THE HORIZONTAL BRANCH IN GLOBULAR CLUSTERS

N. J. WOOLF
Princeton University Observatory
Received August 5, 1963; revised December 12, 1963

ABSTRACT

The distribution of horizontal-branch stars in the globular cluster M3 has been studied. There are significant differences in concentration to the cluster center between the different kinds of star. It is shown that these differences are not the result of systematic errors of photometry or of the diluting effect of field stars. It is also shown that the differences are probably of statistical significance.

The two ends of the horizontal branch show differences, and the entire horizontal branch has a less concentrated distribution than the red-giant stars. In order of decreasing concentration, the stars are red giants, blue end of the horizontal branch, RR Lyrae stars, and yellow end of the horizontal branch. These differences are interpreted as due to mass loss followed by relaxation of velocities in the cluster. If both observations and interpretation are correct, the order given above is also an evolutionary sequence. The total mass loss responsible for the above effect is more than 20 per cent of the star's original mass.

INTRODUCTION

It may be possible to observe dynamical effects of mass loss if the stars in a globular cluster lose mass at some stage of their evolution. The relaxation times for most stellar orbits are in the range 10^8–10^{10} years. The difference of distribution of two types of stars, differing in mass by 10 per cent, is easily observed in a relaxed cluster. Thus there is a possibility of studying stellar evolution by its dynamical effects.

Our present theory of the evolution of globular-cluster stars is quite incomplete. We believe that we have some idea of the way that main-sequence stars form and evolve into red giants. Beyond that stage there is no more than pure speculation. The horizontal branch, semiregular and globular-cluster cepheid variables, planetary nebulae, and some bright blue stars must all be fitted into any comprehensive scheme.

Since we believe that we understand how stars evolve into red giants (Hoyle and Schwarzschild 1955), we presume that horizontal-branch stars are a post-red-giant evolutionary phase. As more massive stars precede less massive stars along their evolutionary tracks because of the main-sequence mass-luminosity relationship, we presume that present-day horizontal-branch stars were initially more massive than present-day red giants. More massive stars congregate nearer a cluster center than less massive stars because relaxation of orbits leads toward equipartition of energy. So we expect the horizontal-branch stars to collect nearer the cluster center than the red giants. If the reverse happens, it is a sign that horizontal-branch stars are now less massive than red giants, i.e., a sign of mass loss.

Oort and van Herk (1959) attempted to study this phenomenon. They used the RR Lyrae stars as tracers for the horizontal branch, and found them less clustered than the red giants. The same result appeared to exist in all four clusters that they studied, M3, M5, M15, and ω Centauri. Unfortunately the results are very uncertain in M5 and M15, while it has been suggested that in M3 the deficiency in variables near the cluster center is merely a selection effect. Where the star density is high, it is harder to discover variables of small amplitude.

The RR Lyrae stars in the four clusters are about one-third of all the stars on the horizontal branches. If the stars on the horizontal branch could be studied without reference to their variability it would be possible to eliminate this selection effect. Color and magnitude measurements *can* separate horizontal-branch stars unequivocally.

If the horizontal-branch stars have really lost mass, then a further possibility is available. The stellar relaxation time must be comparable to the time of evolution along the horizontal branch for any effect to be observable. Thus the stars that have evolved furthest have relaxed most. If one finds which end of the horizontal branch has relaxed most, one has determined the direction of evolution along the horizontal branch.

To overcome statistical uncertainty, one must study clusters with many stars. Furthermore there must be stars in all parts of the horizontal branch. There are many clusters with a well-populated blue end of their horizontal branch, e.g., M10 and M13. There are fewer clusters known to have a well-populated yellow end of the branch, e.g., 47 Tucanae and Palomar 4. Those with an evenly distributed population are rare. Of the clusters studied by Oort and van Herk, M3 is best in this respect. Existing observations permitted a preliminary study of this cluster.

THE PRELIMINARY STUDY

A color-magnitude diagram was constructed for M3 by Sandage (1953). This array is relatively complete for stars brighter than 17th magnitude in an annulus of outer radius 600″ and inner radius 110″. Messier 3 has been very thoroughly searched for RR Lyrae stars (Sawyer 1955).

TABLE 1

RESULTS OF THE PRELIMINARY STUDY USING PHOTOMETERED STARS ONLY

Radius	Red Giants		All Horizontal-Branch Stars		"Blue" Stars		RR Lyrae Stars		"Yellow" Stars	
	No.	Per Cent	No	Per Cent	No	Per Cent	No.	Per Cent	No.	Per Cent
600″–200″	23	32	115	56	28	43	55	60	32	65
200″–110″	50	68	91	44	37	57	37	40	17	35
Total	73	100	206	100	65	100	92	100	49	100

The catalog of stars was divided into an inner and an outer annulus, as well as the various kinds of stars. The annuli were separated by a circle of radius 200″. The kinds of star were grouped as follows:

a) Red giants. These are all stars brighter than m_{pg} 15.0 and redder than color index (C.I.) +0.5.

b) RR Lyrae stars. These were not included in Sandage's catalog and are taken from Mrs. Sawyer's compilation.

c) Other horizontal-branch stars. These are stars brighter than m_{pg} 16.1 and fainter than m_{pg} 15.0. Stars more blue than C.I. +0.1 are called "blue." Stars between C.I. +0.1 and +0.45 are called "yellow." Stars redder than C.I. +0.45 are rejected.

The distribution of these stars is given in Table 1. From this table the following results are apparent: (1) There are proportionately fewer horizontal-branch stars in the inner annulus than there are red giants. (2) The distribution of RR Lyrae stars is similar to the distribution of all the horizontal-branch stars. (3) Of the stars in the horizontal branch, the blue stars are most clustered to the center, and the yellow stars least clustered.

These results are subject to all the selectivities that occurred in the construction of Sandage's catalog. However it seems unlikely that conclusion (3) could be seriously modified by any selection effect since the magnitudes of the stars are so similar.

NEW OBSERVATIONS

New observations have been made to eliminate color or magnitude selection effects. This has been achieved by counting *all* appropriate stars in the region photometered by

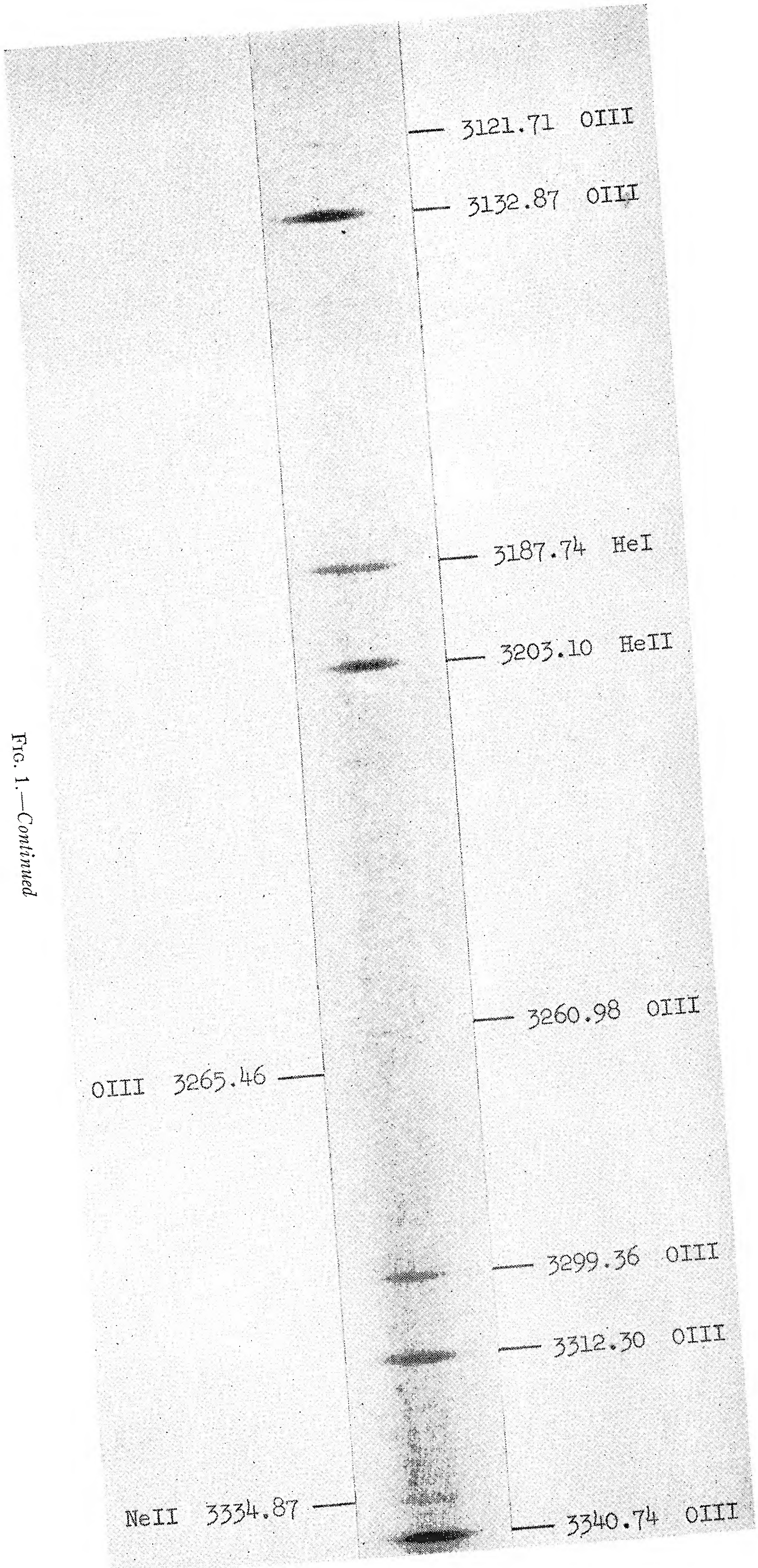

Fig. 1.—*Continued*

Sandage. An iris diaphragm photometer can be used to make accurate measurements only when star images are relatively well separated. This is the reason for Sandage's catalog being incomplete. It was therefore decided to complement Sandage's catalog by blinking red and blue plates. This is possible so long as the cores of images do not overlap. Difficulties occurred with only one pair of stars in the new plate material.

The new material consists of nine plates taken at the prime focus of the Lick Observatory 120-inch reflector by G. H. Herbig and N. U. Mayall. These were all taken with a coma corrector in place. One plate taken by S. Vasilevskis with the 36-inch refractor was also used. The blue photographs were all obtained on 103a-O plates with filter. The red plates were on Eastman Exp. Pan 5–2 with a 2 mm RG 1 filter. This plate and filter combination gives a color baseline almost double that of the conventional C.I. system. This was important in obtaining high accuracy with the relatively crude colorimetry used.

A pair of plates was selected so that the red and blue images matched for a star of m_{pv} 15.5 and C.I. +0.45. All stars that had not been measured by Sandage and that were not known RR Lyrae stars were then blinked to see if they were more blue than this. All uncertain stars were then checked against nearby stars with a C.I. close to +0.45. The few blue stars obviously fainter than m_{pv} 16.1 were rejected. Their scarcity made this selection procedure amply adequate. A second pair of plates was then selected with images matching in the RR Lyrae star color gap. This pair of plates was used to divide the "blue" stars from the "yellow" ones. A repetition of this work at a later date gave substantially similar selection.

TABLE 2

RESULTS OF THE FINAL STUDY USING ALL STARS IN THE REGIONS

Radius	Red Giants		All Horizontal-Branch Stars		"Blue" Stars		RR Lyrae Stars		"Yellow" Stars	
	No.	Per Cent	No	Per Cent	No	Per Cent	No.	Per Cent	No.	Per Cent
600″–200″	53	29	130	37	34	27	55	42	41	44
200″–100″	70	39	130	37	54	42	45	34	31	33
100″–60″	58	32	94	26	40	31	32	24	22	23
Total	181	100	354	100	128	100	132	100	94	100

The red giants not selected by Sandage were first selected on the 120-inch plates. However the relatively crisp overexposed images did not permit a good distinction between stars just fainter or just brighter than 15th magnitude. It was found possible to separate these on the refractor plate because of the large growth of image with magnitude.

Because of the ease with which this work could be carried out, the survey was extended toward the cluster center. The extension was stopped at a radial distance of 60″ from the cluster center. It is believed that in this extension the full accuracy of the original measures has been maintained. However, the extension is only used to give supporting evidence for the phenomena discussed. The final results are given in Table 2.

Some of the stars included in this survey must be field stars. Malmquist (1936) has studied the frequency of stars of different colors in this region of the sky and Seares, Van Rhijn, Joyner, and Richmond (1935) have studied the distribution with magnitude. In the region studied six stars are expected to have simulated the conditions for acceptance as red giants. Most of these should have been in the outer annulus. Two obvious bright field stars were rejected in this region. Only two psuedo-horizontal-branch stars are expected. Thus if more field stars than proposed here are present in the same color proportions, the actual cluster star distribution effects must be even more pronounced than we here suppose.

The systematic errors of Sandage's photometry have been determined. The blue stars of the horizontal branch should have a color independent of their position in the cluster. In the region of the cluster from radii 110″–200″, the mean color of these stars is $+0^m.02 \pm 0.02$ more red than in the annulus from 300″–600″ radii. In the critical region of the diagram there is approximately one star per $0^m.01$ in color.

This critical region of the diagram is at C.I. +0.45. The blinking also is presumably critical in this region. The estimated random errors of blinking were about $0^m.04$ per star. Since every doubtful star was compared with nearby measured stars of similar color, it is believed that systematic errors in the blinking were negligible.

Upon examination of Table 2, all three of the original conclusions appear to be confirmed. The results were checked for significance using a χ^2 test with Yates correction. The peculiar distribution of the blue and yellow stars compared to one another could arise once in thirty-eight tries if it were a random deviation in sets of stars with similar average distributions. The difference between the distribution of the horizontal branch as a whole and the red giants could arise by chance once in ten tries. These two probabilities, neither very large on its own, are independent, and thus in terms of the physical explanation proposed, where the presence of the second effect implies that there should be an effect of the first kind, though uncertain in direction, the probabilities are multiplicative. After correcting for the possibility that a peculiar distribution of the horizontal-branch stars could occur a priori in either sense, the probability that a real effect has been discovered is 190:1.

INTERPRETATION

Sandage has studied the evolution of these stars by semi-empirical tracks (Sandage 1957). The author has repeated this study using more recent stellar models for the early stage of stellar evolution (Woolf 1962). Although the age of the cluster is increased, the time that stars take to evolve along the horizontal branch is hardly changed from Sandage's calculation. This time is 2.3×10^8 years. Evolution up the final 3 magnitudes of the giant branch takes a similar time.

The relaxation time for stars in M3 has been calculated by Oort and van Herk. For stars with the velocities of red giants, the relaxation time is 1.5×10^8 years at the cluster center, and 2.1×10^9 years at a radial distance of 70″.

These figures are not certain, largely because of observational difficulties in determining the velocity dispersions in clusters, but also because there are an unknown number of white dwarfs of uncertain mass. The relaxation times given are probably correct to a factor of 2 or 3. If they were exact, the effect that has been observed would be surprisingly large. The way that stars would move from the central and outer zones of a cluster has not been investigated, so that it is not known which relaxation time is appropriate. With present uncertainties it does not appear improbable that the relaxation time appropriate for these stars is comparable to the time taken for them to evolve along the horizontal branch.

There are several phases in the life of globular cluster stars in which appreciable mass loss may or does occur. One planetary nebulae is known to exist in a globular cluster (Pease 1928). From estimates that their lifetime is 10^4–10^5 years, it appears plausible that all globular cluster stars go through this phase. The mass of gas ejected by a planetary nebula is perhaps 0.1 $M_\odot$. There is mass loss from high-luminosity, low-mass stars (Deutsch 1956; Woolf 1963). There may be mass loss from stars as they leave the tip of the red-giant branch, perhaps associated with the dynamical consequences of the helium flash (Schwarzschild and Härm 1962). Finally, both J. B. Oke and M. Schwarzschild have pointed out to the writer that there is likelihood of considerable mass loss in the RR Lyrae variable phase.

We are now in a position to propose an evolutionary scheme (Fig. 1). When the stars reach the tip of the giant branch they become mixed. This transfers the stars to a new high-luminosity, helium-rich main sequence. Further evolution occurs to the right across the Hertzsprung gap (Schwarzschild 1958). Immediately after the first loss of mass, the stellar orbits begin to relax. However, it is not clear from existing evidence where the major mass loss takes place.

In a cluster in dynamical equilibrium, consider two points, r_1 and r_2, at different radial distances from the center. The space densities ρ_A and ρ_B of two groups of stars of individual masses M_A and M_B are related by equation (1).

$$\frac{\log(\rho_{A,r_1}/\rho_{A,r_2})}{\log(\rho_{B,r_1}/\rho_{B,r_2})}=\frac{M_B}{M_A}. \tag{1}$$

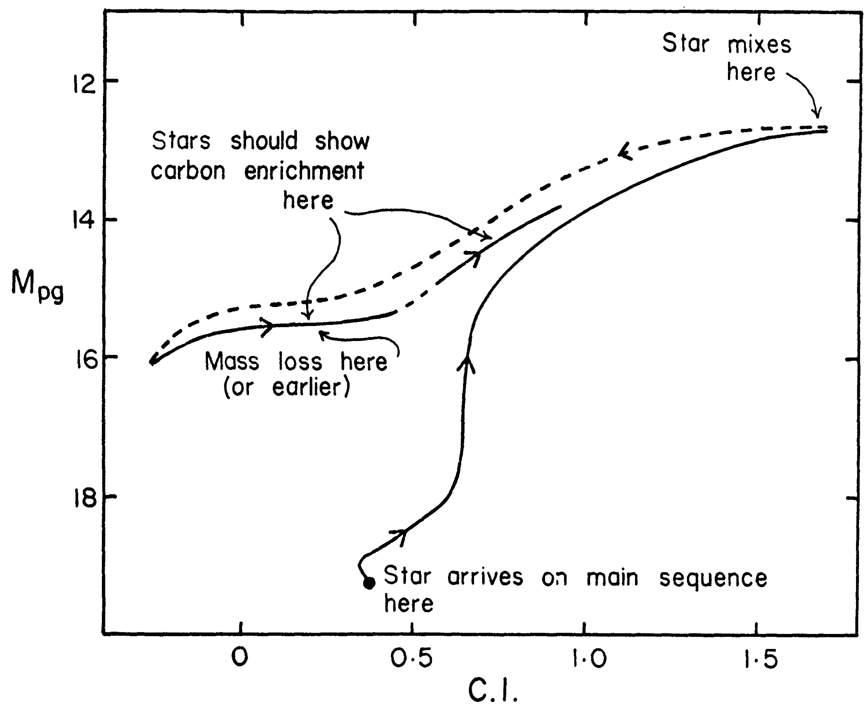

FIG. 1 —Color-magnitude diagram for M3 showing the proposed evolutionary scheme

The densities appropriate for equation (1) are space densities, and the densities that are obtainable from the figures of Table 2 are surface densities.

The logarithm of the surface density can be crudely approximated to vary linearly with radius from 60″ to 600″. Thus the gradients of space density are approximately proportional to gradients of surface density. If one were to assume that relaxation was complete, the present star distribution would imply that the average horizontal-branch star has lost 14 per cent of its initial mass, and the yellow stars have lost 19 per cent of theirs. Since relaxation is probably incomplete, the actual mass loss must be substantially greater. In connection with this result, it may be significant that studies of RR Lyrae stars tend to predict lower masses than those of the red giants if reasonable pulsation constants are assumed (Oke, Giver, and Searle 1962).

OTHER CLUSTERS

Three other clusters exist with good information about the distribution of horizontal-branch stars. In ω Centauri the distribution of red-giant and RR Lyrae stars differs even more strikingly than in M3. To explain this result by observational selection would require that more than twenty variables have been missed within 6′ of the cluster center. The cluster center is very open.

The other two clusters, M13 and NGC 6397, have blue horizontal branches with few or no RR Lyrae stars. The distributions of blue stars and red giants have been compared (King 1962; Woolley, Alexander, Mather, and Epps 1961). No difference was found. In both clusters, the relaxation time should be short enough to show an effect if one occurs in M3. These results taken together suggest that the major mass loss occurs in the RR Lyrae stage itself. This would put some strain on a mechanism for producing so short a relaxation time. On the other hand, it may be that the same factors that determine the color of the horizontal branch also determine whether there is appreciable mass loss in the giant branch.

If the relaxation time is very short, one might hope to see RR Lyrae stars that have recently been ejected from the center of clusters by close encounters. Kurochkin (1959) has made such a study. There are three variables far from the center of M3, RV CVn, SP3-1264 and SP3-1276 at projected distances of 25′, 18′, and 28′ from the cluster center. Since the galactic tidal cutoff should be at about 30′ radius, it is not obvious whether any of these stars have been recently ejected, or whether they are still cluster members.

STELLAR EVOLUTION

If a star at the tip of the giant branch of a globular cluster were suddenly mixed, it would move to lower luminosity on a time scale set by convective energy transport. Then, on reaching a luminosity similar to that of the horizontal branch, it would start to move to the left of the H-R diagram toward a helium-rich, hydrogen-burning main sequence. This motion would proceed on a Kelvin time scale. The entire process resembles the original contraction to the main sequence (Hayashi 1961). Appropriate "main-sequence" models have been discussed by Strömgren (1952). The further evolution occurs back along a similar path, as Hayashi has shown. The difference between the contraction phase and the blue-to-red evolution phase is, as in the initial evolutionary phases, largely one of direction and speed.

It is appropriate to ask whether such evolution could result in the doubling of the giant branch, commented upon by Arp (1955) and Hayashi, Hoshi, and Sugimoto (1962). This is important, because the closeness of these branches near their tips is used as an argument for continuous stellar evolution between these branches. A star reverses its direction at the tip, moving slowly down in luminosity afterward. In contrast, we assume that it moves rapidly in this phase: the main population of the second giant branch consists of stars at a later stage of evolution, moving upward in luminosity.

At present one can only discuss this point in a very qualitative way. The various models that have been evolved by, e.g., Demarque and Geisler (1963), show that a helium-rich star starts its surface-convection-zone rise in luminosity at a higher temperature than a hydrogen-rich star. An increase in heavy elements results in a lowered gradient of evolving track, in the sense that a star becomes cooler as it becomes more luminous. The two giant branches of all globular clusters differ in both these respects.

The models of Schwarzschild and Härm do burn a few per cent of their mass to carbon before they reach the most likely place at which mixing might occur. Thus both helium and carbon enrichment of the stellar envelope should occur if there is mixing. Until a detailed theory is available one can say only that both schemes of evolution could result in there being a second giant branch.

In connection with the production of carbon, the production of oxygen has also been examined. It was concluded that no appreciable amount of oxygen is produced during the helium flash. To the best of the author's knowledge, there have been no determinations of the carbon abundance in horizontal-branch stars. If mixing has been thorough, it should appear at the surface in comparatively large quantities. A CH star has been found in the giant branch of ω Centauri (Harding 1962). Again, if the ideas proposed here are correct, all stars in the second part of the giant branch should be carbon-rich.

It should be noted that the suggestions proposed in this paper are dependent upon there being both mixing and mass loss. One alone is not enough. Both of these effects should be susceptible to observation by different means. Mixing should be examined spectroscopically. Mass loss is harder to observe. It is hoped to continue observations like those described in the present paper with the aid of Stratoscope II.

The results given here are scarcely adequate to use to propose a scheme of stellar evolution. However, further observations will be slow to come, so that it appears appropriate to present the results at this stage.

CONCLUSIONS

From the observational results discussed in this paper the following conclusions are drawn: (1) During red-giant or horizontal-branch evolution, probably the latter, stars in M3 lose at least 20 per cent of their initial mass; (2) evolution occurs slowly along the horizontal branch in the direction blue to red; and (3) the relaxation time in M3 is sufficiently short for the observed effects to be produced.

At present, Conclusion 3 appears to be the only result in conflict with existing conclusions by others. It has been shown that the evidence on which the present conclusions are based are adequately free from systematic errors. However the statistical significance of the result is only modest (190:1).

Conclusion 2 seems to demand that red-giant stars become mixed before they become horizontal-branch stars. On this basis it is predicted that horizontal-branch stars should show carbon-rich atmospheres. It is believed that the second giant branch of a cluster could be a continuation of the horizontal branch. If this is correct, the stars there should also be carbon-rich.

The major part of this work was carried out at the Lick Observatory during the tenure of a Fulbright scholarship. I am indebted to the Lick astronomers for obtaining the plate material that made this work possible. I should also like to thank Drs. I. King, M. Schwarzschild, and R. Sears for several stimulating discussions and encouragement while this work was in progress.

REFERENCES

Arp, H. C. 1955, *A.J.*, **60**, 317.
Demarque, P., and Geisler, J. E. 1963, *Ap. J.* **137**, 1102.
Deutsch, A. J. 1956, *Ap. J.*, **123**, 210.
Harding, G. A. 1962, *Observatory*, **82**, 205.
Hayashi, C. 1961, *Pub. A. S. Japan*, **13**, 450.
Hayashi, C., Hoshi, R., and Sugimoto, D. 1962, *Prog. Theoret. Phys. Suppl.* 22.
Hoyle, F., and Schwarzschild, M. 1955, *Ap. J. Suppl.*, **2**, 1.
King, I. 1962, *Ap. J.*, **136**, 784.
Kurochkin, N. 1959, *Astr. Circ.*, **205**, 14.
Malmquist, K. G. 1936, *Stockholm Obs. Ann.*, Vol. **12**, No. 7.
Oke, J. B., Giver, L. P., and Searle, L. 1962, *Ap. J.*, **136**, 393.
Oort, J. H., and Herk G. van. 1959, *B.A.N.*, **14**, 299.
Pease, F. G., 1928, *Pub. A.S.P* , **40**, 342.
Sandage, A. R. 1953, *A.J.*, **58**, 61.
———. 1957, *Ap. J.*, **126**, 326.
Sawyer, H. 1955, *Pub. David Dunlap Obs.*, Vol. **2**, No. 2.
Schwarzschild, M. 1958, *Structure and Evolution of the Stars* (Princeton, N.J : Princeton University Press), p. 228.
Schwarzschild, M., and Härm, R. 1962, *Ap. J.*, **163**, 158
Seares, F. H., Van Rhijn, P. J., Joyner, M. C., and Richmond, M. L. 1935, *Ap. J.*, **62**, 320.
Strömgren, B. 1952, *A.J.*, **57**, 65.
Woolf, N. J. 1962, *A.J.*, **67**, 286.
———. 1963, *Observatory*, **83**, 260.
Woolley, R. v. d. R., Alexander, J. B., Mather, L., and Epps, E. E. 1961, *R. Obs. Bull.*, No. 43.