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AN INDICATION OF GAPS IN THE GIANT BRANCH OF THE GLOBULAR CLUSTER M15

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ABSTRACT

The color-magnitude diagram for all measurable stars brighter than $V = 17.0$ in M15 shows gaps along the giant branch, the most pronounced of which is $\Delta V = 0.9$ mag brighter than the horizontal branch. Less accurate diagrams of other clusters also appear to show this feature.

Comparison of the known errors of measurement, $\sigma(B - V)$, with the observed residuals from the ridge line of the giant branch shows that the intrinsic width of this sequence for $V < 15.25$ is less than $\sigma(B - V) = \pm 0.01$ mag. This gives an upper limit for the variation of the radii of evolving giants as $\delta R/R \simeq \pm 0.02$ at a given luminosity in M15.

I. THE COLOR-MAGNITUDE DIAGRAM FOR M15

The luminosity function for stars on various sequences of the color-magnitude (C-M) diagram of globular clusters gives, among other things, the rate of evolution and clues to the changing internal structure of the relevant stars. Until recently, the labor required to obtain precise enough data to find certain types of fine structure in C-M diagrams has been prohibitive.

However, our principal iris photometer has recently been modified, following suggestions by R. J. Dickens, in such a way that large quantities of photometric data can be obtained and processed efficiently. This work was done by the Astroelectronics Laboratory, under the direction of E. W. Dennison. Encoders have been mounted on the iris diaphragm and on the two coordinate axes. The digitized data are recorded on punched cards with an on-line key punch, and all subsequent analysis is done by computer.

The bright end of the C-M diagram and the luminosity function of stars along the giant branch of the globular cluster M15 have been obtained in a pilot program using this new instrumentation. All uncrowded stars brighter than $V = 17.0$ (664 in total) within an annulus whose inner and outer radii are 1′1″ and 6′20″ were measured on ten plates in each of two colors obtained with the 100-inch reflector diaphragmed to 58 inches. Known RR Lyrae variables were excluded from the sample. The plate and filter combinations were Eastman 103aO + GG13 for B and 103aD + GG11 for V. Magnitudes were obtained relative to sixty-six stars in the vicinity of the cluster which were measured photoelectrically with the 100- and 200-inch reflectors. The standards define the magnitude range from $12.69 \leq V \leq 16.99$, $13.55 \leq B \leq 17.75$. Photographic magnitudes determined from the large number of plates measured here have substantially higher accuracy than we have heretofore obtained in previous studies. The formal probable error, determined from the residuals from the mean for a final B- or V-magnitude for stars brighter than $V = 15.2$, is $\epsilon \simeq \pm 0.012$ mag.

Fourteen of the program stars showed abnormally large residuals from the mean in both colors. Two of the stars were bright red giants near the tip of the giant branch and are likely to be semiregular long-period variables, characteristic of this region of the C-M diagram. The other twelve stars scatter near the horizontal branch and are undoubtedly new RR Lyrae variables. Finding charts will be given in a later paper where the complete photometric data for all program stars will be discussed.

The C-M diagram for all non-variable program stars is shown in Figure 1*a*. Stars near

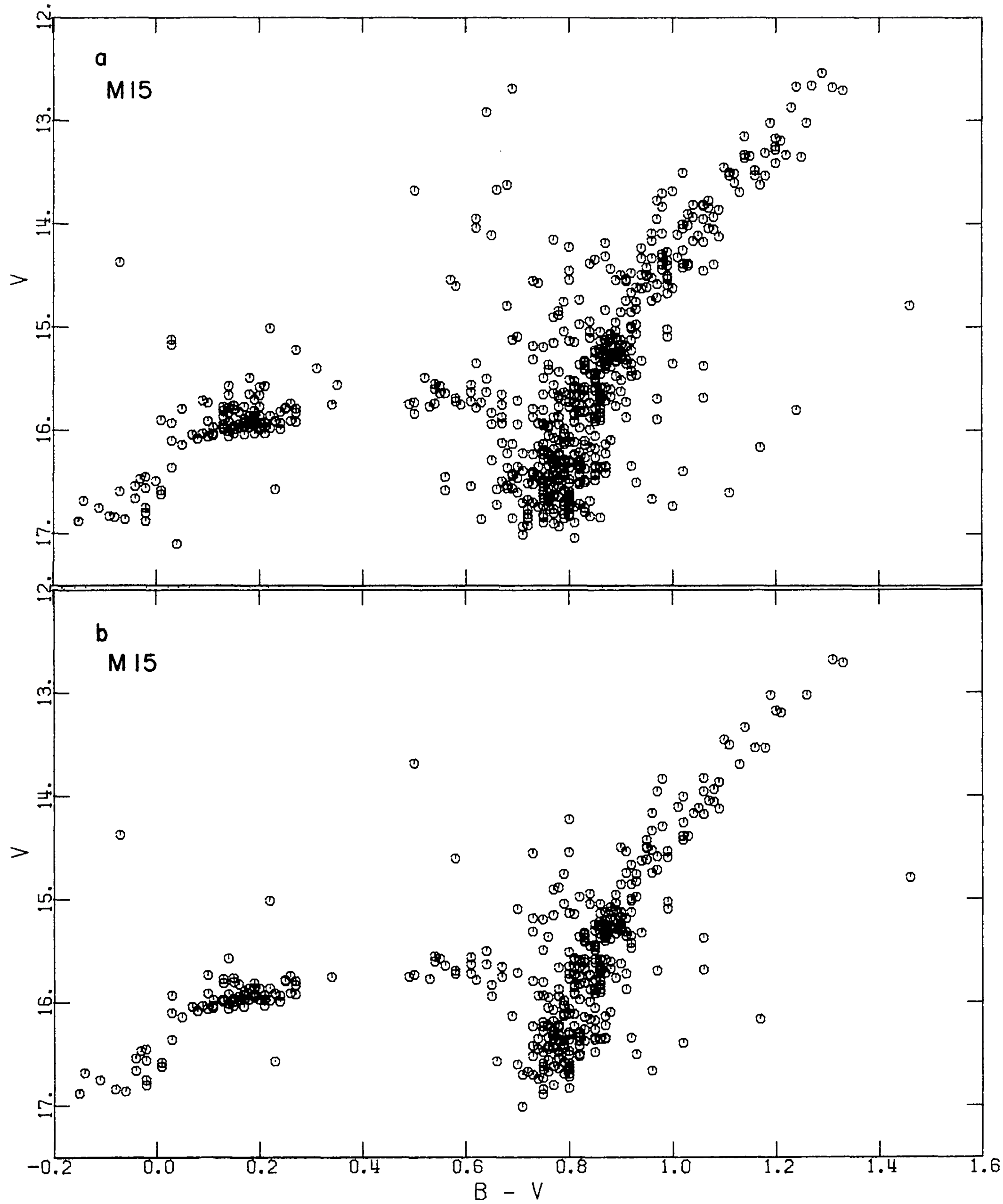

FIG. 1*a*.—C-M diagram of M15 for all non-variable stars brighter than $V = 17.0$ within an annulus of inner and outer radii of 1′1″ and 6′20″. Known variables have been excluded from the sample. Photometric values are from measurements of ten plates in each color, obtained with the Mount Wilson 100-inch reflector diaphragmed to 58 inches.

FIG. 1*b*.—Same as Fig. 1*a*, but only for stars whose measuring errors are $\sigma(V) \leq \pm 0.020$ mag, $\sigma(B) \leq \pm 0.023$ mag.

the cluster center have been included, some of which (especially those fainter than $V \approx 15$) suffer from photometric crowding from the unresolved cluster background. We have not yet inspected the original plates near each of these central stars to decide, on a star-by-star basis, which objects are most affected, but the widening of the subgiant branch fainter than $V \simeq 15.2$ is, in part, due to this effect.

To define the sequences better, we show in Figure 1*b* only those stars whose formal σ-values, determined from the residuals of each of the ten plates in each color, are $\sigma(V) \leq \pm 0.020$ mag and $\sigma(B) \leq \pm 0.023$ mag. This restriction has eliminated many stars near the inner edge of the annulus, leading us to suspect that background and crowding problems do exist at the $\Delta(B - V) \simeq \pm 0.03$ mag level for stars close to the cluster center. Nevertheless, this level of accuracy is sufficient to search for fine structure in the distribution of stars along the various sequences. Furthermore, a first estimate of the intrinsic width of the giant branch can be made by taking into account the known errors of measurement for stars brighter than $V \simeq 15$, where the crowding problems are quite small.

II. GAPS IN THE GIANT BRANCH

Visual inspection of Figure 1*a* shows that the distribution of stars along the giant branch is not uniform. An obvious break in the branch occurs near $V = 13.8$, but the

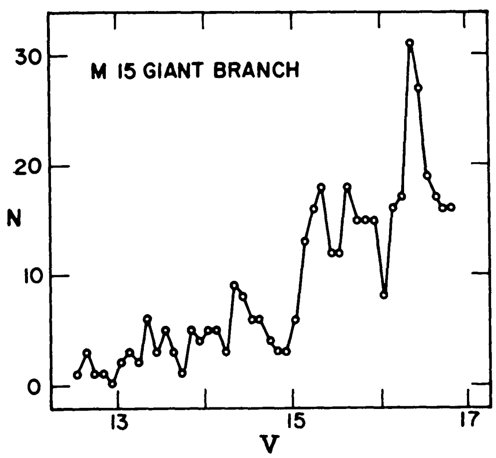

FIG. 2.—Luminosity function in intervals of 0.1 mag for stars along the giant branch of Fig. 1*a*

number of stars above and below the break is too small to make a strong statement concerning the statistical significance of the feature.

A major significant feature occurs near $V = 14.9$, where there is a clear deficiency of stars in an interval of about 0.5 mag in V. The decrease of the luminosity function in this interval, which is centered at $\Delta V = 0.9$ mag brighter than the horizontal branch, is the principal result of the present investigation. Other deeper, but narrower gaps appear at $V = 15.5$ and $V = 16.1$. These two sharp features are especially visible in Figure 1*b*.

The luminosity function, obtained by counting stars in 0.1-mag intervals along the giant branch of Figure 1*a* alone, excluding field stars and stars along the bifurcated or asymptotic giant branch (cf. Arp 1955; Sandage and Walker 1966), is shown in Figure 2. The broad dip, centered at $V = 14.9$ and extending from $V = 14.6$ to $V = 15.1$, is obvious. The narrower gaps at $V = 15.5$ and $V = 16.1$ are also visible.

The statistical significance of the gaps can be tested against the hypothesis that the luminosity curve, $\phi(V)$, is a monotonically rising function of V and that the apparent dips in Figure 2 are not real but are random fluctuations. If $\phi(V)$ were uniformly increasing, passing through the observed points in Figure 2 at $V = 14.35$ and $V = 15.35$, the number of stars expected in the interval $14.60 < V < 15.25$ would be 122, with an expected variance of ± 11. The actual number of stars observed in this interval is sixty-five, with a variance of ± 8. The difference between the expected and the observed number of stars is fifty-seven, which is 4.2 times the combined standard deviation. Such a result should occur less than 1 per cent of the time if the hypothesis is true.

Although suggestive, this evidence alone should not be taken as proof that the gap is real. However, inspection of C-M diagrams of other globular clusters shows the same feature at nearly the same ΔV relative to the horizontal branch as in M15. Particularly good cases, where the number of stars is relatively large, are M5 and M2 (Arp 1955, Figs. 7 and 12), M3 (Sandage 1953), NGC 7006 (Sandage and Wildey 1967, Fig. 3), NGC 362 (Menzies 1967), M92 (Sandage and Walker 1966, Fig. 3), NGC 5897 (Sandage and Katem 1968), and perhaps M53 (Cuffey 1965). Although more work is needed to establish the reality of the gap beyond doubt, the evidence in support of the feature appears strong. To this end we have begun a study of M3 similar to the present work on M15.

The presence of gaps along the giant sequence would show that stars do not evolve at a uniform rate along this sequence. If real, the gaps obviously provide constraints on models of nuclear burning in interior shells as the evolution proceeds.

III. INTRINSIC WIDTH OF THE UPPER GIANT SEQUENCE

The data in the present sample are sufficient to study the intrinsic width of the giant sequence. Figure 3 shows a histogram of the observed residuals, $\Delta(B - V)$, from the

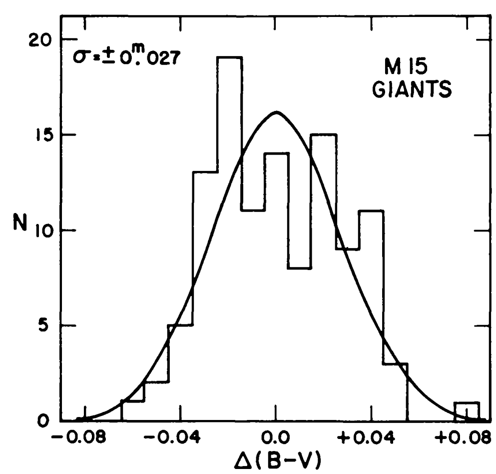

FIG. 3.—Histogram of the observed residuals in $B - V$ from the mean line along the giant branch brighter than $V = 15.25$. A Gaussian with $\sigma = \pm 0.027$ mag and the same area (112 stars) as the histogram is shown.

ridge line drawn by eye through the giant sequence of Figure 1*a*. Field stars and stars along the asymptotic branch have been excluded. Because of possible photometric difficulties with the unresolved background for stars with $V > 15.25$, stars fainter than this limit have also been excluded. The standard deviation of the observed distribution in Figure 3 is $\sigma_0 = \pm 0.027$ mag. A Gaussian with this σ and with the same area as the histogram has been plotted for comparison.

The errors of measurement of $B - V$ for each of the 112 stars in the sample are known from the residuals on each of the ten plates in each color. The $\sigma_M(B - V)$ for each star, due to measuring errors, was found from $[\sigma^2(B) + \sigma^2(V)]^{1/2}$, and the variance in $B - V$

for the entire sample, obtained from $\langle\sigma_M(B-V)\rangle = [\Sigma\sigma_i^2(B-V)/n]^{1/2}$, was found to be $\sigma_M(B-V) = \pm 0.026$ mag. The agreement of this value with the observed dispersion in the C-M diagram itself shows that the intrinsic width of the giant branch is less than ± 0.01 mag in $B-V$ at constant luminosity. This corresponds to an upper limit on the variation of the surface temperature of stars along the giant branch, at a given absolute luminosity, of $\delta T/T = \pm 0.01$. The radii of such stars must, therefore, be constant to better than $\delta R/R = \pm 0.02$, at constant L.

We wish to thank E. W. Dennison and the personnel of the Astroelectronics Laboratory for their design, construction, and maintenance of the data system for the modified iris photometer. This improved instrumentation was carried through at the initial suggestion and active help of R. J. Dickens, who also wrote the first version of the computer reduction program.

REFERENCES

Arp, H. C. 1955, *A.J.*, **60**, 317.
Cuffey, J. 1965, *A.J.*, **70**, 732.
Menzies, J. W. 1967, *Nature*, **214**, 689.
Sandage, A. 1953, *A.J.*, **58**, 61.
Sandage, A., and Katem, B. 1968, *Ap. J.*, Vol. **153**, No. 2.
Sandage, A., and Walker, M. F. 1966, *Ap. J.*, **143**, 313.
Sandage, A., and Wildey, R. L. 1967, *Ap. J.*, **150**, 469.