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THE DISTANCE TO THE HYADES CLUSTER*

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The results of numerous investigations of the distance to the Hyades cluster are reviewed. The principal result is that *all* "secondary" distance indicators yield distance moduli greater than those determined from proper motions. A weighted value of $(m-M) = +3.21 \pm 0.03$ (s.e.) is adopted as the best present distance modulus for the Hyades cluster.

Key words: star cluster — stellar distances

I. Introduction

The Hyades cluster, being the nearest moderately rich cluster, provides us with, (1) the zero point for our galactic distance scale, (2) through the cepheids in open clusters it also gives a zero point for the extragalactic distance scale, and (3) forms the basis for determining the luminosities of supergiants, OB stars, and peculiar stars in clusters. The distance to the Hyades has for many years been based solely on the convergent-point method until Hodge and Wallerstein (1966) suggested that the cluster was located some 20% farther from the sun than indicated by the proper motions. Since that time an enormous effort has been put into examining various methods for determining the distance to the Hyades. In this paper I have attempted to review the various methods and have adopted a revised distance modulus which will hopefully serve as a better approximation to the true value than the proper-motion value. In approximately three years new material should become available that will yield nearly definitive results for the Hyades' distance modulus.

I have not felt it appropriate or necessary to reproduce figures or tables from other publications, therefore the only figures appearing here relate to new results derived for this review or a different way of looking at old results.

II. Methods Used for Determining the Hyades' Distance Modulus

A. *Proper Motions*

A1. The Convergent Point or Moving Cluster

The convergent-point method has traditionally been the principal means used for measuring the Hyades' distance modulus because of its directness, high internal accuracy, and independence from assumptions concerning the "normality" of the Hyades' stars. The main assumptions invoked in determining the convergent point for a moving cluster are (1) the cluster is neither expanding nor contracting, (2) the motion of the cluster is large enough to permit accurate membership determination, and (3) the system of proper motions is inertial and without any systematic errors. The Hyades cluster seems to satisfy the first two criteria adequately, but our knowledge of the proper-motion system is incomplete at this time which should make us cautious in interpreting the results based on proper motions.

The two solutions for the convergent point currently used are due to van Bueren (1952) and Wayman, Symms, and Blackwell (1965), who obtained, respectively, 3.03 ± 0.06 and 3.05 ± 0.09 for the distance modulus, where the errors and all that follow are standard errors. The excellent agreement between the two investigations has led, in my opinion, to unwarranted confidence in the quoted distance modulus, since both use nearly the same proper-motion system. Wayman (1967) has analyzed the potential sources of systematic error in the convergent-point method and derives a value of 0^m18†, which he considers an extreme error.

*A review paper prepared for IAU Commission No. 33, August 1973.

†This number is derived from Wayman's (1967) figures by taking the square root of the sum of the squares of his three sources or error.

A2. Proper-Motion Gradients

The moving-cluster method may be looked at in another manner by considering the change in apparent dimensions of the cluster as it recedes from the sun. A knowledge of the change in proper motion with increasing right ascension or declination and the radial velocity of the cluster yields the distance modulus. Upton (1970) analyzed the Hyades cluster using the proper-motion gradient method and obtained $(m-M)_{\mu\alpha} = +3.01 \pm 0.09$ and $(m-M)_{\mu\delta} = +3.14 \pm 0.07$, or $+3.09 \pm 0.06$ for the weighted mean. The fair agreement between the right ascension and declination solutions may indicate that the proper-motion systems in the two coordinates are not radically different. On the other hand, we expect, and find, the weighted mean value to agree with those cited in section A1 due to the similarity of the proper-motion systems.

A3. Proper-Motion Vector Intersections

When Clube (1973) examined the sky near the Hyades' convergent point he noted that the converging proper-motion vectors intersect in an area covering 15 × 10 degrees, even though all 132 stars are considered probable members by van Bueren (1952). Selecting a subset of 52 stars considered by Wayman et al. (1965) as main-sequence members yields a convergent point closer to the cluster and therefore a smaller distance (27 pc) to the Hyades. Conversely, the other 80 equally probable members would yield a larger distance. Clube's technique of seeking the mode of the proper-motion vector intersections seems well suited to this problem, however the broad, irregular distribution of intersections suggests that errors are present in the proper motions that are substantially larger than the quoted accidental errors. These postulated errors may vitiate the results from all investigations of the Hyades cluster using fundamental proper motions. For this reason it is important to investigate all secondary distance indicators, and this is done in the following sections.

B. *Trigonometric Parallaxes of Hyades Members*

B1. The Yale *Parallax Catalogue*

The use of trigonometric parallaxes offers the most straightforward method for determining the Hyades' distance modulus, however, the small size of the parallaxes makes them more susceptible to systematic errors. Nevertheless, a fairly large number of Hyades stars have had their trigonometric parallaxes determined so that the accidental errors can be reduced to a reasonable level and provide useful results. The weighted mean parallax for 30 Hyades members listed by Eggen (1967)* from the Yale *Parallax Catalogue* is $\pi_a = +0\overset{''}{.}0226 \pm 0\overset{''}{.}0019$ (s.e.) resulting in a distance modulus of $(m-M) = +3.23 \pm 0.19$.

B2. New Hyades Trigonometric Parallaxes

In 1969 I provided a list of 20 very probable Hyades members to several observatories for the purpose of determining a new parallax for the Hyades cluster. This list has since been published in the *Proceedings of IAU Symposium No. 53,* van Altena (1972). The first results from the seven participating observatories have just been published by Upgren, Kerridge, and Mesrobian (1973). The new Van Vleck Observatory relative parallaxes for 16 stars in seven fields were made available to me by Dr. Upgren for analysis and presentation of the results here. Due to the small parallax of the Hyades cluster, the correction to absolute parallax was reevaluated using the new values discussed in the IAU Commission No. 24 meetings, van Altena (1973), which for the Hyades region of the sky at $V = 10.90$ is $+0\overset{''}{.}0034$. Before computing the weighted-mean parallax, two stars were eliminated, one because its membership is doubtful since it would be neither a main-sequence nor a white-dwarf member and the second star because its parallax is more than three times as large as the average parallax. The resulting weighted-mean relative parallax for the 14 remaining stars is $\pi_r = +0\overset{''}{.}0185 \pm 0\overset{''}{.}0019$, or $\pi_a = +0\overset{''}{.}0219 \pm 0\overset{''}{.}0019$ which yields a distance modulus of $(m-M) = +3.29 \pm 0.20$.

The Yale *Parallax Catalogue* values and the new Van Vleck parallaxes are shown in Figure 1 where the individual values and their standard errors are plotted. The remarkably close agreement between the average values suggests that there are no serious systematic errors present in the results. The average distance modulus obtained from trigonometric parallaxes is $(m-M) = +3.26 \pm 0.14$.

*The listed parallax for YPC 1084.0 was corrected before computing the average, van Altena (1969).

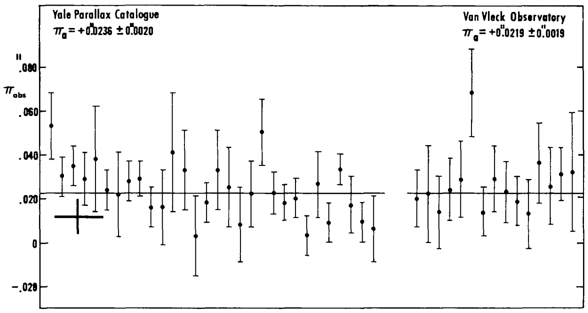

FIG. 1 — Absolute trigonometric parallaxes and their standard errors of Hyades stars from the Yale *Parallax Catalogue* are plotted on the left side and new parallaxes determined at the Van Vleck Observatory are plotted on the right side. The weighted mean YPC parallax is $\pi_a = +0\overset{''}{.}0226 \pm 0.0020$ (s.e.), while that for the VVO is $\pi_a = +0\overset{''}{.}0219 \pm 0\overset{''}{.}0019$ (s.e.) where the VVO point at $\pi_a = 0\overset{''}{.}068$ has not been included in the average.

C. *Dynamical Parallaxes*

The Hyades binaries were first shown to be undermassive for their luminosities by Kuiper (1938), and more recently by Eggen (1967). An analysis of the visual measures by Worley (1970) and Alexander (1968, 1972) resulted in the conclusion that no serious trends or changes in measuring procedures by the observers have affected the resulting orbits. Alexander (1968) has shown that the derived masses are very sensitive to the choice of the orbit and the star's proper motion, which results in a rather poorly determined mass-luminosity relationship for the Hyades cluster, however, the Hyades visual binaries appear to be slightly undermassive at the conventional distance modulus. On the other hand, Wallerstein and Hodge (1967) assumed normal masses for the five Hyades binaries and computed dynamical parallaxes for them resulting in an average value of $(m - M) = +3.25 \pm 0.12$, where the standard error is derived from the scatter in the five moduli.

Some support for the assumption of normal masses comes from Batten and Wallerstein's (1972) analysis of the Hyades double-lined spectroscopic binary HD 27149 whose components lie on the Hyades main sequence. Their well-determined spectroscopic orbit yields *minimum* masses of $1.04\,\mathfrak{M}_\odot$ and $0.91\,\mathfrak{M}_\odot$ in agreement with the observed spectral types of G2 V and G8 V, but in sharp disagreement with the masses predicted by the "Hyades mass-luminosity relationship", $0.6\,\mathfrak{M}_\odot$ and $0.5\,\mathfrak{M}_\odot$. In addition, Young and Nelson (1972) have analyzed the Hyades eclipsing binary BD $+16°516$ which consists of a K2 dwarf and a white dwarf. Adopting a normal mass and radius for the K2 star, $0.80\,\mathfrak{M}_\odot$ and $0.85\,R_\odot$, they compute lower limits to the mass and radius for the white dwarf of $0.79\,\mathfrak{M}_\odot$ and $0.01\,R_\odot$, which are in agreement with the Hamada and Salpeter (1961) mass-radius relationship for pure helium white dwarfs. If the "Hyades mass-luminosity relationship" were used then the adopted mass for the K star would be $0.30\,\mathfrak{M}_\odot$ resulting in a derived mass for the white dwarf in substantial disagreement with that theoretically predicted.

The above two discrepancies with the "Hyades mass-luminosity relationship," when coupled with the fact that it is not possible to build a self-consistent stellar interior model (see section II F) for these stars, lend some support for the dynamical parallaxes computed by Wallerstein and Hodge (1967).

D. *The Ca* II *K-Line Absolute Magnitudes*

The Wilson-Bappu effect provides a means for estimating the distance modulus of the Hyades cluster once the relationship has been calibrated by stars with known trigonometric parallaxes. The calibration problem has been examined by Wilson (1967), Wallerstein (1967), and Lutz (1970) with the latter deriving a distance modulus for the Hyades of $(m - M) = +3.23 \pm 0.25$. Helfer (1969) and Pagel and Tomkin (1969) have stressed the existence of a correlation between M_v and [Fe/H] which will effect the distance derived for the Hyades cluster. Helfer (1969) finds that after correcting for the metal-abundance effect that $(m - M) = +3.25 \pm 0.20$.

E. *Photometric Parallaxes*

The principal problems with the determination of photometric parallaxes are the evaluation or elimination of differential metal abundance and evolutionary effects and the reduction of cosmic scatter. The following investigations attack these problems each with a different photometric system and they can therefore probably be considered as independent determinations of the distance modulus.

E1. The *UBV* System

Upton (1971) selected 28 disk-population stars with parallaxes $\geqq 0''.080$ and standard errors less than 1/8 the parallax in the range G8–K3 and $0.70 \leqq (B-V) \leqq 1.00$ for his analysis of the Hyades' distance modulus. After obtaining the ultraviolet excess and the absolute-magnitude difference between the field stars and the mean Hyades relation at the same $(B-V)$, a plot of these two quantities, ΔM_v vs. $\delta(U-B)$, led to $(m-M) = +3.19 \pm 0.06$ for the Hyades where $\delta(U-B) \equiv 0.00$.

E2. The $(R-I)$ System

The $(R-I)$ color index is not too strongly affected by differing metal abundance and seems to be a good temperature indicator for the later-type stars. Eggen (1969) compared the M_I vs. $(R-I)$ diagrams for 25 young field red dwarfs whose parallaxes and errors yielded standard errors in the absolute magnitude of $< 0^m.22$ and 24 red Hyades dwarfs. Using all stars, a distance modulus of $(m-M) = +3.06 \pm 0.06$ was obtained, while when the selection was restricted to $(R-I) < 1.00$ to eliminate possible evolutionary effects $(m-M) = +3.13 \pm 0.06$ was obtained. It seems unlikely that evolutionary effects are present so an average of the solutions has been adopted. However, there is a zero-point difference of $0^m.02$ between Eggen (1968) and Eggen (1969) that leads to an uncertainty of around $0^m.1$ in the absolute magnitudes, hence the $(R-I)$ results should be viewed with caution.

E3. The Stebbins and Whitford Six-Color System

Sears and Whitford (1969) have compared observations on the six-color system of eight field stars with large parallaxes and 16 Hyades stars in the M_v vs. G-I diagram, which has been shown to be a good analogue to the theoretical H-R diagram. Their observations for $M_v > 5.2$, where evolutionary effects should be unimportant, yield $(m-M) = 3.16 \pm 0.07$.

E4. The Geneva Observatory Seven-Color System

Golay (1972) has shown that when all seven colors in the Geneva system for two stars are equal to within $0^m.01$ then the stars are similar and the difference in apparent magnitude may be used to compute the distance difference very accurately. Comparing the Hyades and Praesepe stars he finds $\Delta(m-M) = 3.00 \pm 0.05$ and then through comparison with five nearby stars with colors equal to an individual Hyades or Praesepe star, the Hyades distance modulus is found to be $(m-M) = +3.28 \pm 0.20$, where I have utilized revised parallaxes and computed the error from the rms scatter among the five star pairs.

E5. The *BVr* System

Mannery and Wallerstein (1971) have shown that $(V-r)$ is a good indicator of effective temperature and have compared their observations of 38 single stars, with $\pi > 0''.080$ and errors 1/7 of the parallax or less, with 24 Hyades stars. A least-squares solution on the straight-line portion $(0.6 < (V-r) < 1.4)$, which is presumably unevolved yields $(m-M) = +3.25 \pm 0.10$.

E6. The Strömgren Four-Color System and White Dwarfs

An inspection of Figure 4 in Eggen and Greenstein (1965) shows that after eliminating the Hyades nonmember white dwarfs the remainder lie below the field white dwarfs in the M_v vs. $(U-V)$ diagram. An analysis of the M_v vs. $(B-V)$ diagram using improved parallaxes for many new stars yielded $(m-M) = +3.23 \pm 0.12$ for the Hyades distance modulus (van Altena 1969). Graham (1972) has shown that when one plots M_v vs. $(b-y)$ for the white dwarfs, a single sequence results instead of the double sequences in the $(U-V)$ plot. Figure 2 shows a plot of M_v vs. $(b-y)$ for all white dwarfs using all available parallaxes. The resulting distance modulus is $(m-M) = +3.25 \pm 0.08$.

E7. Photometric Parallax Summary

The six investigations cited above all indicate a correction to the distance modulus ranging from $0^m.11$ to $0^m.23$ after eliminating the $(R-I)$ solution from consideration. The $(R-I)$ photometry has high potential for determining the distance modulus, but it will be necessary to clarify the zero-point differences noted in section E2. The weighted mean of the remaining five solutions yields $(m-M) = +3.21 \pm 0.04$.

F. *Stellar-Interior Calculations*

Iben (1963) and Bodenheimer (1965) first pointed out that stellar-interior models were unable to simltaneously fit the Hyades mass-luminosity relation and the color-absolute magnitude diagram. Since then, it has been shown for the

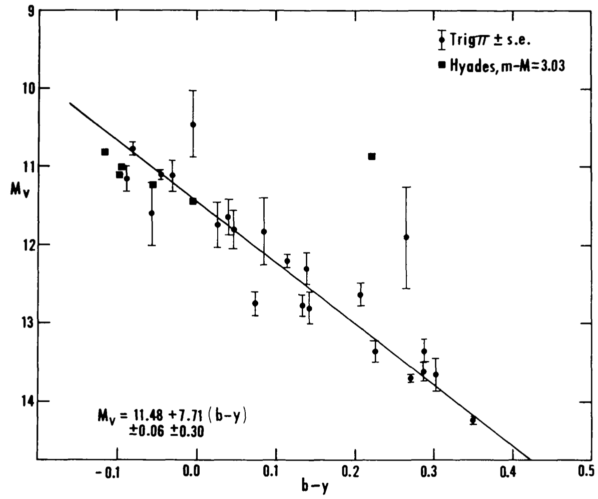

FIG. 2 — The M_v vs. $(b-y)$ diagram for field white dwarfs with parallaxes and Strömgren photometry by Graham (1972) and six Hyades white dwarfs. A weighted least-squares fit to the relation yields $M_v = 11.48 + 7.71(b-y)$ thus giving a distance modulus for the Hyades of $(m-M) = +3.25 \pm 0.08$ (s.e.), where the Hyades white dwarf lying far above the relation was not included since it is composite (DA + dMe).

Hyades cluster by Faulkner (1967), Demarque (1967), Wallerstein and Hodge (1967), and Koester and Weidemann (1973) that given the spectroscopically observed metal abundance, the color-magnitude diagram and the relation between V and log $\mathfrak{M}$ that a self-consistent set of main-sequence stellar models can be computed for $(m-M) = +3.24$, but not for any other significantly different value. On the other hand, Iben (1967), using similar arguments came to the conclusion that agreement between theory and observations could be achieved for $(m-M) = 3.40$.

Iben and Tuggle (1972) examined in detail the apparent discrepancy between the pulsation and evolution masses for cepheid variables. Adopting data for 13 cepheids in open clusters and analyzing their observed and predicted positions in the mass-luminosity, magnitude-period, and magnitude-temperature planes, they found internal consistency if the cepheids were made brighter by 0^m25 to 0^m3, which, if due to an error in the Hyades distance alone, would yield $(m-M) = 3.28$ to 3.33. Iben and Tuggle's predicted distance modulus for the Hyades may not be strictly applicable since as they point out, the cepheid luminosities are based on ZAMS-fitting far up the main sequence and include errors made in forming the ZAMS from the Hyades, Pleiades, etc. Nevertheless it is in the same direction as all other secondary distance indicators.

TABLE I

THE HYADES DISTANCE MODULUS

Method	m-M ± s.e.	Weight
A. Proper motion		
1. Convergent point	+3.05 ± 0.09	12
2. Gradients	+3.09 ± 0.06	28
B. Trigonometric parallaxes		
1. Yale Parallax Catalogue	+3.23 ± 0.19	3
2. Van Vleck Observatory	+3.29 ± 0.20	3
C. Dynamical parallaxes	+3.25 ± 0.12	7
D. K-line absolute magnitudes	+3.25 ± 0.20	3
E. Photometric parallaxes		
1. UBV	+3.19 ± 0.06	28
2. R-I	+3.10 ± 0.06	28
3. Stebbins & Whitford	+3.16 ± 0.07	20
4. Geneva	+3.28 ± 0.20	3
5. BVr	+3.25 ± 0.10	10
6. ubvy (white dwarfs)	+3.25 ± 0.08	16
F. Stellar interiors	+3.24 ± ?	
Weighted mean (A-E)	+3.16 ± 0.03	161
Weighted mean (B-E)	+3.19 ± 0.03	121
Weighted mean (B-E) (without E2)	+3.21 ± 0.03	93

III. Summary and Conclusions

The main results of section II are listed in Table I. The outstanding feature of this table is that *all* "secondary" distance indicators give greater distances than those derived from proper motions. At the present time it seems that the best distance modulus for the Hyades cluster is that obtained by taking the weighted mean of items B–E (without E2) to give, $(m-M) = +3.21 \pm 0.03$ s.e.

Within the next three years many more parallaxes for Hyades members will become available and a new convergent point based on proper motions with respect to faint galaxies being determined at the Lick Observatory by R. Hanson will be completed. These new results will give us a potentially much more accurate distance and will hopefully resolve the question of the true distance to the Hyades cluster.

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Note added in proof: Dr. A. R. Upgren (private communication) has recently observed 56 Hyades stars in the Kron $(R-I)$ system. He finds that a comparison of the new $(R-I)$ photometry with low W-velocity field stars yields a distance modulus of $+3.22 \pm 0.04$. The $(R-I)$ value is now in excellent agreement with the weighted average B-E (without $(R-I)$) $+3.21 \pm 0.03$. $\pm$ 0.03.