PHOTOELECTRIC STUDIES OF STELLAR MAGNITUDES AND COLORS

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1. Introduction

The problem of the interpretation of the H-R diagram can be approached from two different directions: one, from the standpoint of the theory of stellar structure, the other, from the standpoint of observations. It is of interest to approach the problem from the second, observational, direction using only enough of the results of theory to insure that the conclusions that are drawn are reasonably consistent with theory.

The distribution of stars in the H-R diagram (or its approximate equivalent, the color-luminosity diagram) should, when properly interpreted, supply us with a great deal of information regarding the physical characteristics of the stars. The basic theory of stellar structure predicts that the positions of stars in these diagrams should be defined primarily by the three parameters, mass, age and initial chemical composition, although there may be others, such as rotation, having significant effect.

That the mass of a star must, on an empirical basis, be one of the principal parameters governing the position of a star in the H-R diagram has been known for some time. The empirical mass-luminosity relation demonstrates this dependence clearly. On the other hand, this relation cannot alone explain the existence of stars of similar mass and luminosity but of greatly different temperature. Furthermore, there are deviations from this empirical relation that, as Strand and Hall [1] point out, are consistent with the theoretical evolutionary tracks computed by Schönberg and Chandrasekhar [2]. A second parameter, which probably is age, obviously is required.

One might expect that these two parameters, mass and age, would be the principal factors determining the positions of stars in the H-R diagram. The effect of a third parameter, initial chemical composition, is now becoming apparent observationally and, if recent ideas are correct, is considerable in certain regions of the diagram.

2. The H-R diagram

The observational results to be discussed here are largely photometric and, as a result, yield color-luminosity diagrams instead of H-R diagrams. The two methods of presentation are, however, quite similar and lead to comparable results. In the following discussions, the term H-R diagram will be used to designate color-luminosity diagrams as well as spectral type-luminosity diagrams.

It appears to be reasonable to assume that the initial chemical compositions of the galactic clusters are similar and that the differences among these clusters are due principally to the different ages of the clusters and different masses of the stars in the various clusters. The H-R diagram for a number of galactic clusters is outlined by the heavy dark lines in figure 1. The clusters that were used to make up the diagram are indicated. For all clusters, it has been necessary to assume that the main sequences fit the standard main sequence of Johnson and Morgan [3]. The

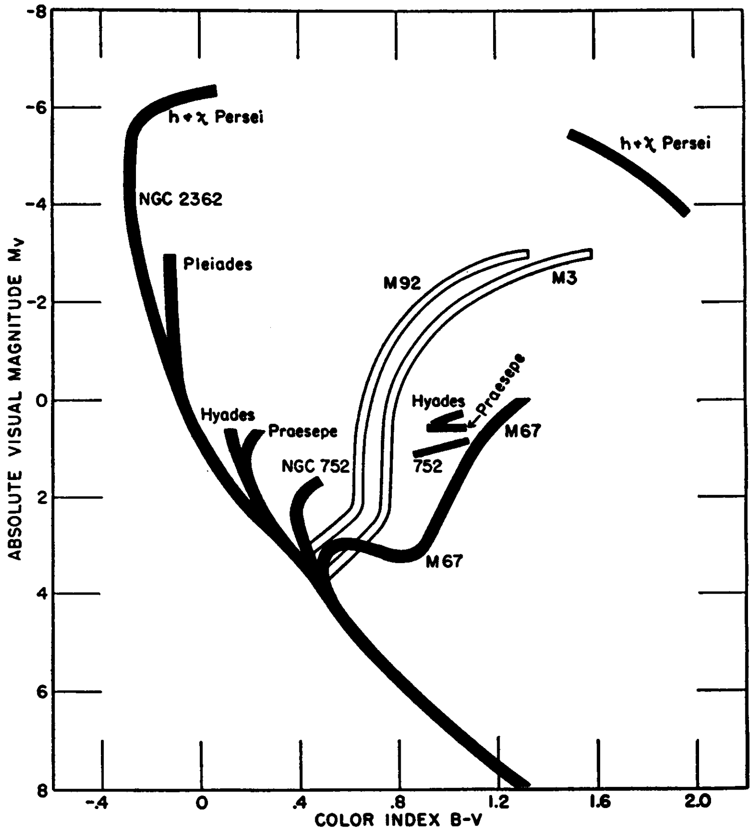

FIGURE 1

Composite color-luminosity diagram for some galactic and globular clusters

bright outer stars discussed by Bidelman [4] have been included in h and χ Persei. Corrections for interstellar reddening and absorption have been made where necessary.

The upper ends of the cluster main sequences deviate from the standard main sequence just as we would expect from the theoretical evolutionary tracks of Schönberg and Chandrasekhar, while the positions of the super-giant stars in h and χ Persei and the giant stars in the Hyades, Praesepe and NGC 752 agree qualitatively with the theoretical tracks of Sandage and Schwarzschild [5]. The positions of the stars in M 67 suggest evolutionary tracks differing from the computed ones of Sandage and Schwarzschild, but still in qualitative agreement with them.

The results for some double stars in the neighborhood of the sun also agree qualitatively with the theoretical tracks of Schönberg and Chandrasekhar. For the double stars, it is found that many of the brighter components are brighter than main-sequence stars [6].

Figure 1 also shows schematic giant sequences for the globular clusters M3 and M 92. It is apparent that these sequences (and those for other globular clusters as well) pass through regions of the H-R diagram that are very little populated by the

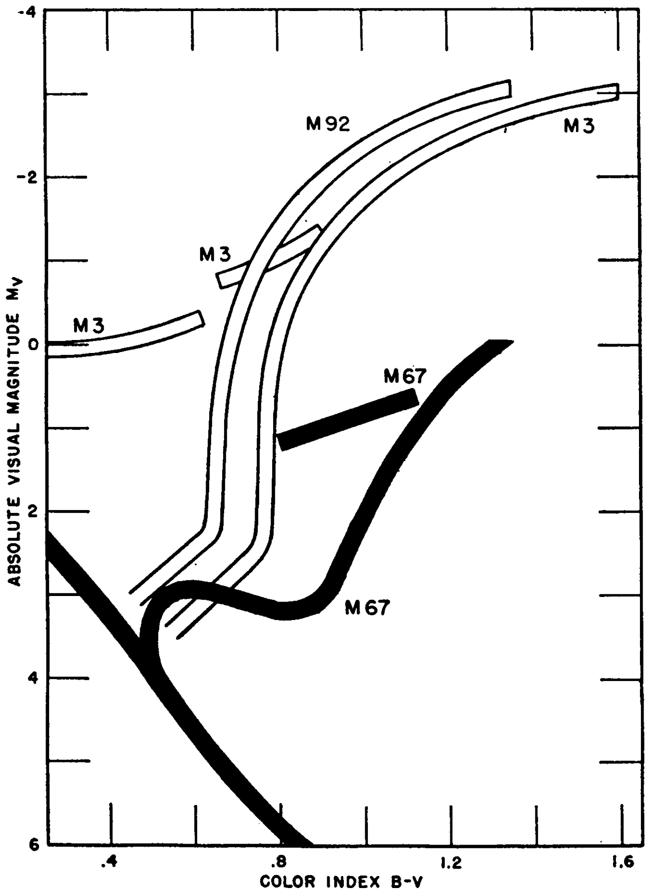

FIGURE 2

Composite color-luminosity diagram for M 67, M 3, and M 92

galactic clusters and the stars in the neighborhood of the sun [7]. Figure 2 shows a more detailed comparison of these two globular clusters with the galactic cluster M 67. The fact that the subgiant sequences in all three clusters break off from the main sequence at about the same place suggests that all three clusters may be about the same age—about 5×10^9 years, according to the theory of Schönberg and Chandrasekhar.

The spectra of the brightest stars in M 3 and M 92 show peculiarities, such as the weakening of CN and the metallic lines, quite strongly and to a much greater degree than shown by the spectra of high-velocity stars [8]. That this weakening of lines in high-velocity stars compared with the low-velocity stars probably is due to a lower ratio of metals to hydrogen in the high-velocity stars has been shown by Schwarzschild, Spitzer and Wildt [9]. On this basis, the M 3 and M 92 stars would have an even smaller ratio of metals to hydrogen. Since the M 67 spectra do not differ significantly from those for nearby bright stars of similar luminosity [10], figure 2 suggests, on an empirical basis, that the difference in the regions of the H-R

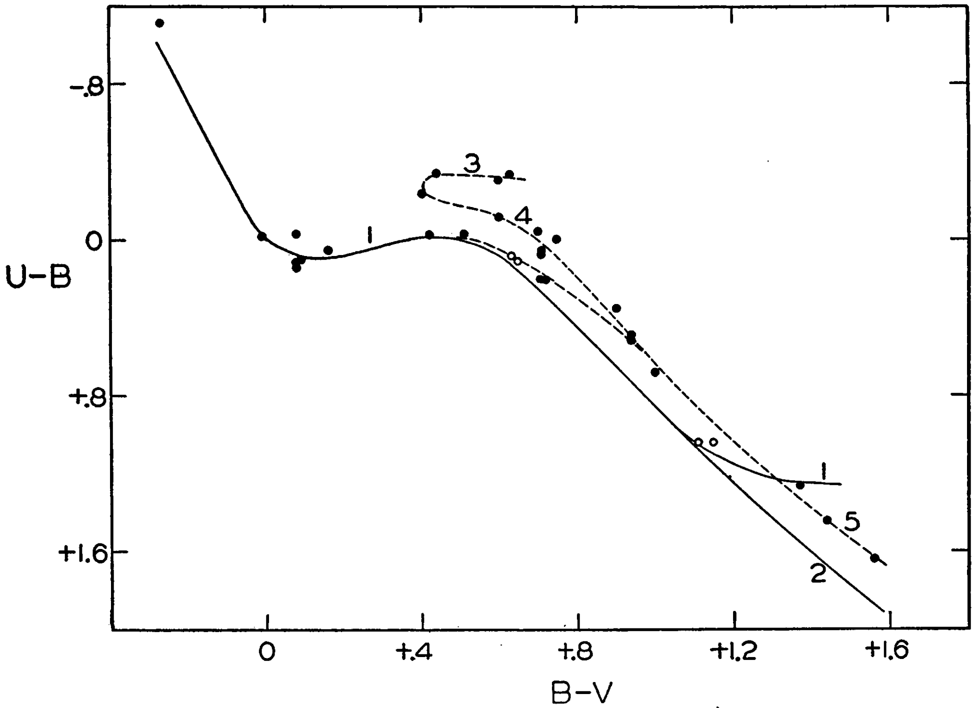

FIGURE 3

U-B versus B-V for M 3 (dotted lines) and nearby stars (solid line). The numbers on the diagram indicate the following: (1) M 3 horizontal sequence and nearby dwarf stars; (2) Nearby giant stars; (3) M 3 main sequence; (4) M 3 sub-giant sequence; (5) M 3 giant sequence. The open circles designate field stars.

diagram occupied by the giant sequences of the globular clusters and the type I stars is caused by the difference in the initial chemical composition of the two groups of stars. In making this statement, we do assume, of course, that the present composition of the stellar atmospheres accurately reflects the initial composition throughout the stars.

Miss Roman [11] has shown by means of three-color photoelectric photometry that the intensity of the ultraviolet light from some high Z-velocity stars, probably subdwarfs, is about 0.2 magnitude, on the average, brighter than for the nearby low-velocity stars. As she has pointed out, this ultraviolet "excess" probably is due to the general weakness of the metallic lines in this spectral region. It therefore seems reasonable, in view of the theoretical results of Schwarzschild, Spitzer and Wildt, to interpret this ultraviolet "excess" as a qualitative measure of the ratio of metals to hydrogen, in the sense that the larger the excess, the smaller the ratio.

Three-color photometry should, on the basis of these arguments, provide information, otherwise unobtainable, regarding the spectra of the fainter stars in globular clusters.

Such three-color photometry has been done with the 82-inch telescope of the McDonald Observatory on a number of stars down to V = 20.4 in M 3. These observations include a one-magnitude section of the cluster main sequence. Throughout the entire range of the observations, the main sequence, the subgiant sequence and giant sequence all show ultraviolet excesses even greater than that found by Miss Roman for the high Z-velocity stars. Figure 3 shows the relation between U-B and B-V for this cluster. It is obvious that this excess is an intrinsic property of the cluster stars; no amount of shifting of the points by interstellar reddening material could produce from the standard lines the observed results. The zero-points have been thoroughly checked; furthermore, two bright stars, obviously not cluster members, that were used as cluster photometric standards fall right along the normal relation derived from nearby stars. The photoelectric observations in M 3 are, therefore, in good agreement with the suggestion that chemical composition may explain the difference in the regions of the H-R diagrams occupied by the golbular cluster stars and the type I stars.

In this connection we may mention a recent unpublished theoretical result by Hoyle and Schwarzschild.[1] They have made computations of the evolutionary tracks to be expected from stars with low metals to hydrogen ratios (for comparison with the globular clusters) and those to be expected from stars having the same chemical composition that has been found for the young O and B stars in our galaxy. The synthetic H-R diagrams obtained for stars with low metals to hydrogen ratios are similar to the observed diagrams for globular clusters, while the diagram obtained for "normal" composition (computed for the same age as those for the globular clusters) is quite similar to the observed diagram for M 67.

No three-color photoelectric observations are yet available in M 92,[2] but Walker and Sandage [12] have made three-color observations in NGC 4147. The ultraviolet excess found in NGC 4147 is even greater than the one found in M 3. Walker and Sandage did not observe the main sequence of NGC 4147, but, presumably, the main-sequence stars would have an excess at least as great as that found in M 3.

The ultraviolet excess found for the M 3 main-sequence stars suggests that they should be compared with the high Z-velocity stars studied by Miss Roman. These latter stars show, on the average, a very small rotational velocity around the galactic center and a small concentration to the galactic plane. In both respects, they resemble the globular clusters, again suggesting that we should compare the M 3 main-sequence stars with them. These high Z-velocity stars have about the same average B-V as the brightest main-sequence stars in M 3.

As Miss Roman points out, there is evidence that these high Z-velocity stars probably are subdwarfs lying about 1½ magnitude below the main sequence. This suggests that the M 3 main-sequence stars may be subdwarfs. On the other hand, on the assumption that the cluster type variables lie at $M_v = 0.0$, the photoelectric observations do not permit the M 3 main sequence to be more than a few tenths of

[1] Communicated to me by Dr. W. Baade.

[2] Recent unpublished preliminary results by Walker indicate that the ultraviolet excess in M 92 is about the same as that in M 3.

a magnitude fainter than the type I main sequence. Furthermore, the reduced absorption of the metallic lines that produces the ultraviolet excess in the spectral region of the ultraviolet filter will also be present to a lesser extent in the blue filter band, causing the observed B-V colors in M 3 to be *bluer* than those for nearby type I stars of the same temperature. We must conclude that the M 3 main sequence does not differ significantly in position from that for the nearby type I stars.

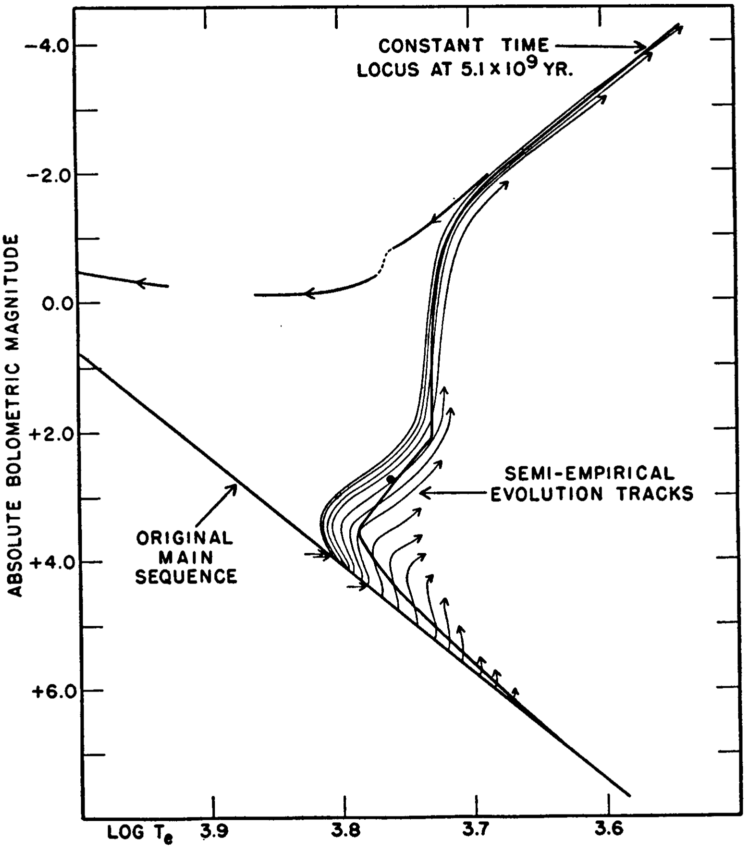

FIGURE 4

Semi-empirical evolution tracks for M 3

The only other globular cluster for which three-color photoelectric observations have been made is M 13 [13]. Unfortunately, the three-color observations do not go more than three magnitudes below the horizontal branch, but Baum [14] has made blue and yellow observations sufficiently faint to include about four magnitudes of the cluster main sequence. According to the three-color measures, the ultraviolet excess, if any, is very much smaller than that found for M 3 and NGC 4147.

On the assumption that the cluster-type variables are at $M_v = 0.0$, Baum's photometry on the faint stars in M 13 places the main sequence approximately two magnitudes fainter than the M 3 main sequence, and about the same amount fainter than the type I main sequence near the sun. If we should assume, as seems reasonable on the basis of the M 3 results, that the ultraviolet excess, or lack of it, in the bright cluster stars is a measure of the amount of excess to be found in the main-sequence stars, then the M 13 main-sequence stars do not fit in with the high Z-velocity stars studied by Miss Roman. The implication would be that the M 13 main sequence should be fitted to the type I main sequence. But, of course, this speculation can be tested only by direct three-color photoelectric observations on the main-sequence stars in M 13. Baum has suggested, as an alternative proposal to fitting the cluster variables, that we might make this fit to the type I main sequence. This procedure results in putting the very few cluster variables in M 13 at $M_v = -2$, and a cluster age of 2×10^9 years.

3. Interpretations

Any interpretations based upon the meager and rather contradictory data available at the present time must be considered to be extremely tentative. Nevertheless, it is possible to make several interpretations that may be representative of the true state of affairs.

We seem to be on fairly safe ground in concluding that the three parameters, mass, age and initial chemical composition, may be sufficient to explain the differences between the H-R diagrams of some globular clusters (for example, M 3, M 92, NGC 4147) and those for stars of Baade's population type I. M 13 presents difficulties here: its lack of an ultraviolet excess for the giant and subgiant stars (contrasted to M 3 and NGC 4147) and the position of its main sequence both indicate that we do not have the whole story.

Sandage [15] has derived semi-empirical evolutionary tracks for M 3; these are shown in figure 4. If this derivation should be correct, it follows that stars having the same absolute magnitudes and color indices (occupying identical positions in the diagram) must have entirely different masses. This comes about because the old stars that might have evolved along Sandage's empirical tracks, say, to $M_v = +0.5$, would necessarily be less massive (having started from a lower point on the main sequence) than younger stars evolving across the Hertzsprung gap from, say, the brightest A-stars in Praesepe. While there are not many of the latter stars, there are a few; one, in fact, is a member of the Praesepe cluster. The components of Capella are in this region of the diagram and have masses around 3.0 [16]; according to Sandage's tracks, equivalent stars in M 3 would have masses of 1.5, or less.

It is possible to derive semi-empirical evolutionary tracks for M 67 in the same manner as for M 3. Inspection of figures 1 and 2 shows that, if we assume such analysis to be valid, we would expect the giant stars of M 67 to be less massive, having come from a lower point on the main sequence, than the giant stars of Praesepe or NGC 752. Yet the stars of the two groups occupy much the same region of the H-R diagram.

It is now evident that we cannot consider the H-R diagram for all stars to be a simple two-dimensional array. At least one additional dimension is required; the divergence of M 13 from the other globular clusters discussed here suggests that even a fourth parameter may be required.

The dependence upon initial chemical composition, indicated by the data presented here, of the region of the H-R diagram in which the giant sequences fall, suggests that the difference between Baade's population types I and II may be due primarily to differences in initial chemical composition. A possible mechanism by which this difference in initial chemical composition might have been produced has been discussed by Schwarzschild and Spitzer [17]. They consider the possibility that the type II stars were formed first from material having a low concentration of metals, while the type I stars were formed later from material produced during the life and death of massive, fast-living type II stars.

Many of the observations and ideas that have been discussed in this paper are the product of cooperative work with Dr. A. R. Sandage, who should really have been one of the authors.

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