THE HYADES CLUSTER DISTANCE

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This paper reviews recent astrometric progress in determining the Hyades cluster distance, emphasizing critical assessment of the precision and accuracy of the observations. Substantial improvement in the trigonometric parallaxes yields a mean Hyades distance modulus $m - M = 3.25 \pm 0.08$ mag, nearly twice as precise as previous parallax results. New proper motions from three independent sources yield a mean distance modulus 3.31 ± 0.06 mag. The close agreement of the recent astrometric results suggests that the overall mean Hyades distance modulus 3.30 mag may be used with confidence in cosmic distance scale calibrations.

1. INTRODUCTION

The role of the Hyades cluster as a fundamental starting point for cosmic distance scale calibrations is well known; indeed the importance of the Hyades distance and the problem of its uncertainty have led to a great variety of attempts, direct and indirect, observational and theoretical, to determine it. These have been comprehensively reviewed by van Altena (1974a) and Hanson (1975). Recently, the substantial progress of astrometric work, in both trigonometric parallaxes and proper motions, has led to the possibility that the Hyades distance can be precisely measured from these fundamental observations alone. This review will discuss the most recent and most accurate astrometric observations of the Hyades distance, emphasizing critical assessment of their precision and accuracy. I will consider only direct observational determinations, so as to provide a valid basis for comparison with other observations (e.g., cluster and field main-sequence fitting) and with theoretical results (e.g., the HR diagram and mass--luminosity relation).

2. TRIGONOMETRIC PARALLAXES

Although trigonometric parallax is in principle the most direct

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astrometric distance measurement, its usefulness in measuring the Hyades distance has always been limited by the very high precision required. The Hyades parallax observations fall into two distinct categories: (a) the classical long-focus refractor parallaxes from the General Catalogue (GCTSP; Jenkins 1963) observatories, for bright stars ($m \leqslant 8$); and (b) the new programs to determine high-precision parallaxes for faint ($10 \leqslant m \leqslant 14$) stars (Vasilevskis 1966). For the bright stars, Hyades cluster membership can be definitively assigned from radial velocity and proper motion data. The chief problems lie in assessing the precision of the parallaxes and in achieving a uniform system of absolute parallax (Lutz 1978, Hanson 1978).

To obtain a complete list of "classical" Hyades parallaxes, I searched the GCTSP, its Supplement (Jenkins 1963), and the subsequent literature for Hyades members. The area of the sky covered was $3^h < \text{R.A.} < 5^h20^m$, $0° < \text{Dec.} < 32°$. Strict membership criteria according to van Bueren (1952) and Wayman, et al. (1965) were used. Several stars on Eggen's (1967) list are not Hyades cluster members on the basis of these proper motion and radial velocity criteria. A total of 44 parallax determinations, for 28 Hyades members, was found. These parallaxes were put onto the preliminary system of the new Yale Parallax Catalogue (van Altena 1978), following the precepts recently discussed by IAU Commission 24 at Vienna (Prochazka and Tucker 1978) and Montreal (IAU 1979). The Allegheny parallaxes were corrected (to B = 5.5) for their systematic apparent magnitude error (Hanson 1978, Hanson and Lutz 1979). The GCTSP observatory weighting system and corrections from relative to absolute (Jenkins 1963) were applied in the normal manner, to derive a combined absolute parallax for each star.

The Hyades stars are not all at the cluster center distance D_H. Indeed, their actual relative distances D_*/D_H are <u>known</u> from their proper motions (Wayman, et al. 1965):

$$D_*/D_H = \mu_H/\mu_*$$

where μ_* is the individual star's proper motion and μ_H is the mean Hyades proper motion at this position on the sky. This allows a test of the accuracy of the parallaxes: if the absolute parallaxes are plotted against the inverse relative distances D_H/D_*, then the parallax variance due to the distance dispersion of the cluster stars can be distinguished from the remaining variance, due to observational error. It was found that 30% of the total parallax variance was due to the distance dispersion, and the RMS error of an individual Hyades parallax was found to be only 0ʺ.0075. This is twice the precision of a typical GCTSP parallax (Upgren and Carpenter 1977). To take full advantage of the high precision of the Hyades parallaxes, the regression of absolute parallax on D_H/D_* was calculated and the parallax value corresponding to unit relative distance (i.e., the cluster center distance) was determined. The parallax results from the General Catalogue observatories are summarized in the first row of Table 1.

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New parallax observations are now available from four observatories participating in the program to observe faint Hyades members near the cluster center from the van Altena (1973) list. Here I have taken each observatory separately to test for systematic errors, and to assess the precision of the parallaxes. The external errors and absolute zero point for each observatory were studied using the statistical techniques described by Hanson (1978), and, in the case of Lick Observatory, by detailed comparison of the nearly 60 stars in common between the Lick (Vasilevskis, et al. 1975) and US Naval Observatory (Harrington, et al. 1978) programs. Several observatories have observed faint Hyades stars additional to the van Altena (1973) list. For these additional stars, only those having Hyades membership confirmed by van Altena (1969) and Hanson (1975) were included in the present study. The van Altena (1974b) corrections to absolute were applied to all the new parallaxes. Since the van Altena (1973) stars are all near the cluster center distance, the procedure used to allow for the distance dispersion in the GCTSP parallaxes need not be applied here. Rather, for each of the four observatories a weighted mean Hyades parallax was formed, using the external error estimates found in the present study. No significant systematic differences were found among the four observatories. The remainder of Table 1 summarizes the new Hyades parallax results (57 determinations, for 27 stars).

The weighted mean parallax from all 101 observations of 55 Hyades members results in a cluster distance modulus m - M = 3.25 ± 0.08 mag. (Throughout this paper, the formal error of a mean quantity will be given as the larger of the internal and external standard errors of the mean.) This is nearly twice as precise as the previous parallax result summarized by van Altena (1974a), due to the increased precision of the classical parallaxes on the new Yale Catalogue system, as well as to the additional data incorporated in the present result. The excellent agreement among the individual sources, and the stability of the mean Hyades parallax when subjected to various treatments of the data, give confidence that the formal standard error of the mean reliably represents its true external error.

3. PROPER MOTIONS

Historically, the most important means of measuring the Hyades distance has been the convergent-point method, which uses proper motions to measure the perspective effect of the Hyades' recession from the Sun. When this "convergence" of the proper motions, in angular units, is compared with the cluster radial velocity, the Hyades distance immediately follows (Upton 1970, Hanson 1975). Only the simple, observationally verifiable geometry of the cluster motion needs to be assumed. The classical (Wayman, et al. 1965) method locates the actual convergent point of the proper motions on the sky. This allows a star's transverse velocity to be determined; the ratio of this to the observed proper motion yields the distance, for each star in the cluster. Alternatively, the perspective effect can be measured directly

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TABLE 1. HYADES TRIGONOMETRIC PARALLAX SUMMARY. PARALLAX UNITS ARE 10^{-3} ARCSEC.

Source Observatory	Reference	$\langle \pi_{ABS} \rangle \pm \sigma$		Number of Stars N	Number of Observations	Typical Precision $\sigma\sqrt{N}$	$(m-M)_H \pm \sigma$		NOTES
General Catalogue Observatories	Jenkins (1963)	22.23	1.41	28	44	7.47	$3^m.26$	$0^m.14$	Parallaxes combined according to new precepts. Regression of π on (D_H/D_*) used.
Lick	Klemola et al. (1975)	22.63	1.52	18	26	6.46	3.23	0.15	External errors from U.S. Naval Observatory comparison.
Van Vleck	Upgren (1974 a)	22.10	1.87	10	14	7.00	3.28	0.18	$\sigma_{EXT} = \frac{1}{2}(\sigma_{INT})$ + CONST.
Herstmonceux	Scales (1979)	24.00	3.42	5	5	7.64	3.10	0.31	
Cambridge	Argue and Kenworthy (1972)	18.50	6.46	12	12	22.39	3.66	0.76	$\sigma_{EXT} = \sigma_{INT}$
MEAN		22.38	± 0.87	(Total) 55	(Total) 101		$3^m.25$ ±	$0^m.08$	cf. van Altena (1974a) $3^m.26 \pm 0^m.14$

TABLE 2. HYADES DISTANCE MODULUS FROM NEW PROPER MOTIONS

Reference	Source	Hyades Stars	Magnitude Range	$(m-M)_H$	$\pm \sigma$	NOTES
Hanson (1975) (corrected for magnitude effect in bright stars)	Lick Astrograph proper motions with respect to galaxies	140 in central $6^\circ \times 6^\circ$ field	8 - 18	$3^m.42$ $\underline{3.37}$	$0^m.20$ $\underline{0.18}$	Proper motion gradients solution
Hanson (1977)		200 (4 outer fields)	10 - 18	$\underline{3.32}$	$\underline{0.06}$	P.M. gradients re-calculated for this review.
Corbin, et al. (1975) Carpenter (1977)	AGK3R Meridian circle proper motions	150	4 - 9	$\underline{3.19}$ 3.27	0.04 (internal) $\underline{0.1}$: (external)	Convergent point solution
Morris (1979)	Palomar Schmidt proper motion survey	200 (16 fields)	10 - 19	$\underline{3.66}$	(internal) 0.04 $\underline{0.2}$: (external)	Convergent point solution; preliminary membership segregation
WEIGHTED MEAN				$3^m.31 \pm 0^m.06$		Values underlined are used in forming the weighted mean.

from the cross-cluster gradients of the proper motions in either observational coordinate (Upton 1970). Given the cluster radial velocity this yields two independent Hyades distance measurements, which serve as a useful check against systematic errors in the proper motions (Hanson 1975).

The Hyades proper motion data fall into two distinct categories: (a) For bright ($m \leqslant 9$) stars, the proper motions are visually observed with meridian circles. The van Bueren (1952) and Wayman, et al. (1965) Hyades proper motions are the classic examples. The most modern meridian circle proper motions are those determined by Corbin (1974) for the AGK3R northern hemisphere reference star system. (b) For faint ($9 \leqslant m \leqslant 20$) stars, photographic proper motions must be used. The most recent Hyades data have been obtained by Hanson (1975, 1977) from the Lick Astrograph proper motion survey plates, and by Hill and Morris (1976) from the Palomar Schmidt plates.

Each type of proper motion data requires a somewhat different method of analysis. For the bright stars having meridian circle proper motions, radial velocities are available so that the Hyades membership of each star can be settled definitively. The proper motions are nominally absolute, but regional systematic errors are important (Hanson 1975, Corbin 1979) and in practice may limit the accuracy of the Hyades distance determination. The photographic proper motions of the faint stars can be reduced to a uniform absolute system, either by using external galaxies as reference objects (as on the Lick plates), or by allowing for the secular parallaxes of the reference stars (Morris 1979). A chief problem is the segregation of the faint cluster members from the field stars. For an individual star, the cluster membership cannot be determined definitively from the proper motion alone; all that can be expressed is the probability that a star with a given proper motion is a member of the cluster, and not a field star (Vasilevskis 1962). With sufficiently precise proper motions, Hyades cluster members can be segregated from the field with better than 90% probability (van Altena 1969, Hanson 1975). However, for very faint stars ($m \gtrsim 16$), the number of field stars with any given proper motion rises so rapidly that clear segregation of the faintest Hyades stars from the field may not be possible. This problem becomes particularly severe far from the cluster center (Morris 1979).

The recent Hyades proper motion programs and their results are summarized in Table 2. The meridian circle results are preliminary (Carpenter 1979) and may be uncertain due to regional systematic errors in the proper motions (Corbin 1979). Carpenter, et al. (1975) found that the proper motions suggest an elongation of the Hyades, nearly in the line of sight. This conflicts with other observations (van Bueren 1952, Pels, et al. 1975), and points strongly to the existence of systematic errors in the meridian circle proper motions. For this reason, the formal error of the Corbin, et al. (1975) Hyades distance is likely to be a substantial underestimate of the true error;

in Table 2 I have assigned these results an error estimate appropriate to the likely size of these systematic errors. For this review, the Lick proper motions (Hanson 1975, 1977) have been subjected to a detailed examination of internal, external, and systematic errors. Except for the slight systematic apparent magnitude effect in the brightest ($m \simeq 9$) stars' motions, reported by Hanson (1976), no significant effects have been found. The Lick proper motions have been analyzed in both coordinates by the proper-motion gradient method, to provide another check against systematic errors. The Palomar Schmidt proper motions have been subjected to a preliminary cluster membership segregation and convergent-point solution by Morris (1979). The discordant Hyades distance result seems due to contamination of the convergent-point solution by faint non-members. This would dilute the apparent convergence of the Hyades motions, giving a spuriously large cluster distance. The convergent point (Morris 1979) of the Palomar Hyades motions is displaced toward the solar antapex; the mean Hyades proper motion is displaced toward the field star distribution in the proper motion diagram (Hanson 1975, Morris 1979). Both these effects represent additional circumstantial evidence that the segregation of faint Hyades stars from the general field has not yet been adequately accomplished for the Palomar data. Hence the preliminary Hyades distance result obtained by Morris (1979) must be viewed with caution and has been assigned low weight in Table 2.

The interagreement among the proper motion results is about as close as could have been expected from the external errors of the individual determinations. The Lick proper motions carry most of the weight in the mean Hyades distance modulus (Table 2), reflecting the preliminary nature of the AGK3R and Palomar Schmidt results. The mean value $m - M = 3.31 \pm 0.06$ mag is much more precise than the previous results summarized by Hanson (1975), owing to the new observational data in the outer regions of the cluster.

4. DISCUSSION AND CONCLUSIONS

The principal result of this review has been the finding that direct astrometric determinations of the Hyades cluster distance, from trigonometric parallaxes and proper motions, are now rather more precise than previous results. This reflects the substantial recent progress in both fields of observation. The weighted mean of all determinations reviewed here results in a Hyades distance modulus $m - M = 3.30 \pm 0.04$ mag, corresponding to a distance of $D_H = 45.6 \pm 0.9$ pc. The systematic and accidental errors of the observations have been assessed critically by a variety of methods, giving reason for confidence that the formal error of the mean represents a realistic estimate of the present uncertainty of the Hyades distance. Thus the precise result obtained should serve as a strong basis for cosmic distance scale calibrations and for comparison with other observational, and theoretical, results.

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The classical (van Bueren 1952, Wayman, et al. 1965) Hyades distance modulus m - M = 3.0 mag is definitively excluded by the modern astrometric observations. It is worth pointing out that the reasons for the 0.3 mag error in the classical Hyades modulus are now well understood: (a) Serious systematic errors were present in the old meridian circle proper motions (Hanson 1975), and no suitable photographic proper motions were available to check the meridian circle results. (b) The General Catalogue trigonometric parallaxes (cf. van Altena 1974a) were insufficiently accurate to support or confute the proper motion results. (c) The field main sequences calibrated from large trigonometric parallaxes (e.g., Eggen 1969) and then used to check the Hyades distance suffered systematic calibration errors due to the observational errors in the parallaxes (Lutz and Kelker 1973); for the parallax stars used these errors amounted to 0.2 to 0.4 mag (Upgren 1974b, Hanson 1979), subtly concealing the Hyades distance error, which coincidentally was of nearly equal size.

Finally, several prospects for further improvement in the Hyades distance measurements may be noted. Improved radial velocity data for faint Hyades stars (Griffin and Gunn 1974) will assist in determining cluster membership and improve the convergent-point determinations of the Hyades distance. Photoelectric photometry of faint Hyades proper-motion candidates (Upgren and Weis 1977) will also aid membership assessment for these stars. In the coming decade, astrometric data from space (Høg 1979, Murray 1979) may improve the Hyades parallax precision by roughly a factor of two. With continued progress in ground-based astrometry as well, the long era of uncertainty over the Hyades distance seems to be coming to a close.

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DISCUSSION

LYNGA: Thank you very much. It was a great pleasure to listen to this very accurate stuff. Comments?

KING: As a matter of historical interest, I'd like to ask what value Hodge and Wallerstein quoted when we all knew that they were crazy?

HANSON: 3.42, I recall.

KING: 3.42? So you've gone about two thirds of the way there.

HANSON: They weren't as crazy as people thought.

BROSCHE: What kind of motions do you assume to determine the convergent point? I mean, is it just the mean space motion plus isotropic noise?

HANSON: The assumption is, essentially, that all the stars have the same space velocity and this is verified empirically since we know the internal motions are much too small to be measured either from the proper motions or from the radial velocities. With future, more accurate data the internal motions will be important, but for these studies they are not.

HARRIS, W.: How accurate are the present radial velocities and what kind of accuracy would you like to see?

HANSON: The present radial velocities are certainly good enough to help determine the membership of the bright stars. Of course, any systematic error in the radial velocities would propagate directly into a systematic error in the Hyades distance. I am not suggesting there is such an error, but since the distance would be sensitive to such an error, one needs to keep it in mind.

VAN LEEUWEN: If you are giving the distance of the Hyades with an accuracy of 0.9 pc and you know the cluster itself has a diameter of the order of 20 to 30 pc, shouldn't you then give the distance for a certain group of stars and say that that is the mean distance for those stars, because that's what you actually did?

HANSON: You can, of course, determine the individual distances now for all of the stars. The Hyades distance that I quoted is the mean distance of the several hundred stars that have been measured.

VAN LEEUWEN: In the table that you gave for the different catalogues, did you determine a mean for that parallax from the mean determinations of the parallaxes for the individual stars and collect them that way? Or did you determine the mean of the parallaxes determined for each of those catalogues?

HANSON: Well, I can answer it directly from my own work, and refer to Dr. Morris for his work. For my own work I used a direct determination of the mean distance of all the stars by the proper motion gradient method, which essentially says that the mean distance is the ratio of the mean radial velocity at the cluster center to the proper motion gradient of all the stars. So that formally gives a quantity that determines the mean distance directly.

MAEDER: A mean of parallaxes does not give you the same center as a mean based on distance moduli or a mean defined on the mean distances. What is the size of these effects for the Hyades?

HANSON: These effects are very small compared to the observational errors. In the case of the trig parallaxes, the parallax itself is the directly observed quantity; so I took the mean of the parallaxes and then translated that into the distance modulus. I did not calculate individual distance moduli and form the mean of those. Such a procedure would be invalid in principle; in practice, however, the result would have been much the same.

BOK: But the mean parallax always gets you closer to home than the mean distance?

HANSON: In this case the effect is really quite small, because the . . .

BOK: No, what is the depth of the Hyades?

HANSON: The depth of the Hyades is on the order of 10% of the distance; but it's such that, and this is the important point, it is barely visible in the Gaussian observational errors.

BOK: I don't know. If you have, after all, a certain distance, then the mean parallax gets closer in and the mean distance gives a distance farther away. Is that so small?

HANSON: Quantitatively, the point is that the mean parallax is about 0.020 seconds of arc. The distance scatter is about 10% of that, which amounts to about 0.002 seconds of arc. Errors of even the best parallaxes are only about 0.005 seconds of arc, so that even for most of the data taken into the calculation the observational errors dominate over the effect of the distance in the cluster, so we are not making an appreciable error by assuming the dispersion is Gaussian.

LYNGA: Can I just make a point? The other association or cluster we used to rely on a lot is Scorpius-Centaurus; can you think about the general revaluation of the distance to that?

HANSON: Yes, this would be possible. This is a difficult problem; the distance is very sensitive to systematic errors in the proper motions, as Derck Jones of the Royal Greenwich Observatory has emphasized. I believe that Jones is still interested in redetermining the Scorpius-Centaurus distance.