the MAP-based parallax of 51 Tauri is approximately 0.4 mas too large. Such a correction applied to the parallax of 51 Tauri yields a total mass of 2.7 as compared to the 2.8 $M_\odot$ predicted by the mass-luminosity relation.

It is not the purpose of this paper to review other techniques as applied to the determination of the distance of the Hyades cluster, but it is difficult not to note the nearly 3 standard error difference between the trigonometric mean parallax and that of the most recent convergent point study of Schwan (1991). That the latter is also substantially greater than the recent radial velocity study of Gunn et al. (1988) suggests caution. The distance to the Hyades cluster is not yet well established.

The process followed in the present study can of course be greatly improved by choosing several cluster stars per region, and by observing several regions within the cluster.[4] At the distance of the Hyades cluster, an error of one thousandth of an arcsec in the parallax results in an error of approximately 0.1 mag in the distance modulus. Thus, assuming individual precisions similar to those achieved above and in the Pleiades study, it should be possible to reduce the error of the trigonometric estimate of the Hyades distance modulus to approximately 0.05 mag per region studied, or a few hundredths of a magnitude in the mean of several regional studies in the cluster. Yet higher precision will have to await mountain-top facilities (Gatewood, Meinel, & Meinel 1989b) or new space instrumentation (Levy et al. 1986).

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[3] They report it in their abstract.

[4] As noted earlier, the inclusion of several regions would allow a purely astrometric determination of the convergent point.

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