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THE COLOR-MAGNITUDE DIAGRAMS OF GALACTIC AND GLOBULAR CLUSTERS AND THEIR INTERPRETATION AS AGE GROUPS

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I. *Open Clusters*

Much of the observational evidence for the evolution of the stars comes from color-magnitude diagrams of star clusters. The modern observational era begins with O. J. EGGEN's photoelectric studies of bright galactic clusters such as Pleiades, Hyades and Praesepe. EGGEN's work was followed by H. L. JOHNSON's three color studies of these and other open clusters. The principle results were; (1) evidence that in any one cluster the cosmic scatter of stars around the main sequence was very small or even zero, (2) the bright end of the main sequence terminates at different absolute magnitudes in different clusters, (3) in clusters where yellow giants occur, the position of the giant sequence is systematically related to the turn-off point of the main sequence.

The observational data relevant to the evolutionary problem is summarized in a composite color-magnitude diagram of ten galactic clusters and one globular cluster shown in Figure 1. Here the absolute visual magnitude M_v is plotted against the normal unreddened $B - V$ color on the JOHNSON and MORGAN *UBV* photometric system. The same data are displayed in the more useful M_{bol}, log T_e plane in Figure 2 which was obtained

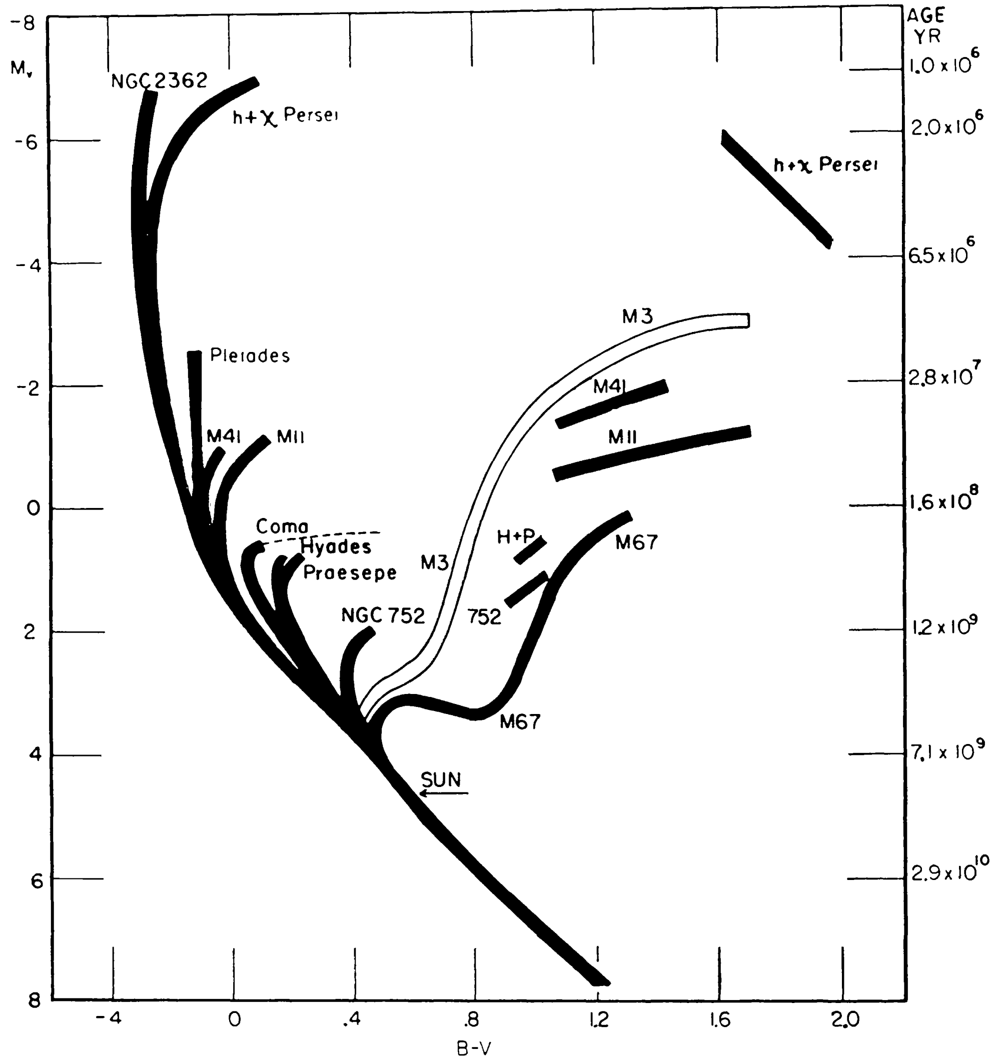

FIGURE 1 — A composite color-magnitude diagram of ten galactic clusters and one globular cluster. Ages corresponding to the various main sequence termination points are given along the right hand ordinate.

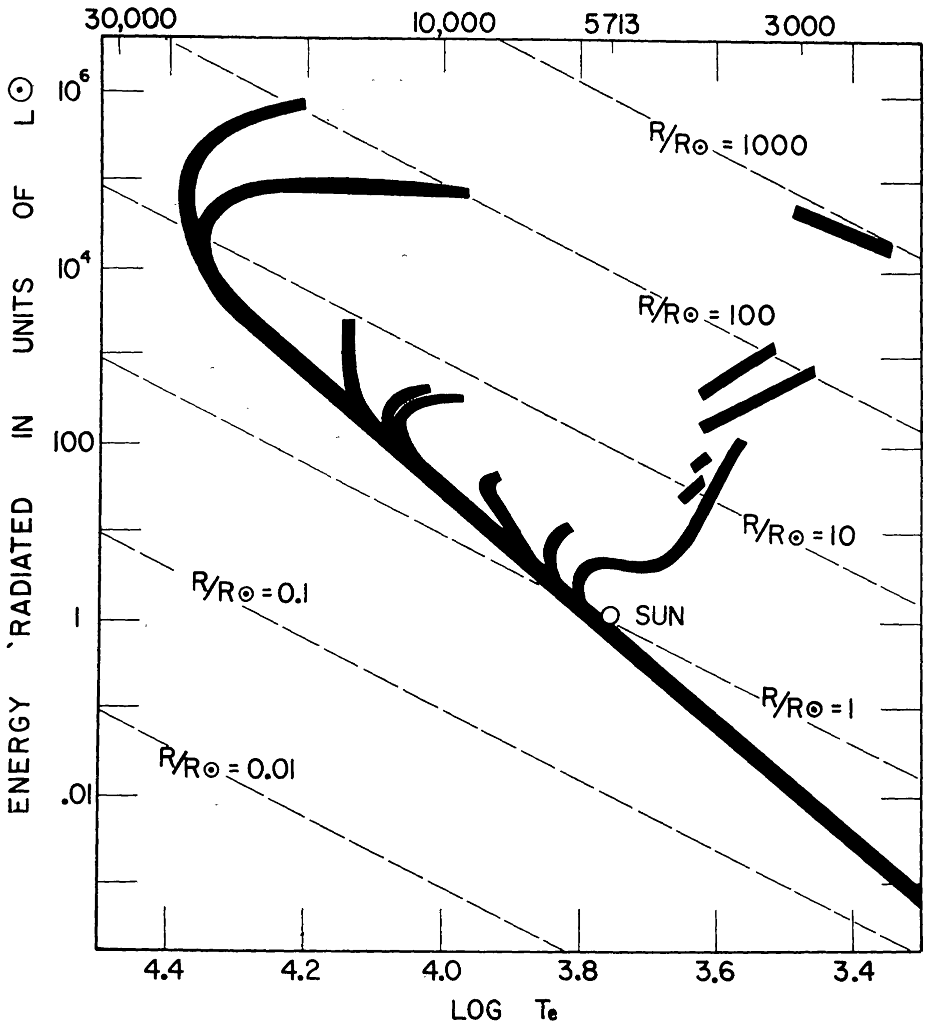

FIGURE 2 — A composite H-R diagram in the M_{bol}, log T_e plane for the same ten galactic clusters shown in Figure 1. The ordinate gives luminosity in terms of the sun. Temperature is in °K. Lines of constant radii are dashed.

from Figure 1 by the usual $B\text{-}V = f(T_e)$ and $\Delta M_{bol} = f(B\text{-}V)$ relations. The dashed lines of Figure 2 show the lines of constant radii.

Is there evidence from these data for a spread of ages among the galactic clusters? The most striking feature of Figures 1 and 2 is the range in absolute magnitude for the main sequence termination points in the various clusters. No main sequence stars are present in h and χ Persei brighter than $M_v = -7$; in the Pleiades brighter than $M_v = -3$; in Hyades and Praesepe brighter than $M_v = +0.5$; and in M 67 brighter than $M_v = +3.5$. Furthermore, near the termination points, the slope of the main sequence in each cluster steepens from the next brighter cluster. These results, which have been known in preliminary form since the time of R. J. TRUMPLER's work, are interpreted as the result of stellar evolution and are the evidence for age differences among the clusters.

Current ideas of star formation and subsequent evolution (due principally to early work by ÖPIK, SCHÖNBERG and CHANDRASEKHAR, GAMOW, and later by SCHWARZSCHILD and his school) require that stars are formed from the interstellar medium and contract toward the main sequence with a Helmholtz contraction time scale. The central temperature rises during contraction, until, at a certain critical value, thermonuclear reactions begin, contraction stops, and a stable star is born. The luminosity of the stable star depends upon the mass of the initial condensation. Because there is a mass distribution function for the initial condensation, stars are spread continuously along the main sequence at the time of stellar birth.

The first result of the nuclear reactions is to convert hydrogen into helium in the central regions of the star. This causes a readjustment of the stellar structure so as to compensate for the increase in the mean molecular weight. Detailed computations of this structural change were first made by SCHÖNBERG and CHANDRASEKHAR [1] and later by many other authors. The general result is that the evolving star remains close to the main sequence until a critical fraction, q_c, of its mass has been exhausted of hydrogen, at which time the star rapidly expands and moves redward in the color-magnitude diagram into the region of the yellow giants.

These theoretical expectations find direct support in Figures 1 and 2. When a cluster has been in existence for a time T, all stars brighter than a certain luminosity will have exhausted the critical mass q_c and will have left the main sequence. Stars only slightly fainter than this limit will have exhausted a smaller fraction $q_i < q_c$ and will have evolved only slightly from their initial stellar structure on the main sequence. The details of the theoretical evolution explain rather well the observed change of slope of each galactic cluster main sequence near its termination point.

The age of each cluster follows immediately if we identify the main sequence termination point with the stage when a star has exhausted q_c of its mass of hydrogen. In exhausting q_c, the star has released an amount of nuclear energy

$$E_n = \Delta Mc^2 = .007\,\mathfrak{M}\,Xq_c c^2 \tag{1}$$

where X is the fractional hydrogen abundance by mass. The star releases this energy at a rate L_i ergs/sec which varies with q_i. The function $L_i = f(q_i)$ is given by the various theories. The total time required to burn $Xq_c\,\mathfrak{M}$ grams of hydrogen is

$$\tau = .007\,\mathfrak{M}\,c^2 X \int_{q_i=0}^{q_i=q_c} \frac{d\,q_i}{f(q_i)} \,. \tag{2}$$

Let L_T be the luminosity of the main sequence termination point. The function $L_i = f(q_i)$ may be written as $L_i = L_T h(qi/q_c)$. The age of a cluster whose luminosity at the main sequence termination is L_T is then

$$\tau = \frac{.007\,\mathfrak{M}\,c^2}{L_T} \int_{Xq_i=0}^{Xq_i=Xq_c} \frac{X\,dq_i}{h(q_i/q_c)}\,. \tag{3}$$

If we adopt the Schönberg-Chandrasekhar evolution, $Xq_c = 0.07$ and $h(q_i/q_c)$ is known. Equation (3) becomes

$$\tau = 1.10 \times 10^{10}\,\frac{\mathfrak{M}}{L_T} \text{ years} \tag{4}$$

where $\mathfrak{M}$ and L_T are in solar units. L_T is known from observations and $\mathfrak{M}$ is given by the mass-luminosity relation.

The ages of the clusters shown in Figure 1 have been computed from equation 4 and are given in Table 1. These ages are not precise because in equation 4 we have assumed that $Xq_c = 0.07$ independent of the mass. This requires homologous models from $\mathfrak{M} = \mathfrak{M}_\odot$ to $\mathfrak{M} = 30\,\mathfrak{M}_\odot$ which is probably not strictly true.

Table 1

Cluster	$M_{v,T}$	τ (*years*)
NGC 2362	< -7.0	$< 1 \times 10^6$
h + χ Per	-7.0	1×10^9
Pleiades	-2.5	2×10^7
M 41	-1.5	6×10^7
M 11	-1.3	6×10^7
Coma	$+0.5$	3×10^8
Hyades	$+0.8$	4×10^8
Praesepe	$+0.8$	4×10^8
NGC 752	$+1.9$	1×10^6
M 67	$+3.5$	5×10^9

The stages of the evolution after the star has left the main sequence are not adequately accounted for by present theoretical stellar models for masses greater than $2\,\mathfrak{M}_\odot$. But

Figures 1 and 2 show certain aspects of the history. For clusters brighter than M 67 (mass $>1.2\ \mathfrak{M}_\odot$) a distinctive Hertzsprung gap appears between the termination of the main sequence and the beginning of the giant sequence. This suggests that for $q_i > q_c$ the increase in the radius of the evolving star is very rapid until a $B-V$ of about 1.0 is reached. Here the rate of expansion slows down and stars spend appreciable time in the giant region of the M_v, $B-V$ plane. The observational manifestation of this change in rate is the appearance of giant sequences in most clusters. The width of the Hertzsprung gap appears to be a function of mass. It goes to zero in M 67 where the mass of an individual giant star is about $1.2\ \mathfrak{M}_\odot$. It widens to about $\Delta(B-V)=0.7$ magnitude at Hyades and finally to about 1.6 magnitute for h and χ Persei. The presence or absence of the gap may be connected with the presence or absence of a convective core. It is perhaps significant that the p - p thermonuclear reactions probably give way to the C - N cycle with the consequent onset of convection at masses of about $1.5\ \mathfrak{M}_\odot$ (absolute magnitude $\approx +3$). This is close to where the Hertzsprung gap begins.

Figures 1 and 2 suggest that the shape of the evolutionary tracks are dependent upon mass. For stars as massive as those in the Hyades, the tracks in the M_v, $B-V$ plane are nearly horizontal. Younger clusters such as M 11, M 41, and h and χ Persei, also suggest nearly horizontal tracks. For masses less than $3\ \mathfrak{M}_\odot$, the tracks from the main sequence bend upward like in NGC 752 and M 67. Because of this change of shape of the tracks with mass, all clusters older than Hyades ($\tau = 4 \times 10^8$ years) have the property of funnelling their stars into a narrow band in the giant region between $M_v = +2$ to $M_v = 0$. Consequently, stars of different mass and different ages end up in the same region of the H-R diagram along what appears to be a sequence when data for the field stars are plotted. But actually, because of the funnel effect, this is no sequence at all but rather a region of the diagram which contains stars whose ages range from $\tau = 4 \times 10^8$ years to 5×10^9 years, whose masses range from $\mathfrak{M} = 3\ \mathfrak{M}_\odot$ to about $\mathfrak{M} = 1.2\ \mathfrak{M}_\odot$, and whose original spectral class along the main sequence ranged from B7 to F7 with the consequent change of kinematical properties. Computation of the luminosity function for K0 - K2 stars from $M_v = +5$ to $M_v = -4.5$ using the tracks suggested by Figures 1 and 2, indicate that the observed luminosity class III giant "sequence" can be explained in this way. Good agreement is obtained between the observed and the predicted luminosity functions [2].

II. *Globular Clusters*

Color-magnitude diagrams for globular clusters were first obtained by SHAPLEY around 1915. These early diagrams showed clearly that the brightest stars were red in contrast to the situation in normal galactic clusters. In the 1930's and early 1940's SHAPLEY's early work was extended to other clusters by several workers, but no study went faint enough to locate the connection of the observed sequences with the main sequence. Post-war work with the large reflectors on Mount Wilson and Palomar has located the main sequences in M 3, M 13, and M 92, although there still remain unsolved photometric problems at very faint light levels. Agreement between the various observers has not yet been reached for stars fainter than $V = +20$, so, although the main sequences have been found in the three clusters, their exact positions in the M_v, $B - V$ plane are not yet known.

The location of the main sequences and, in particular, their exact termination point, is fundamental for the problem of finding age differences among globular clusters. However, use of this method is quite unsatisfactory at present not only because of the current observational uncertainty but also because of the lack of precision of the method at $M_v = +3.5$. A difference of only 0.3 magnitude in the main sequence termination point corresponds to the large age difference of 10^9 years at $M_v = +3.5$. We are therefore compelled to look at the more easily accessible, brighter parts of color-magnitude diagrams for globular clusters to see if differences here can be interpreted as age parameters.

Since the time of S. BAILEY's discovery of RR Lyrae stars in globular clusters, much work has gone into obtaining periods and light curves for these stars. Although most RR Lyrae variables have periods between 0.3 and 0.8 days, it is a curious fact that the distribution of periods from one globular cluster to another is not the same. OOSTERHOFF pointed out in 1939 [3] and 1944 [4] that the mean period of the type *a* and *b* RR Lyrae stars in any cluster was either near 0.54 days or 0.64 days and the separation of clusters into two groups seemed definite. Further work by Dr. HELEN HOGG has confirmed this conclusion. It was further shown that the mean period of the type *c* variables was divided in the same ratio with values of either near 0.31 days or 0.37 days. The data upon which these conclusions rest are shown in Tables 2 and 3 and are taken from the compilation of OOSTERHOFF. Table 2 contains data for both the *a, b* type and the *c* type variables in clusters which have been well observed. Table 3 gives less complete data for only the *a, b* variables in a number of clusters. This table is divided into two sections, one for the short period group, and the other for the longer period group. When more clusters are observed, it may be that the period difference will form a continuum rather than two separate groups.

We now seek an explanation for this phenomenon and ask if these differences can be a possible age parameter.

RR Lyrae stars are found only along the horizontal branch of color-magnitude diagrams of globular clusters in a discrete region of instability extending from $B - V = 0.17$ to $B - V = 0.39$ from which non-variable stars are excluded. Suppose there is an absolute magnitude difference in the horizontal

TABLE 2

Cluster	$\overline{P}_{a,b}$	*No.*	$\overline{P}_c$	*No.*
ω Cen	0^d.65	77	0^d.37	58
M 15	.65	31	.38	28
M 53	.62	17	.37	15
M 92	.63	9	.37	3
M 3	.55	124	.32	27
M 4	.55	31	.29	9
M 5	.54	63	.32	13

TABLE 3

NGC	*M*	$P_{a,b}$	*No.*	*NGC*	*M*	$P_{a,b}$	*No.*
362		0^d.54	7	5024	53	0^d.62	17
3201		.56	55	5139	ω Cen	.65	77
5272	3	.55	124	6341	92	.63	9
5904	5	.54	63	6656	22	.63	7
6121	4	.51	17	7078	15	.65	31
6723		.51	17	7089	2	.63	11
6981	72	.55	21			.643	152
		.545	304				

branch between two clusters A and B, with A the brighter. If RR Lyrae stars occur in both clusters, the period distribution of those in A will not be the same as in B because the horizontal branch of each cluster cuts the domain of instability at different levels. Figure 3 illustrates the situation where two hypothetical horizontal branches are drawn. The domain of instability is

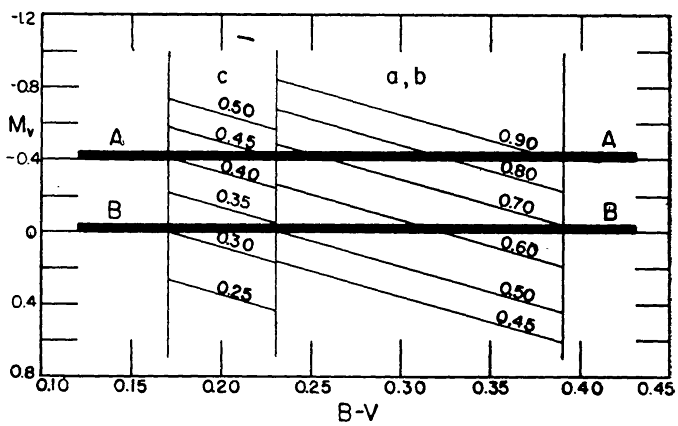

FIGURE 3 — A section of the color-magnitude diagram for globular clusters showing the domain of the RR Lyrae stars along the horizontal branch. Lines of constant period slant from the upper left. Sections of two horizontal branches of hypothetical clusters A and B are drawn.

shown with a range of M_v ± 0.8 magnitude and with color boundaries which do not change with M_v. Lines of constant period are drawn separately for the *a, b* stars and the *c* stars. These lines satisfy $P\sqrt{\bar{\rho}} = Q$ where $Q_{a,b}/Q_c = 1.5$ (see ROBERTS and SANDAGE [5]). Figure 3 shows that the mean period for variables in cluster A will be longer than in cluster B. Furthermore, this model predicts that in cluster A and B the ratio $P_{a,b}/P_c$ will be the same. And this is true from the observational data.

If this is a reasonable explanation for the period differences between clusters, then the difference in absolute magnitude,

M_v, of the horizontal branches must be small enough so as not to conflict with other data for RR Lyrae stars in the general field. An estimate of $\Delta M_v = f(\Delta P)$ can be made.

It has been shown by SCHWARZSCHILD [6] and by ROBERTS and SANDAGE [5] that variables in M 3 satisfy the pulsation criterion $P\sqrt{\rho} = Q$. This equation can be expressed in the observable quantities by use of the $B - V = f(T_c)$ and the $M_{bol} = h(B - V)$ relations with the result that

(5) $$\log P + 0.3 M_v = 0.840 (B - V) + \log Q - \frac{1}{2} \log \mathfrak{M}/\mathfrak{M}_\odot + \text{const.}$$

(Equation 5 was used to compute the lines of constant P in Figure 3). If the magnitude differences between clusters A and B are small, we can, to a first approximation, neglect the slight variation of $\mathfrak{M}/\mathfrak{M}_\odot$ between the clusters. If we further assume that the color boundary of the unstable region is vertical. equation 5 predicts

(6) $$\Delta M_v = - 3.3\, \Delta \log P$$

If we do *not* neglect the variation of $\mathfrak{M}/\mathfrak{M}_\odot$ with a change ΔM_v but assume that $\Delta\, \mathfrak{M}/\mathfrak{M}_\odot = g(\Delta M_v)$ as given by the main sequence mass-luminosity relation (this assumes that the difference in magnitude of the main sequence termination points between cluster A and B is the same as the ΔM_v of the horizontal branch), then

(7) $$\Delta M_v = - 2.8\, \Delta \log P$$

The ratios of the mean periods for the two groups of clusters in Table 3 requires that the absolute magnitude of the horizontal branches differ by $\Delta M_v \approx 0.2$ magnitude. This is small enough to be reasonable from other considerations.

Do these results imply an age difference? If the magnitude difference of $\Delta M_v = 0.2$ continues to the main sequence termination point we predict an age difference of

(8) $$\Delta\tau/\tau = 0.7\, \Delta M_v \quad \text{or} \quad \Delta\tau = 7 \times 10^8 \text{ years} .$$

The assumptions made in deriving equations 6, 7 and 8, are:

1) The color boundaries of the domain of instability for RR Lyrae stars do not differ between the clusters.

2) The pulsation constant does not differ between the clusters.

3) The magnitude difference computed from equation (6) or (7) is the same as that of the main sequence termination points.

The validity of these assumptions is unknown at present. The present hypothesis predicts certain consequences for the period-amplitude relation, the period-color relation, and the color-amplitude relation among the RR Lyrae stars. These are discussed in detail in a forthcoming paper in the *Ap. J.* The predictions can be checked observationally and will help to test assumption 1. But as yet the required data are too meagre for a test. Check of assumption 2 will eventually come from theory. Assumption 3 will be checked observationally only when the photometry at low light levels is perfected.

The present discussion should be considered only as suggestive that differences in the properties of RR Lyrae stars can be considered as age parameters. The discussion does suggest that there may be age differences among the globular clusters but that these differences are small. Our present estimate gives $\Delta \tau < 10^9$ years for globular clusters, while Figures 1 and 2 show a continuous age distribution from 10^6 to 5×10^9 years for galactic clusters. This confirms current ideas that globular clusters were formed in our galaxy at nearly the same epoch, 5×10^9 years ago (with a possible spread of 10^9 years), while galactic clusters have been formed continuously.

III. *Comparison between Globular Cluster and Galactic Cluster Color-Magnitude Diagrams*

Figures 1 and 2 show that the shape and position of the various evolutionary tracks in the M_{bol}, $\log_{T_e}$ plane depend not only upon the mass of the stars but also on a second parameter.

The case in point is the M 3 - M 67 difference. M 67 is an old galactic cluster located close to the galactic plane. M 3 is a globular cluster in the halo. Both are about the same age because their main sequence termination points occur at about the same absolute magnitude. Consequently, the mass of the stars along the evolving sequences in both clusters are nearly the same (1.2 $\mathfrak{M}_\odot$). But the tracks of evolution differ. Stars in M 3 reach $M_v \approx -3$ while those in M 67 brighten only to $M_v \approx 0.0$. For two reasons, the second parameter responsible for the difference is believed to be chemical composition.

1) The theoretical models of Hoyle and Schwarzschild [7] predict a difference similar to that observed between M 3 and M 67 if M 67 has a higher metal abundance by about a factor of 15.

2) *UBV* photometry of individual stars in both clusters shows a great difference in the energy distribution curves. Stars in M 3 show an ultraviolet excess of $\Delta\ (B\text{-}V) \approx 0.3$ magnitude compared with stars in M 67. Following Strömgren, this is interpreted as a difference in the blanketing of the absorption lines which would result from a low heavy element content in M 3. Stars in all other globular clusters tested (M 3, M 13, M 92, NGC 4147) show the $\Delta\ (U-B)$ excess.

If M 3 and M 67 are exactly the same age, then present ideas of an enrichment of the heavy element abundance of our galaxy as a unique function of time are untenable because here are two clusters of the same age but with greatly different chemical composition. In this case, one must postulate that a chemical separation existed between the disk and the halo 5×10^9 years ago, with the disk having the higher metal abundance. However, we are not yet forced to this conclusion with the present data. Inaccuracy of the distances to M 3 and M 67 permit some difference in the absolute magnitude of the main sequence termination points with a resulting difference in the ages. The modulus of M 3 depends upon the assumption that $M_v = 0.00$ for the RR Lyrae stars. For this case, the main sequence break point is at $M_v = +3.3$ (JOHNSON and SANDAGE [8]. But if the RR Lyrae stars have $M_v \approx +0.5$ — as the results of P. P. PARENAGO [9] and of E. D. PAVLOVSKAYA [10] suggest, and as the M 3 data require when the main sequence is fitted to an age zero sequence taking into account the $\Delta (U - B)$ — then the break point is at $M_v = +3.8$ which is about 0.3 magnitude fainter than M 67. In this case, a spread in age of about 10^9 years between M 3 and M 67 is possible, which may be sufficient for enrichment to occur according to current ideas of element synthesis (BURBIDGE, et al. [11]. Thus, the observations do not contradict the enrichment hypothesis. They do, however, put an upper limit of about 10^9 years for the time available to achieve an enrichment factor of ~ 15 at an epoch 5×10^9 years ago, unless we assume a chemical separation between disk and halo.

IV. *Summary*

1. Evidence is presented for assigning different ages to galactic clusters ranging from 10^6 to 5×10^9 years.

2. Age differences among globular clusters are not well established but interpretation of the differences in the mean periods of RR Lyrae variables from cluster to cluster may suggest age differences of the order of 10^9 years, centered about a creation epoch about 5×10^9 years ago.

3. Evidence from the M 3 - M 67 case suggest that differences in chemical composition greatly affect the shapes of the evolutionary tracks in the M_{bol}, $\log_{T_e}$ plane. A time difference of the order of 10^9 years is required to achieve an enrichment factor of ~ 15 at an epoch about 5×10^9 years ago, unless a chemical separation existed between disk and halo.

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DISCUSSION

CHAIRMAN: J. H. OORT

SCHWARZSCHILD

Should theoreticians take small differences in the colour-magnitude diagrams of open clusters of the same age seriously?

SANDAGE

Some of the differences are probably not significant but it seems that the Pleiades main sequence near the breakoff point has a significantly different shape than the main sequences of say Hyades or Praesepe near their breakoff points.

HECKMANN

The alpha Persei cluster has the same main sequence as the Pleiades. Alpha Persei itself very probably belongs to the cluster and would lie in the Hertzsprung gap.

SANDAGE

There are other examples of stars in the gap also. This must mean that the gap is not a region which is completely devoid of stars but rather a region of faster evolution where occasionally a star may be found.

MORGAN

Observations of NGC 6231 confirm the presence of stars of very high luminosity of types earlier than in *h* and χ Persei. This suggests that the observed differences in the HR diagram of *h* and χ Persei compared with NGC 2362 are due principally to the fact that the number of stars created of very large mass is much greater for the former cluster than for the latter. The main sequence turn-off occurs at the same spectral type (B1) for both clusters.

BAADE

Are the M-type supergiants of *h* and χ Persei members of the clusters or of the surrounding association?

SANDAGE

They are spread over a wider region than the clusters proper, but probably have had the same evolutionary history as the cluster stars.

SANDAGE

The differences in the colour-magnitude diagrams of M 67 and M 3 which have about the same age should be emphasized. We have here a clear indication of some sort of chemical difference between disk and halo at nearly the same cosmic time.

OORT

Is M 67 not a disk globular cluster?

SANDAGE

It looks more like a dense open cluster.

HOYLE

It is interesting that the beginning of the Hertzsprung gap occurs at absolute magnitude +2. This is just where the carbon nitrogen cycle should become effective.

SCHWARZSCHILD

A lot of other things happen in this region, e.g. degeneracy becomes unimportant in the exhausted cores of the brighter stars, while it is important for stars fainter than $+2^{m}$.

SALPETER

Is the horizontal branch absent in M 67?

SANDAGE

We think it is present, but the numbers are certainly small. There are not more than ten possible cases.

SALPETER

How accurately do we know the breakoff points of the main sequence in M 3 and M 67?

SANDAGE

The determination involves fitting to a standard main sequence for M 67 and the assumption of absolute magnitude zero for RR Lyrae variables for M 3. There is an uncertainty therefore of at least half a magnitude, because each of these assumptions is uncertain.

BAADE

How close do the RR Lyrae variable gaps in globular clusters coincide in colour? If, for example, one attributes the shifts in colour to reddening one finds occasionally a value for the absorption not consistent with the high galactic latitudes.

SANDAGE

But is this not a statistical relation, which, in any individual case, might give quite incorrect results?

SCHWARZSCHILD

Since there is no unreddened case observed in the second group of clusters on SANDAGE's list it appears that there is no observational answer to BAADE's question.

SCHWARZSCHILD

How much colour shift would be needed to explain the difference in period between the two groups of globulars?

SANDAGE

About $0^m.09$, too small to observe, without some independent estimate of the reddening.

SPITZER

Is there a slight progressive colour difference in the vertical branches of the different groups?

SANDAGE

Yes. In addition, there appears also to be a difference between the energy distribution of individual stars in globular clusters and stars of high metal content. STRÖMGREN has suggested a blanketing effect. In a star like the sun this would make the *B-V* colour bluer by $0^m.2$, and the *U-B* colour bluer by $0^m.6$.

STRÖMGREN

This mechanism of blanketing could explain the difference between F subdwarfs and normal main sequence stars.

SANDAGE

Three-colour photography should make it possible to identify stars like the globular cluster stars in the general field.

HOYLE

If the objects of the halo condensed at an early stage, when matter occupied a volume somewhat greater than the galactic system as it is at present, the density must have been about 10^{-25} grams per cc and the time scale for gravitational contraction about 10^9 years. This is the order of age differences which have been suggested for globular clusters.

OORT

The local density might be much higher.

SCHWARZSCHILD

SANDAGE's proposed interpretation of the period distribution of RR Lyrae variables indicates only one possibility. He assumes homology for small ranges of mass and age. One could, for example, just as well assume that the luminosities are essentially the same, but that the depth of the convection zone critically depends on differences of chemical composition in the photosphere. Variations in the depth of the convection zone might seriously affect the period-density relation.

With regard to BAADE's stars of period 0.3 days near the galactic nucleus, for which SANDAGE quotes a possible magnitude difference of $0^m.7$ from variables in our surroundings, could this indicate a possible alteration in the distance of the galactic centre? If BAADE's absorption is right, this correction brings us to about 5 kpc from the centre.

OORT

That I think would be very objectionable. I would not mind putting the centre a little further out.

SCHWARZSCHILD

That means that BAADE has to subtract from his absorptiom something like $0^m.7$.

BAADE

I should feel uncomfortable about a change of $0^m.7$. I feel more certain about the value of the absorption, which was derived from NGC 6522, the globular cluster in the centre. I feel more certain because MORGAN has checked the integrated spectrum of this cluster and it belongs to the weak-line globular clusters. It was assumed that it was comparable to those clusters for which we know the integrated spectrum, i.e. those in the halo. STEBBINS made measures in four colours for a number of globular clusters in the halo and for 6522, and this led to an absorption of $2^m.75$. But there is a second argument. This field was at latitude $-4^\circ.5$. SHAPLEY's field, which he investigated carefully, was at latitude -20°. He selected a field as high as that in order to escape the effects of heavy absorption, because at -20° latitude the extragalactic nebulae appear to be there in normal numbers. SHAPLEY checked a large field and came to the conclusion that a small correction for absorption was still necessary. My corrected distance modulus of $14^{m}.56$ for the galactic centre is very close to the value of $14^{m}.43$ which I derived from SHAPLEY's data, and the small discrepancy can be accounted for by the assumption of spherical equidensity surfaces.

SANDAGE

What was the apparent magnitude scale for the distribution of RR Lyrae variables in the galactic nucleus and how secure do you consider the magnitude scale to be?

BAADE

The peak occurs near $m_{pg} = 17.5$. To this limit the scale seems to be secure because WHITFORD's photoelectric scale in S.A. 68, which was used for the photometric transfer, extends to magnitude 19.

SPITZER

I would like to ask SANDAGE about the correlation between the spectra of globular clusters and characteristics of the RR Lyrae variables present.

SANDAGE

ARP concluded that those clusters containing the shortest periods showed the more nearly normal spectra.

MORGAN

ARP has recently compared my recent results with his and he finds good agreement, except for ω Centauri.

SANDAGE

One would expect the globular clusters with the weakest lines to be the oldest from the enrichment ideas of FOWLER, HOYLE and others. If the clusters with the shortest period variables are older, then this expectation would not be realised, because the clusters with short-period variables have the more normal spectra. This may argue against the interpretation of period differences as due to age differences.

OORT

Disintegration of Galactic Clusters and Statistics of Their Ages

The assumption that the age of a cluster is given by the brightest main-sequence stars, as indicated by SANDAGE, and that the colour-magnitude diagram of a cluster corresponds to stars having all approximately the same age, appears very plausible. The evidence in favour of the theory of evolution of galactic clusters as summarized by SANDAGE is very convincing.

There is, however, one piece of information which does not seem to fit into this picture, and which has worried me for some time. Why don't we observe more old clusters? The difficulty may be illustrated by the following table, in which the observed numbers of clusters are given for which the earliest stars have spectral types in the limits shown in the first column. The table was compiled from the catalogue published by TRUMPLER (1930). The statistics will have been influenced by selection effects, because the clusters with early-type stars will be discovered more readily and up to greater distances. We have therefore confined ourselves to clusters whose distances according to TRUMPLER are less than 1000 pc, and have divided these again into two groups, with distances less than 500 pc and between 500 and 1000 pc, respectively. There appears to be no conspicuous difference between the results for these two distance groups. It seems safe to assume that the shortage of clusters with main sequences beginning with types later than Ao is a real phenomenon.

TABLE I.

Spectrum earliest stars	*Observed numbers* $r < 500$	$500 < r < 1000$	T (10^6 *years*)	ΔT (10^6 *years*)
O	1	3	10	10
B0	3	1	60	50
B1-2	1	1	150	90
B3-5	8	10	290	140
B6-8	5	10	400	110
B9-A0	8	10	540	140
A1-8	1	5	1800	1260
F0 and later . . .	1	1	long	(1200)

This lack of later-type clusters would seem to indicate that clusters generally disintegrate before they attain ages corresponding to a main-series beginning with A1 or later. The approximate ages computed on the assumption that all main-sequence stars brighter than the earliest stars observed in a cluster have transformed the hydrogen in the convective core into helium and have moved off the main sequence, while the earliest stars present are on the verge of this condition, are given in the next to last column. They refer to the latest spectral type indicated for each line. They were estimated from data given by STRÖMGREN (1952); complete rotational mixing was assumed to have taken place in the core. The last column gives the time, ΔT, during which a cluster would have its earliest stars in the spectral interval concerned.

Should we suppose that clusters have been formed at the same rate during the last 3×10^9 years, that they do not disintegrate to an appreciable extent and that all of them had originally contained O or B0 stars, the numbers of clusters in different spectral stages should be proportional to ΔT. Should some of them not have contained such very-early-type stars at their birth, the relative numbers in the last part of the table would be still higher.

It is evident that the observed distribution does not conform with these expectations. The numbers in the last two lines are about 50 times too low. We must conclude either that the clusters do not live longer than about 500 million years, or that the lives of A0 stars have been underestimated by a factor of 5 or more. The latter appears improbable, for we have already assumed that there would be complete mixing in the nuclear part. It is conceivable that new stars are continually formed in clusters, and that they would thus conserve their young appearance. But the available data on interstellar matter in clusters give no indication that such a rejuvenating process would be in progress. If we discard this possibility, we appear to be forced to the conclusion that in general the clusters do not live longer than about 500 million years.

A cluster can dissolve in two ways. Either it is unstable, like an expanding association, or it is semi-stable, being only gradually disrupted by mutual encounters between its members. In the first case the internal velocities must generally exceed the velocity of escape from the cluster. For a typical specimen like the Pleiades the velocity of escape is about 0.8 km/sec at a distance of 1.7 pc from the centre. This means that the cluster would double its radius in 2 million years and would have become unrecognizable as a galactic cluster in 10 or 20 million years. Ages of the same order would result for most clusters. It should be mentioned that DIECKVOSS (1) has suggested that observations would indicate an expansion of the Pleiades. From an analysis of HERTZSPRUNG's proper motions he found a coefficient of expansion of 4.0×10^{-7} year^{-1}, with a mean error of $\pm$ 1.4×10^{-7}, the coefficient of expansion being defined as the fraction by which the distance to the centre increases per year. As the Pleiades move away from the sun with a velocity of about 6 km/sec, they must show a geometrical shrinking of 0.4×10^{-7} year^{-1}. The true expansion coefficient would therefore be 4.4×10^{-7} year^{-1}, corresponding to an age of 2.3 million years. The corresponding velocity of expansion at 1.7 pc from the centre would be 0.8 km/sec, of the same order as the velocity of escape.

(1) *Naturwissensch.* 40, 505 (1953).

The indication should be considered as quite uncertain and, moreover, concerns only one cluster (2). The ages that can be attributed to expanding clusters are from 10 to 100 times lower than those derived on the evolutionary theories that have been outlined. Acceptance of the idea that clusters are expanding groups would, therefore, mean that we would have to reject the notion of appreciable evolution in any cluster, except in the very youngest ones.

The evidence for evolution in clusters is so convincing that we seem to be forced to accept the other alternative, viz: that clusters are being dissolved by internal encounters. Extensive calculations about this process have been made by CHANDRASEKHAR (3). If due account is taken of the phenomenon which he calls dynamical friction, the disintegration time of a cluster like the Pleiades is found to be 3×10^9 years. This is incompatible with the statistical data shown in Table 1. It would, therefore, appear to be desirable to reconsider CHANDRASEKHAR's calculations and the effects of dynamical friction, taking into account the fact that clusters are not homogeneous bodies as was assumed in these investigations. A reduction factor of at least 5 would be needed to bridge the discrepancy.

Note added October 1957.

Prof. SCHWARZSCHILD has drawn my attention to a recent computation by IVAN KING (4) who has shown that the shrinking of a cluster caused by the "evaporation" of members causes a decrease in the relaxation time. As a consequence, the time needed for total disintegration is shortened by a factor of about 2.5. It was further pointed out to me by SPITZER that the rate of ejection of stars may be larger than estimated by CHANDRASEKHAR because of the influence of tidal forces due to large agglomerations of interstellar clouds.

It appears likely that these and other effects may bring the

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(2) DIECKVOSS himself now considers his discovery of the expansion of the Pleiades to be inconclusive (comment made to W. W. MORGAN June, 1957).

(3) *Ap. J. 98,* 54, (1943).

(4) *A. J. 62,* 144 (1957), abstract.

theoretical disintegration times into accordance with the value of about 0.5×10^9 years suggested by the table given above.

HOYLE

One interesting possibility is that open clusters that start by having O and B type stars would presumably lose mass, due to the O and B type stars losing mass during their evolution. If this were to go on in a more or less gentle fashion, by some spherically symmetrical emission from the surface of the stars at quite low speeds, it would presumably not have disastrous effects on the stability of the clusters, but if at a certain stage the stars began to lose their mass by violent emission then the remaining nuclei after a star had emitted material with violence would presumably get a very considerable recoil from the explosion and this could have the effect of greatly increasing the effective temperature of the cluster and increase the rate of escape.

OORT

I would like to comment on the consequences of accepting that open clusters are expanding objects. If their lives were really as short as ten million years, the number of stars poured into the galactic system from the galactic clusters would be enormous and for the A type stars would be about of the same order as all the A type stars that are now present. One would come to the conclusion that all the stars may have been formed originally in dense galactic clusters, instead of having been formed singly or in associations. But that is pure speculation. I repeat that in my mind the evidence for the evolution of the clusters, and for the halfway long ages of the order of 5×10^8 years, is very strong.

SPITZER

One process that would reproduce the observed distribution would be to evaporate preferentially stars of small mass.

OORT

It would still take rather long.

SPITZER

If the mass of the clusters is rather high a few relaxation times would be enough.

STRÖMGREN

The fact that we are in the neighbourhood of a spiral arm may affect the ratio between the numbers of young and old galactic clusters observed within 1000 pc.

HECKMANN

Furthermore, there is a strong observational selective effect. Only about half of the clusters in TRUMPLER's list have been studied and the loose clusters have been ignored.

MORGAN

We may be missing many F-type clusters in the galactic plane because they are difficult to distinguish from the field stars, due to the absolute faintness of the brightest stars.

NASSAU

STOCK has found some twenty such clusters of this type.