MAIN SEQUENCES DEFINED BY HYADES AND FIELD STARS

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1. INTRODUCTION

This paper reviews the main sequences defined by members of the Hyades cluster and by the field stars in the solar neighborhood. For this purpose, the discussion is limited primarily to the stars of the lower portions of the main sequence, especially those of spectral classes K and early M. There are two reasons for emphasis on the faint red dwarf stars. First, the value of a parallax depends on its size or, more accurately, on the error in parallax divided by the parallax itself. Large parallaxes of high precision occur in large numbers only for stars inhabiting the lower main sequence. Furthermore, brighter stars of earlier spectral classes are more likely to be influenced by evolutionary effects which may differ between the Hyades and field stars, and which are difficult to calibrate.

For these relatively cool red stars, it is well known that the (M_V, R-I) or (M_V, V-I) color magnitude diagram has a considerable advantage over the more conventional (M_V, B-V) diagram in determining the loci of main sequences. This is due to the linearity of the main sequence, at least over the K2-M2 spectral range, and also to the much lower sensitivity of (R-I) or (V-I) color indices to variations in metallicity than the (B-V) index, while remaining good indicators of surface temperature. This paper will concentrate on the photometric results in (R-I) since a considerable amount of observational data is now available, unlike (V-I), for both Hyades and field stars. The linearity was noted by Kron (1954, Kron et al. 1957) in his development of his R, I system of photometry, and later by Eggen and Greenstein (1965).

A. G. Davis Philip and D. S. Hayes (eds.), The HR Diagram, 39-48.

2. THE HYADES

Although photometry is a useful method of identifying members of a cluster such as the Hyades, and distinguishing them from field stars, photometry of stars which have been independently recognized by their proper motions as highly probable members, makes identification more certain since contamination by field stars becomes a problem especially at appreciable distances from the cluster center. Colors in the (B-V) and (R-I) systems are the only ones which cover a large number of the members found in the proper motion surveys by van Bueren (1952), for the stars with visual magnitude V generally brighter than 9^m, and by van Altena (1969) and Pels et al. (1975) for fainter stars. Many more stars with proper motions resembling the Hyades have been recognized, mostly through the work of Luyten (1971) but photometry is not yet available for them.

The photometric observations of Hyades members in the UBV system have been made by Johnson and his collaborators (Johnson and Knuckles 1955, Johnson et al. 1962) and extended by Upgren and Weis (1977). Observations in R and I were obtained by Eggen (1968, 1969) for a few of the Hyades identified in van Altena's proper motion study. Systematic differences between these two papers were noted and evaluated by Upgren (1974) and also by Eggen (1974) where revised values for Eggen's earlier observations are given. Upgren obtained (R-I) measures for 56 of van Altena's stars including all of those in the three papers by Eggen (Upgren 1974). Since then, Upgren and Weis (1977) have obtained BVRI photometry for the 119 newly identified members found by Pels et al. at Leiden. Some overlap occurs between the Leiden stars and the list of van Altena.

Other photometric systems have been used to measure the magnitudes of Hyades stars and to determine the distance to the cluster. The numbers of stars observed, especially those identified as members from their proper motions, is generally very small; some of these results are summarized by van Altena (1974) who shows that all but Eggen's (R-I) values lead to a Hyades distance modulus about $0\overset{m}{.}2$ larger than that of $3\overset{m}{.}05$ found by van Bueren (1952) from a convergent-point solution from proper motions. Since then, Hanson (1975) and Upgren (1974) have shown that the convergent-point method and the (R-I) sequence fit to field stars, respectively, also yield moduli of more than $3\overset{m}{.}2$.

3. THE FIELD STARS

The locations of main sequences defined by nearby field stars in color-magnitude diagrams are best determined from trigonometric parallaxes. However, care must be taken to avoid

https://doi.org/10.1017/S0074180900145231 Published online by Cambridge University Press

systematic errors introduced by a lower limit in parallax among the stars selected. Such an error can be introduced because the observed parallaxes are, on average, spuriously too large and the high-parallax tail of the frequency distribution of more distant stars will be erroneously included. Furthermore, Lutz and Kelker (1973) have shown that a systematic error is present in any set of observed parallaxes and have calibrated the necessary corrections to absolute magnitudes derived from parallaxes, including even the largest ones. Even the rather high lower limit in parallax of 0ʺ125, which has often been adopted in defining main sequences (e.g. Eggen 1968) introduces a systematic error of about $0^{m}_{\cdot}2$ according to Lutz and Kelker, since the true external mean errors in parallaxes, $\varepsilon(\pi)$, are well known to average about ±0ʺ016.

Lutz and Kelker show that the error in absolute magnitude is dependent upon the ratio $\varepsilon(\pi)/\pi$ and cannot be calibrated whenever this ratio is larger than about 0.2. (Investigations are now in progress which aim to extend the calibration to larger ratios but they are inconclusive at the present time.) The constraint imposed by this limit reveals the great value gained in decreasing the size of parallax error. A twofold reduction in $\varepsilon(\pi)$ leads to an eightfold increase in the volume of space over which the condition of $\varepsilon(\pi)/\pi < 0.2$ holds, and hence, an eightfold increase in the number of stars available for a determination of a main sequence. In recent years, the Van Vleck Observatory has become the first to achieve such a reduction in $\varepsilon(\pi)$ and apply it to obtain parallaxes of this precision for a large number of nearby dwarf stars. For more than 100 stars from Vyssotsky's lists of dwarf stars found spectrophotometrically (Vyssotsky 1963 and references therein) the Van Vleck parallaxes show a mean external error of only ±0ʺ008 (Upgren 1975). The mean position of the main sequence has been calculated for these stars and compares closely with the one found by Gliese (1969a, 1971) from his catalogue of nearby stars. For intervals of (R-I) the main sequence found from the Van Vleck parallaxes is given in Table I in the second column, and also in the third column after corrections are applied as determined by Lutz and Kelker. Gliese's (1971) sequence is also shown, in the last column, and is in close agreement with the previous column. The dispersion about the main sequence of dwarfs inhabiting the solar neighborhood has been shown to be about $\pm0^{m}_{\cdot}4$ by Upgren (1973) after the elimination of the component of dispersion produced by errors in the parallax determinations. The intrinsic dispersion of $\pm0^{m}_{\cdot}4$ is consistent with a more recent result of Veeder (1974) from a detailed analysis of bolometric magnitudes of similar stars. In his paper, Veeder notes that the intrinsic dispersion of the lower main sequence is about the same in the (M_V, B-V) color-magnitude diagram as it is in the (M_V, R-I) and (M_{bol},R-I) diagrams.

TABLE I. MEAN M_V, (R-I) RELATIONS FOR NEARBY DWARF STARS

(R-I)	Uncorrected Van Vleck	Corrected Van Vleck	Gliese
$0^m.35$	$7^m.0$	$6^m.6$	$6^m.5$
0.40	7.3	6.9	6.9
0.45	7.5	7.2	7.3
0.50	7.8	7.4	7.7
0.55	8.0	7.7	8.0
0.60	8.3	8.0	8.3
0.65	8.6	8.3	8.6
0.70	8.8	8.6	8.9
0.75	9.1	8.9	9.2
0.80	9.3	9.2	9.5
0.85	9.6	9.5	9.7
0.90	9.9	9.8	10.0
0.95	10.1	10.1	10.3
1.00	10.4	10.4	10.6
1.05	10.6	10.7	10.8

The main sequence and its dispersion are unlikely to be in error by any significant amount. However, they are derived from many red dwarfs in the solar neighborhood. Variations in the main sequence caused by differences in kinematical or chemical properties among the stars are much more difficult to measure. This is especially true for the (B-V) colors where the slope of the lower main sequence is very steep and where ultraviolet excess and line blanketing, so well known for the F and G dwarfs and subdwarfs, cannot be extended to the lower main sequence stars with confidence (see e.g. Greenstein (1965)). Among these fainter stars, the (R-I) colors are more likely to distinguish stars with differences reflecting differences in age, even though (R-I) is rather insensitive to stellar properties other than temperature, at least among the unevolved stars. The R and I indices are affected in an unknown manner by TiO blanketing since TiO bands extend beyond both of these colors. For stars later than about M0 (or (R-I) larger than about $0^m.7$), several investigators found high velocity dwarfs (which are likely to be old and metal deficient) to be fainter than their low-velocity counterparts of the same (R-I) color. The difference was considered by Kron (1954) to define a separate sequence. Greenstein (1965), Eggen (1968) and Gliese (1969b) have also detected the same difference, but none of these investigators included more than a few of the earlier K dwarfs which lie generally in the interval defined by $0^m.3 < (R-I) < 0^m.7$. Recently K dwarfs have been observed for (R-I) and from them Upgren (1972) found a dependence of the slope of the (M_V, R-I) main sequence upon the $|W|$ motion (the component of space motion perpendicular to the galactic plane). The slope is such that high-velocity K-dwarfs lie above the younger low-velocity dwarfs but for the

M-dwarfs the situation is reversed as Kron and others had reported. The influence of the $(U^2 + V^2)^{1/2}$ or planar motion was not as pronounced. More recently Eggen (1973) noted the same effect; his Fig. 1 shows the old-disk stars with a steeper slope than the young-disk stars with a crossover also near $(R-I) = 0^m.7$ or about dM0. It is not easy to make a direct comparison between Upgren's and Eggen's conclusions, because their definitions of young and old stars differ, but the trend is the same in both papers.

The identification of main sequences belonging to different stellar populations is even less certain when the population criteria are based on spectral or chemical differences. In the same paper, Eggen (1973) notes that the K-dwarfs of the halo population (identified as such by their motion) lie about one magnitude below the $(M_V, R-I)$ main sequence defined by young stars, specifically the Hyades. But among disk K-dwarfs of all ages, stars with greatly differing metal abundances reflected by ultraviolet excesses all define the same main sequence. Another indicator of age differences among K and early M dwarfs is the intensity of the emission component of the H and K lines of ionized calcium. Wilson and Woolley (1970) measured CaII emission intensities of 325 late main sequence dwarfs, 103 of which have recently determined Van Vleck parallaxes as well as photometric measures in the B, V, R and I colors. Fig. 1 shows a plot of these stars in the $(M_V, R-I)$ diagram. No significant difference appears between the three groups of stars of differing CaII intensities, although the groups reveal a very definite correlation between intensity and space motion, strongly suggesting a difference in age.

Despite the fact that the late-type dwarf stars in general define nearly the same main sequence, a few are known to be clearly subluminous in both the $(M_V, B-V)$ and $(M_V, R-I)$ diagrams. These include some whose space motion identifies them as belonging to the halo population (halo stars make up about one percent of the total number of nearby dwarfs). But there are also a few dK-M stars whose space motions are small. Eggen's (1971) review of red subluminous stars lists several stars whose (R-I) places them in the dK range and about one magnitude below the Hyades sequence. Two recent studies confirm that not all subluminous stars are halo members. Upgren and Weis (1974) discovered an M-type subdwarf which resembles Kapteyn's star, a well known high-velocity subdwarf, but with a low space motion of only about 25 km/sec. They list it along with 20 other sdM stars; of the ten with measured radial velocity, five have a space velocity less than 40 km/sec. Hartwick et al. (1976) discuss ten sdM candidates and identify eight as old-disk stars from their motions and only two as halo stars. Clearly the situation of subluminosity among K and M dwarfs is still a confused one, and must await more observations for clarification.

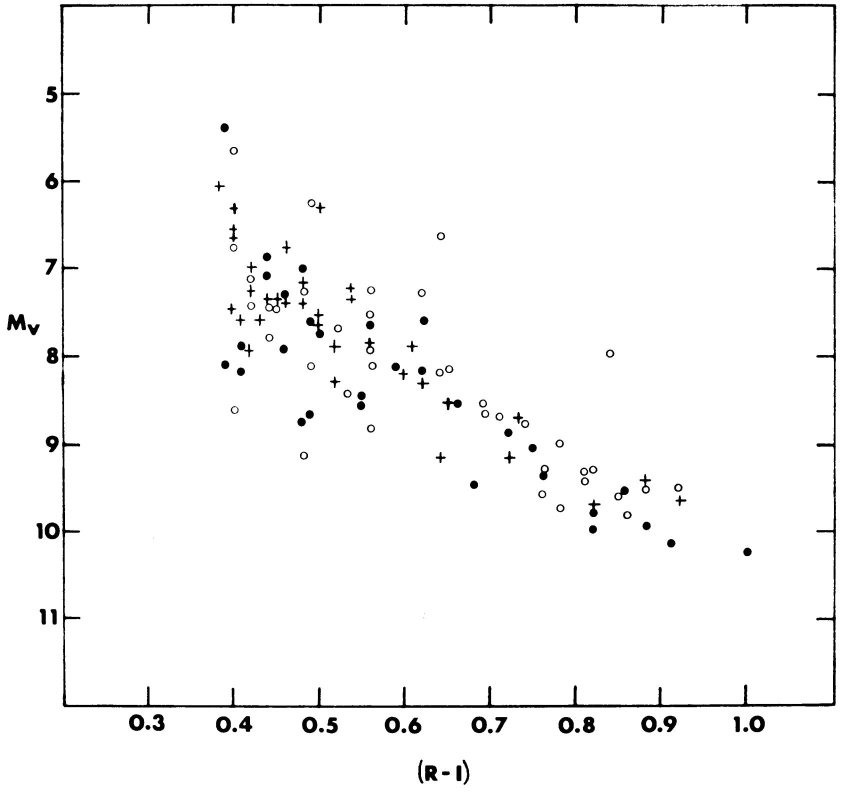

Fig. 1. The (M_V, (R-I)) diagram for stars of different CaII intensity. The 34 crosses, 39 open circles and 30 filled circles represent stars with intensities of +6 to +2, +1 to 0 and -1 to -4, respectively.

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4. COMPARISON OF HYADES AND FIELD-STAR SEQUENCES

Figs. 2 and 3 show the (V, B-V) and (V, R-I) color-magnitude diagrams for all 119 stars identified from their motions as Hyades members by Pels et al. (1975) along with 25 additional stars claimed by van Altena (1969) to be Hyades members also from proper motion data. The photometry is taken from Upgren (1974) and Upgren and Weis (1977) who include the photometry of Johnson et al. (1962) along with their own and take an average when both are available. Every star has the same symbol in both figures, except that some obvious non-members indicated by crosses in Fig. 2 do not appear in Fig. 3 since they were not observed for (R-I). The stars lying above the main sequence by an average in both diagrams of $0^m.5$ or more are shown as open circles and are most likely to be binary

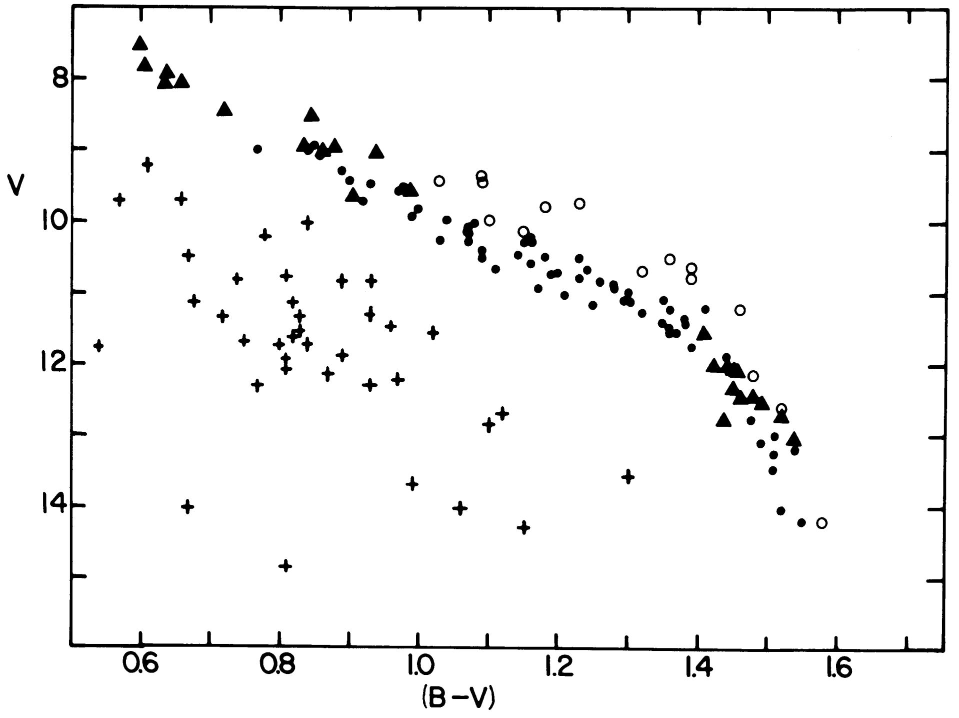

Fig. 2. The (V, B-V) diagram for stars identified as Hyades members from their proper motions. Filled circles and triangles are members according to Pels et al. and van Altena, respectively; open circles are probable binary members; crosses are non-members.

members although a few could be foreground stars. The 62 filled circles and 25 triangles, representing the remaining members from Pels et al. and van Altena, respectively, comprise the best representation of the Hyades main sequence in both diagrams.

A linear least-squares solution was made for the 72 stars lying on the main sequence in Fig. 3 which fall within the range $0^m.32 <$ (R-I) $< 1^m.08$, (after excluding the probable binary members). The resulting relation is V = $7^m.84$ + 5.68 (R-I), almost identical to the relation of V = $7^m.85$ + 5.67 (R-I) found in an identical way (Upgren 1974) from only 28 stars which then had photometric observations because they were taken from van Altena's (1969) list alone. The addition of many more members from the list of Pels et al. (1975) does not preceptibly change the Hyades main sequence, and indicates that the distance modulus of $3^m.22 \pm 0^m.04$, derived in the 1974 paper from the 28 van Altena stars, is not in need of revision.

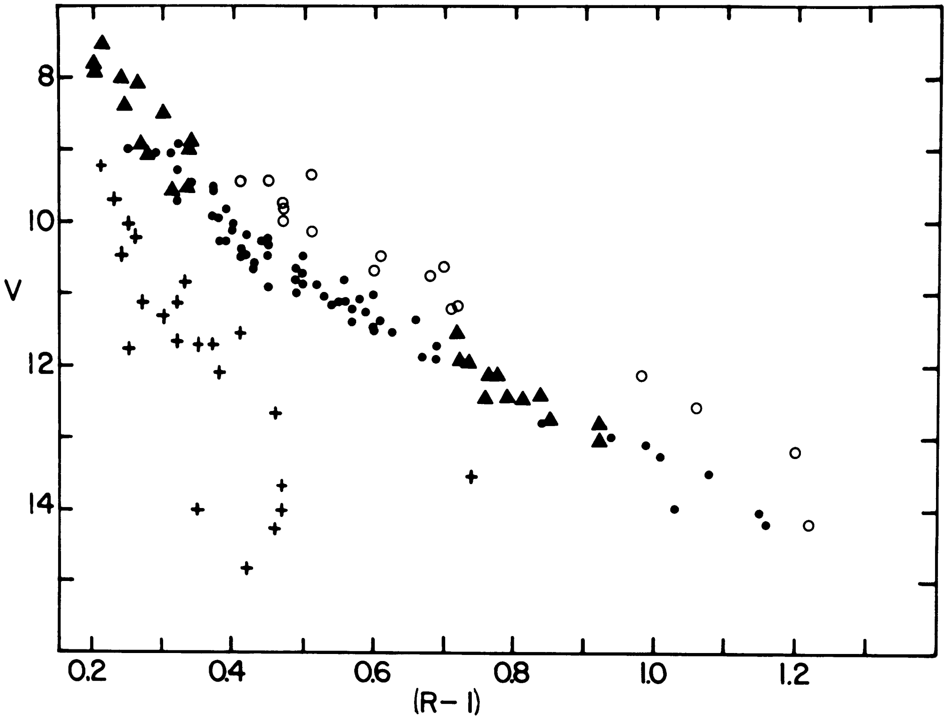

Fig. 3. The (V, (R-I)) diagram for stars identified as members from their proper motions. The symbols are defined in the same way as in Fig. 2. Each star has the same symbol as it has in Fig. 2.

This study was supported by the National Science Foundation through research grant no. AST74-00758 A03.

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https://doi.org/10.1017/S0074180900145231 Published online by Cambridge University Press

DISCUSSION

WEIDEMANN: Did you consider that even in (R-I) there may be differential blanketing effects shifting the sequences if there are abundance differences between the Hyades and the field stars (cf. Koester and Weidemann, Astron. Astrophys. 25, 473, 1973)?

UPGREN: For the young field stars, the difference should be very small.

LUYTEN: Concerning the alleged 115 NEW members of the Hyades Cluster announced by Pels and Oort about half of these were well known before, including some found and announced by Oort's teacher - van Rhijn.

Secondly, I might mention that Graham Hill of the Dominion Astrophysical Observatory came and processed twenty pairs of 48" Schmidt plates in the Hyades and Pleiades region with my automatic measuring machine - we now have 45000 proper motions for stars brighter than 20^m pg with mean errors of $0\farcs007$. But, in the Hyades, the more accurate your motions the more troubles you have because you begin to see the difference in the motions of the stars in the front part and those in the back part of the cluster. Then you decide that they are members of the cluster if their motions about fit and if their magnitudes and colors agree with what is known about the main sequence in the Hyades but this really involves a circular argument if then you use these stars later to make up the main sequence in the Hyades.

UPGREN: A circular argument is avoided here because the background stars are clearly separated from the stars near the Hyades main sequence in both the (B-V) and (R-I) diagrams. The only stars which could be in doubt one way or another are the few which lie just above the main sequence, but it is most likely that these are members which are unrecognized binaries.

GREENSTEIN: The degree to which the average high-velocity star is subluminous must be affected by differential line and band blanketing; the furthest infrared index I could use (1 micron) had about one-half the ΔM as did the visual luminosity. Undoubtedly a color-color system in the red-infrared would permit removal of the differential blanketing in (R-I). But bolometric measures as analyzed by Mould leave Kapteyn's star one-magnitude subluminous.