THE MASS OF THE GLOBULAR CLUSTER M92

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Received July 24, 1953

ABSTRACT

Radial-velocity measurements of 23 spectrograms of 15 red giant stars in M92 are discussed. A mass of $3.3 \times 10^5 \odot$ is derived for the cluster, and the corresponding mass-to-luminosity ratio is 2.0 in solar units. It is probable that there are intrinsic velocity variations in some of the cluster stars.

The recent completion of the coudé spectrograph of the Hale telescope, particularly of the 8″4-focus aplanatic-sphere camera,[1] offers the opportunity for a successful attack on observational problems hitherto beyond the range of existing equipment. One important problem of this type is that of the motions of stars within globular clusters. Is the radial-velocity distribution function the same all over a cluster, or are there systematic differences between the center and the outlying regions? The answer, if obtainable, has a direct bearing on the nature of the dynamical equilibrium of the system.[2]

With the intention of investigating the velocity distribution over the cluster, a number of spectrograms of red giants in M92 were obtained in 1952. Subsequently, exploratory work in other clusters has shown that M92 is the least suitable of the bright globular clusters for this purpose, because of the general weakness of the metallic lines in the spectra of its brighter members. It has been decided, therefore, to discontinue observing M92 and to pursue detailed studies in a more favorable system; and for this reason the material accumulated on M92 is presented here.

Measured radial velocities are in Table 1, where the symbol "B" indicates a star number from Barnard's list[3] and the other designations are co-ordinates measured from the axes used by Baum.[4] Columns headed V_w and V_c are radial-velocity measures by Wilson and Coffeen, respectively, which were obtained in the usual fashion by making settings on star and iron-arc lines with a standard measuring engine. After the measuring was completed, a careful study was made of the results, and a number of lines judged to be spurious were rejected. The wave lengths of a number of other lines were adjusted to remove systematic residuals, and the velocities given in Table 1 are the final values obtained with the adjusted wave lengths. Five of the spectrograms were taken by A. J. Deutsch and one by I. S. Bowen, and we are indebted to these colleagues for permission to utilize this material.

The velocity from a single plate depends in general upon measures of from 12 to 20 star lines; and the probable errors are satisfactorily small, considering the poor quality of the metallic lines and the narrowness of the spectra (about $\frac{1}{8}$ mm). The agreement between two measures of the same plate is also good in all but two or three instances; in fact, the average difference between the two measurers for 17 plates measured by both is only 3.5 km/sec. The situation is less favorable when the velocities from two plates of the same star are examined. Of the seven stars for which there are two plates well separated in time,[5] at least four—B 61, 74, 75, and 82—exhibit differences between the

[1] I. S. Bowen, *Ap. J.*, **116**, 1, 1952.

[2] See, e.g., G. L. Camm, *M.N.*, **112**, 155, 1952.

[3] *Pub. Yerkes Obs.*, Vol. **6**.

[4] *A.J.*, **57**, 222, 1952.

[5] Plates 313–327 were taken in May, 1952; 406–414, in August.

two plates which are disconcertingly large. The reason for these differences cannot be exactly specified, but, for the present, one would be inclined to attribute them to intrinsic variations in the stars themselves. If this is so and if such variations prove to be a general characteristic of the red giants in globular clusters, it is clear that detailed studies of the internal motions in the clusters are going to be difficult and time-consuming.

The dependence of the mass of a cluster upon the internal motions can be found if the potential function is known. R. Kurth[6] has derived an approximate expression based upon a hypothetical division of the total mass between a point at the center and a surrounding sphere of uniform density. His equation, adequate for our purpose, is

$$M = 800\overline{(\Delta V)^2}r\ , \tag{1}$$

where ΔV is the deviation of radial velocity of a star from the cluster velocity in kilometers per second and r is the cluster radius in parsecs. For M92, Shapley gives the radius as 21 psc.[7] The other quantity in equation (1), $\overline{(\Delta V)^2}$, is to be derived from the measured

TABLE 1

RADIAL VELOCITIES OF STARS IN M92

(Km/Sec)

Star	x	y	Plate (Pe)	V_w	V_c	Plate (Pe)	V_w	V_c
B 39	....	....	.....	....	....	421	−128.2±2.7	−121.0±2.1
43	....	....	.....	....	....	417	−123.4±2.5	−119.2±1.6
54	....	....	.....	....	....	420	−128.2±2.2	−128.9±2.6
61	....	....	322	−116.7±2.2	−115.6±1.3	410	−127.4±2.0	−123.0±1.6
62	....	....	327	−113.7±2.5	−118.3±1.7	413	−112.9±2.2	−121.5±1.8
74	....	....	319	−116.2±1.9	−117.6±1.7	409	−120.0±1.9	−123.8±2.0
75	....	....	325	−124.2±2.1	−126.9±2.1	414	−113.3±2.3	−115.4±1.9
82	....	....	315	−113.1±1.6	−112.6±2.1	408	−117.2±2.7	−118.9±2.4
85	....	....	314	−117.5±3.4	−114.3±2.4	407	−116.2±1.7	−118.9±2.6
88	....	....	313	−128.8±2.3	−129.7±2.0	406	−131.1±1.6	−141.5±2.2
III-13	+2′.65	+4′.61	914	−117.5±2.5	....	929	−111.6±1.1	....
III-65	+1′.27	+2′.54	.....	....	....	928	−124.3±2.0	....
VII-18	−5′.35	−1′.91	.....	....	....	297	−122.7±0.9	....
X-49	+1′.01	−2′.49	.....	....	....	927	−135.8±2.5	....
XII-34	+2′.60	−0′.53	.....	....	....	917	−112.6±1.6	....

radial velocities, with proper correction for scatter not due to real velocity differences between stars.

The data of Table 1 were treated as follows: For plates measured by both of us, the mean of the two measures was formed, and the values of ΔV were obtained by taking the differences of these means from the general mean of all the measures, −121.0 km/sec. Where only one measure was available, the corresponding ΔV followed directly, and no differences in weight were applied, whether a ΔV depended upon one or upon two measures. The measured mean-square deviation $\overline{(\Delta V)^2_m}$ obtained in this fashion is 45.7 (km/sec)^2.

A value, or rather estimate, of the deviation due to other causes than real differences in velocity between stars can be had only from those stars for which there are two plates. The differences between the mean velocities for the two plates have been taken for each star, and the mean of these quantities, without regard to sign, is considered to be a mean deviation (M.D.) between epochs. Table 1 yields M.D. = 5.8 km/sec. Multiplication of

[6] *Zs. f. Ap.*, **29**, 26, 1951.

[7] *Pop. Astr.*, **57**, 203, 1949.

the M.D. by 1.25 then gives $\sigma_e^2 = 52.5$ (km/sec)^2 for the standard deviation between epochs.

The true mean-square deviation $\overline{(\Delta V)_T^2}$ should be related to the other quantities mentioned above through the expression

$$\overline{(\Delta V)_T^2} = \overline{(\Delta V)_M^2} - \sigma^2 , \qquad (2)$$

where the standard deviation σ is measured from the mean velocity for each star, which is, however, unknown.

Consider the two plates on a given star taken at two epochs, and let the measured velocities be V_1 and V_2 and the deviation from the true mean velocity for the star be ϵ_1 and ϵ_2. Then, if V_T is the true mean velocity for the star,

$$V_T = V_1 + \epsilon_1 = V_2 + \epsilon_2 .$$

Also

$$V_1 - V_2 = \Delta V = \epsilon_2 - \epsilon_1 .$$

Since there is no relationship between ϵ_1 and ϵ_2, it follows that

$$\overline{(\Delta V)_M^2} = \overline{\epsilon_2^2} + \overline{\epsilon_1^2} = 2\sigma^2 .$$

In other words, the value of σ^2 to be used in equation (2) should be half of σ_e^2, or 26.2 (km/sec)^2. Hence, from equation (2) one finds $\overline{(\Delta V)_T^2} = 19.5$ (km/sec)^2, and then, from equation (1),

$$M = 3.3 \times 10^5 \odot .$$

From Christie's[8] apparent photographic magnitude of the cluster and a modulus of 15.12, it follows that $M_{\rm pg} = -7.82$. Taking the absolute photographic magnitude of the sun[9] to be $+5.26$, one finds, for M92, in solar units

$$\frac{M}{L} = 2.0 .$$

It does not appear feasible to estimate the order of accuracy of these results. Kurth's equation is an approximation which can be improved only by greater knowledge of the true potential function for the cluster. Also, our determination of σ is based on less extensive material than is desirable. Nevertheless, it is perhaps not unreasonable to expect that the foregoing values are not in error by more than factors of the order of 2 or 3.

We are greatly indebted to Dr. G. Strömberg for helpful discussion of the method of treating the data.

[8] *Ap. J.*, **91**, 8, 1940.

[9] G. P. Kuiper, *Ap. J.*, **88**, 429, 1938.