GLOBULAR CLUSTERS AND THE STRUCTURE OF THE GALACTIC SYSTEM

By Harlow Shapley

The continuation of my work on clusters has yielded information that seems to have some significance in the problem of the extent and arrangement of the general sidereal system. During the past two years the magnitudes of several thousand stars in thirty globular clusters have been measured, some rather extensive studies of variable stars and open clusters have been carried out, and methods have been investigated for the determination of the distances of clusters and variables. The results are discussed at length in several contributions from the Mount Wilson Solar Observatory, which are now in process of publication and will appear within a few months. Meanwhile the more striking features may be briefly outlined, omitting, as is necessary for an article of this kind, the computations and numerical tables. In fact, the present announcement can be little more than a summary of methods, observations, and conclusions, and indulgence must be asked for presenting these results in advance of the observational material upon which they are based. The accompanying diagrams, however, may partially serve in the place of tabular data.

A. Methods of Determining the Distances of Globular Clusters

1. The parallaxes of stellar systems that are too remote for direct trigonometrical measurement are best determined from the luminosities of the individual stars they contain. To give such a method accuracy, we must first find stars both near the Sun and in the distant system having intrinsic luminosities which, within allowable uncertainties, are comparable, and in the second place we must be able to derive the absolute magnitudes of such stars near the Sun. To estimate provisionally the distances of the *Perseus* cluster and the Small Magellanic Cloud, Kapteyn has used the B-type stars, for which the differences in real brightness are not great and for which the absolute magnitudes are determined with considerable certainty from proper motion data. Hertzsprung, on the other hand, has resorted to the use of Cepheid variables to estimate the parallax of the Small Magellanic Cloud, basing the value of the absolute luminosity on a discussion of parallactic

motions for galactic Cepheids and using mainly Miss Leavitt's well-known work on the variables in the Cloud as evidence of the small dispersion of luminosity. The giant red stars form a third type suitable for such work.

2. All three of the above stellar types are common in globular clusters, and when used for parallax work give results in satisfactory agreement. The Cepheid variables, however, are of so much greater weight, because of more definite knowledge of the dispersion of absolute brightness, that the other types can best be used as checks or as secondary standards. In many clusters all of these highly luminous objects are of very faint apparent magnitude, indicating that the distances are uncommonly great.

3. The galactic Cepheids with well-determined proper motions are few in number, but they are well distributed over the sky; their peculiar proper motions and radial velocities are small in comparison with the parallactic motions, and they show no preferential drift. With relatively small computed probable errors, the mean parallax and luminosity were derived independently by Hertzsprung and Russell, and have been recomputed by the writer. It is found that Cepheids are giant stars, with parallaxes rarely exceeding a few thousandths of a second of arc. Direct measures of distance, so far as they have been attempted, confirm the high luminosities, but in the mean the parallactic method gives absolute magnitudes appreciably brighter. An inquiry into the possible systematic errors in the proper motions reveals nothing capable of affecting to any important degree the adopted mean absolute magnitude, which is further checked thru the luminosities of the B-type stars and the red giants in clusters.

4. For the work on clusters the relation between period and luminosity has been thoroly investigated. Data for between two and three hundred typical variables with periods ranging from a few hours to a hundred days have been collected from five globular clusters, the Small Magellanic Cloud, and the galaxy proper, to form a curve which shows that total light emission is a simple function of period of light variation (Fig. 1*a*). For all periods less than a day the median absolute magnitude is nearly constant at -0.4, visually a hundred times brighter than the Sun. The luminosities of Cepheids with longest periods exceed -4.0 and apparently are rarely surpassed by other stars:

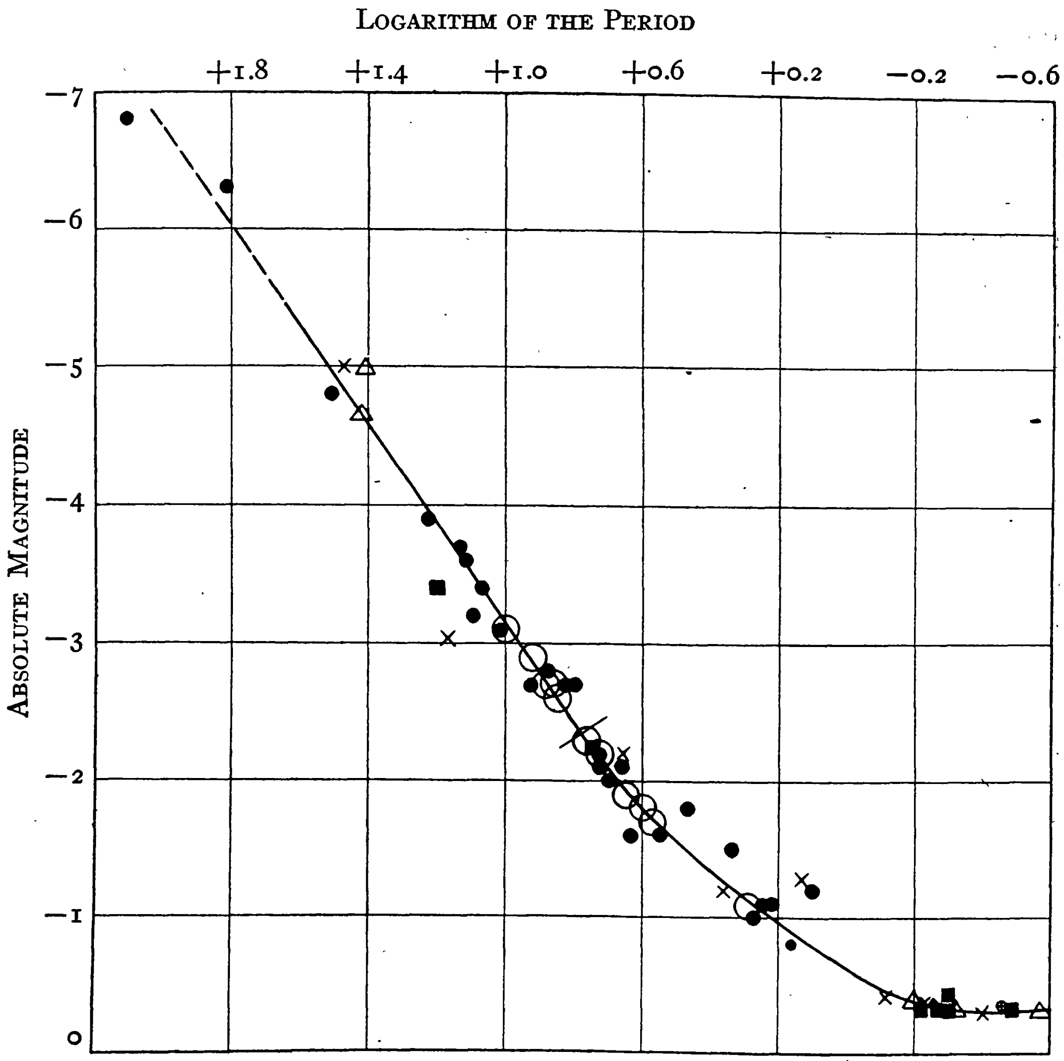

FIG. 1*a*. Luminosity-period curve of Cepheid variation. The various symbols designate variables from different systems, the large open circles referring to galactic Cepheids. The bisecting line at absolute magnitude = −2.35, log period = 0.775, indicates the mean values for Cepheids of known proper motion. Most of the symbols for periods less than a day represent averages of about ten variables.

5. The luminosity-period curve gives immediately the parallax of Cepheids of measured apparent magnitude and known period. It also gives the distance of the clusters whose variable stars have been sufficiently investigated.

6. A comparison of the magnitudes of the bright stars and the cluster-type variables in ten globular clusters fixes the mean absolute photographic magnitude of the 25 brightest stars* of each at −1.5, with an estimated uncertainty of 0.4 mag. This relation permits the determination of the distances of all clusters for which

*After excluding the five most luminous stars in order to make sure that non-cluster stars and chance superposition of stellar images do not affect the result unduly.—*Mt. Wilson Communication*, No. 47, 1917.

accurate measures of photographic magnitude are possible, without the necessity of extended investigations of variable stars.

7. The 25 brightest stars of each system are chiefly the red giants to which reference was made above. These results indicate that there exists a definite upper limit to the luminosity attainable by stars—a limit that appears to be a function of mass.

8. For 30 clusters, whose magnitudes were obtained with the 60-inch reflector, a plot of the parallaxes against the diameters, as measured on the Franklin-Adams charts, gives a very definite curve (Fig. 1*b*), which is used to determine the distances of all clusters now recognized as globular. Nearly 90 per cent of them are on charts made from the uniform series of Johannesburg plates; the homogeneity of the results and serviceability of the method are attested by the small deviations from the parallax-

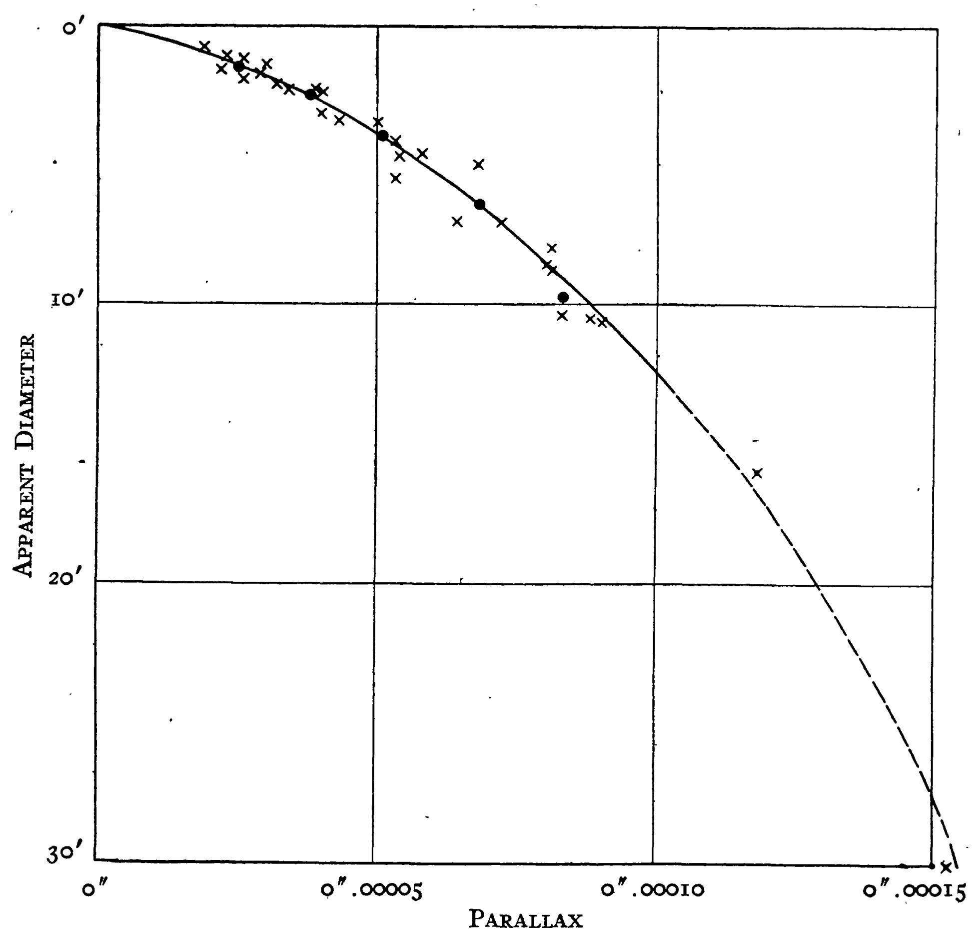

FIG. 1*b*. The parallax-diameter curve for globular clusters. Black dots are normals based upon parallaxes from magnitudes; crosses are the values for individual clusters.

diameter curve. For many clusters the parallaxes may be derived by two or three of these methods.

9. Irrespective of the adopted absolute magnitude and of future redetermination of the luminosities of Cepheids, the relative distances, based upon the above methods, are of considerable value and, of course, are much more accurately determined than the absolute quantities; but a careful consideration of the errors involved in all the operations indicates that the probable errors of the absolute distances are rarely in excess of 25 per cent, and more often fall below 20 per cent. The computed distances and dimensions would have been still greater than those given below if more weight had been placed on the blue stars; but various lines of evidence indicate that the brightest B-type stars in a cluster are not strictly comparable with the most luminous B's of the galaxy.

B. The Distribution in Space of 69 Globular Clusters

1. The survey of the distances and space distribution of globular clusters may be considered complete except for some whose brightest stars are fainter than the 16th photographic magnitude; that is, complete up to a distance of 30,000 parsecs* from the Sun[1].

2. The nearest globular clusters, *ω Centauri* and 47 *Tucanae*, are just less than 7,000 parsecs distant; the average distance of 69 systems is 23,000 parsecs. The parallax of the most distant now known, N. G. C. 7006, was first found from diameter measurement alone to be $0''.000015$, corresponding to a distance of 67,000 parsecs; within the last month magnitude observations have been secured, giving $\pi = 0''.000014$—a highly satisfactory confirmation. One-fourth of the clusters are more distant than 100,000 light-years (30,000 parsecs).

3. North of the galactic plane are 32 recognized clusters; south of it are 37. Their average distance from the plane is 6,900 parsecs, and the algebraic mean of the distances is only -100 parsecs. There can be no doubt that the galactic plane is the fundamental and symmetrical plane in the system of globular clusters.

4. The apparent concentration of globular clusters in the direction of the richest part of the galaxy has been known since the time of the Herschels. More than half of them have galactic longitudes between 300° and 350°, with a conspicuous maximum at 325°, while between longitudes 45° and 190° there is none.

*A parsec is the distance corresponding to a parallax of one second of arc.

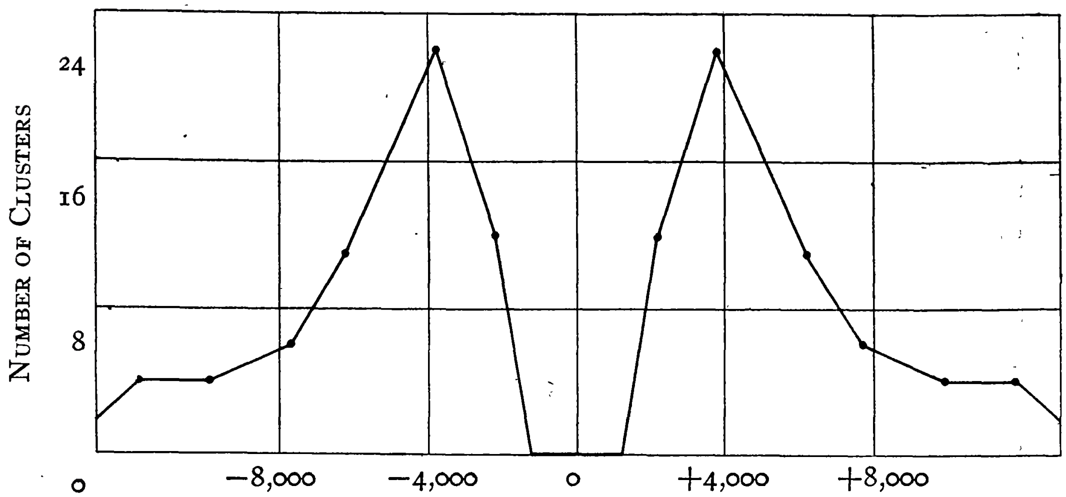

FIG. 2a. Reflected frequency-curve of distances from the galactic plane, illustrating the equatorial region avoided by globular clusters. The unit of distance is one parsec, the equivalent of about three and a fourth light-years.

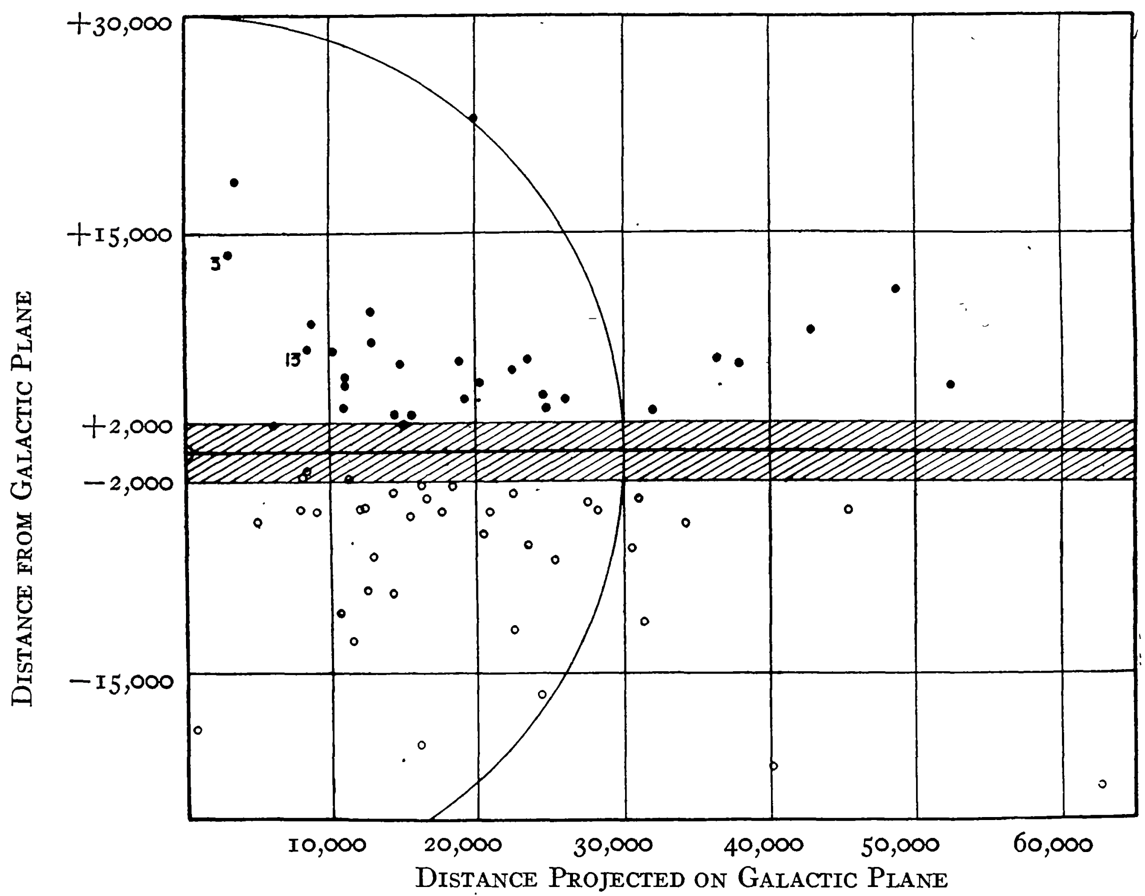

FIG. 2b. Distribution of globular clusters, illustrating the segment of avoidance. The unit of distance is one parsec. The small semi-circle, with radius corresponding to a parallax of 0″.002, illustrates the region around the Sun that contains all but a few of the stars in Charlier's B-type cluster. The large semi-circle shows the distance to which the present results are thought to be complete. N. G. C. 4147, with co-ordinates 10,900 and +51,400, is not on the diagram. The well-known clusters, Messier 3 and Messier 13, are indicated by numbers.

5. Two clusters, N. G. C. 7006 and 4147, are separated by a distance of 100,000 parsecs, which may be taken for the present as the diameter of the system of clusters. The center of the system appears to be at a distance of about 20,000 parsecs, but there is considerable uncertainty in this estimate because of the probable lack of complete data for clusters more distant than 30,000 parsecs. The center, which lies in the region of the rich star clouds of *Sagittarius* near the boundary of *Scorpio* and *Ophiuchus*, has the coördinates R. A. = $17^h\ 30^m$, Decl. = $-30°$.

6. The equatorial segment of the system of clusters is devoid of all globular clusters—a phenomenon that can not be accounted for by error in the coördinates of the galactic pole, by incompleteness of data, by scattering or obstruction of light in space. The smallest distance from the plane is 1,300 parsecs. Figs. *2a* and *2b* illustrate the region of avoidance.

C. Variable Stars and Stellar Luminosity

1. With the aid of the luminosity-period curve, the parallax, luminosity, and distribution in space of 155 Cepheid variables of the galactic system have been derived from available magnitudes and periods. Of the 124 for which the results are considered most definite, 32 have periods shorter than a day.

2. The well-known concentration of ordinary Cepheids to the galactic plane and the indifference to that plane on the part of the isolated cluster-type variables are shown in the present results. The most distant variables are 6,000 parsecs away, and two of the cluster-type are outside the region of avoidance.

3. Spectroscopic observations by Adams of a few isolated cluster-type variables indicate radial velocities between 50 km/sec and 300 km/sec. From the known proper motions of XZ *Cygni* (unpublished determination by Tucker) and RR *Lyrae*, I find their space velocities to be 400 km/sec.

4. The wide dispersion in galactic latitude of cluster-type variables may simply be the result of their extraordinary speeds; being stars of high luminosity, they present a striking deviation from the luminosity-velocity relation of other stars.[2]

5. The general characteristics of the luminosity-period curve (Fig. *1a*) may be accounted for on the pulsation hypothesis of Cepheid variation.

6. The composite color curve of a hundred variables in Messier

3 shows the periodic change in color typical of Cepheids, and thru giving values of the color in agreement with the well-known changes of spectral type, affords an excellent check of the magnitude scales to 16.0 mag.

7. In the most distant clusters, some of which are of low galactic latitude, negative color-indices appear and the typical variables show normal colors and color-variations, further indicating the absence of light scattering in space. Evidence of light obstruction appears for only two clusters, one of which is on the border of the *ρ Ophiuchi* nebulosity; the effect is being investigated.

8. An examination of the magnitudes, with special reference to the color of 50 cluster-type variables in Messier 15 shows that the median brightness is independent of the length of the period, at least photographically (corroborating Bailey's results).

9. Measures of the magnitudes of five thousand stars in five globular clusters suggest that the median magnitude also marks a critical luminosity for the stars that are not variables. The

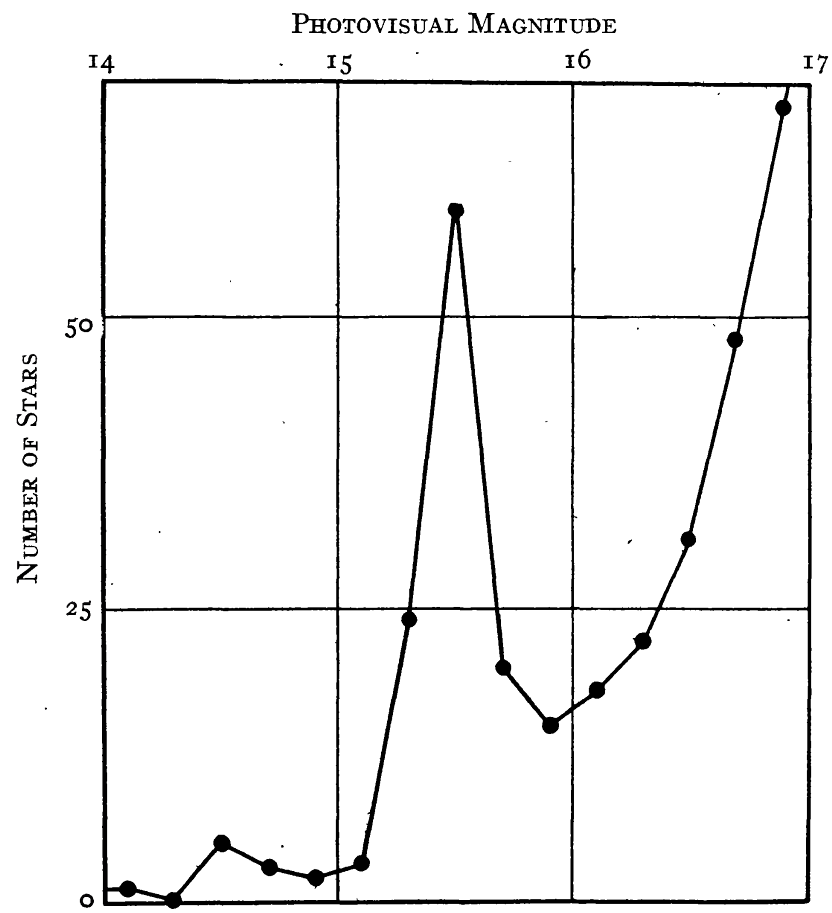

Fig. 3. Luminosity curve of blue stars in Messier 3. Variable stars are not included. On the absolute scale the sharp maximum occurs at −0.2.

phenomenon is illustrated in Fig. 3, which shows the frequency in Messier 3 of magnitudes for invariable stars bluer than color-class f5; the median photovisual magnitude is about 15.35. Obviously Cepheid variation involves a periodic oscillation about a mean brightness rather than a periodic outburst superposed upon a normal condition at minimum. The propriety of the use of median magnitude for parallax work rather than the use of maximum or minimum is emphasized by this study. Some fairly definite evidence suggests that we may be able to witness the beginning or dying out of Cepheid variation in stars most like the variables in color and magnitude.

D. Notes on the Structure of the Galactic System

1. A consideration of the foregoing results leads naturally to the conclusion that the globular clusters outline the extent and arrangement of the total galactic organization.

2. Adopting this view of the stellar universe, all known sidereal objects become a part of a single enormous unit, in which the globular clusters and Magellanic Clouds, tho extensive and massive systems, are clearly subordinate factors. Its volume is more than a hundred thousand times that commonly assigned to the stellar universe. The distance to its center is more than 200 times the distance to the center of our local group. (Fig. 4).

3. A striking characteristic of the general system is the equatorial region avoided by globular clusters. Its width is between 3,000 and 4,000 parsecs—less than one twenty-fifth its probable extent in the galactic plane. But between the planes adopted as its boundary are the open clusters, the planetary nebulae, the diffuse nebulosities, the naked-eye stars, and, in fact, nearly all the stars of our catalogs.

4. Outside the region of avoidance are the globular clusters, the Magellanic Clouds, a few isolated cluster-type variables, and probably the spiral nebulae—all of which appear to be objects of exceptionally high average velocity. Very likely other isolated stars are scattered throughout this extra-galactic domain, and occasionally a very faint open cluster (N. G. C. 7492).

5. The equatorial segment is untenanted by globular clusters perhaps thru their inability to form in an intense gravitational field, and thru impossibility of existence as compact organizations if they enter that region from without. The cluster nearest to the

galactic plane, Messier 22, is one of the least compact of globular systems.

6. While Slipher considers his radial velocities for ten globular clusters preliminary,[3] we may note that the average of the five most distant from the plane is 133 km/sec, and for the five nearest, 155 km/sec. Máking the questionable assumption that the actual

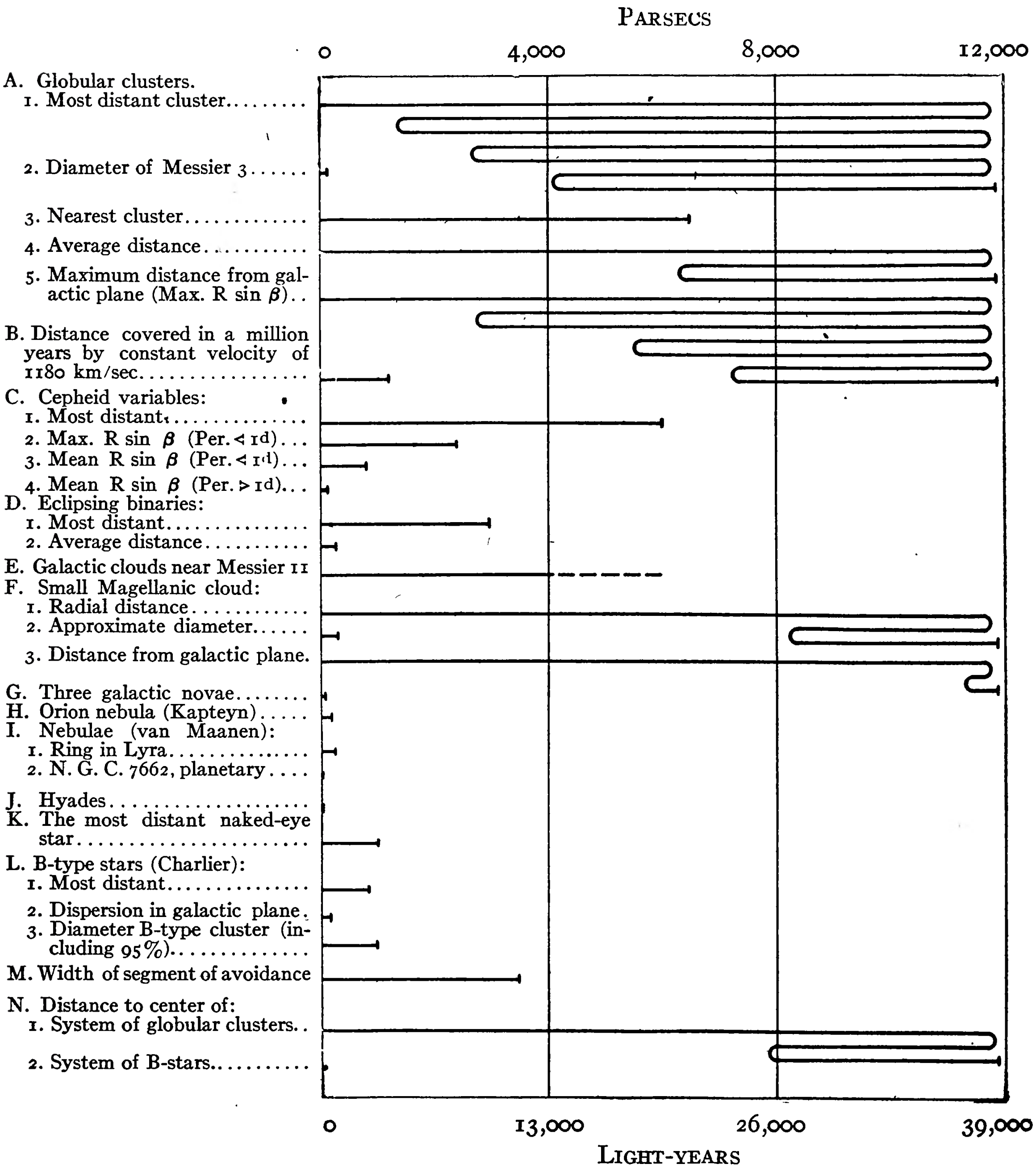

FIG. 4. Comparison of distances in the galactic system. Notes to key: *B*. The spiral nebula N. G. C. 4594 has the radial velocity of 1180 km/sec (Pease); *F*. Provisional values, awaiting an accurate determination of magnitudes; *G*. Nova Persei, Nova Lacertae, Nova Geminorum No. 2; *K*. Assuming that the difference between apparent and absolute brightness, m-M, does not exceed ten magnitudes ($\Pi = 0''.001$).

motion is perpendicular to the plane, the averages become 270 and 470, respectively.

7. From computations based on the observed radial motions and the distances from the plane, it is found that more than half of these systems probably will have entered the avoidance region within 125,000,000 years (assuming that the velocities remain unaccelerated). The great Hercules cluster, it seems, will have reached the plane in less than 30 million years. These intervals of time must be considered so short in the history of the sidereal system that very likely in the past the mid-galactic region has been penetrated by globular clusters. Shall we look upon the moving clusters of the galactic system (*Ursa Major* group, the *Hyades*, the double cluster in *Perseus*) and upon the widely scattered, rapidly moving, isolated cluster-type variables as remnants of large clusters that attempted to cross the galactic region?

8. The frequency of clusters diminishes rapidly with increasing distance from the galactic plane. The most distant from the plane, N. G. C. 4147, which may be assumed tentatively to have formed in a region of low material density, shows the decrease of color with decreasing brightness that is apparently universal for giant stars in globular clusters. While it appears to be poor, in giant stars at least, the apparent diameter is not abnormal for the magnitude of its brightest stars. The open clusters of the galactic plane, tho relatively very poor in stars, also conform to the relation connecting brightness (distance) with apparent diameter, which is manifested by all typical globular clusters.[4] Therefore, we may need to look for dynamical laws that give a fixed radius to a cluster of stars, regardless of the masses involved.

9. The general system of clusters appears to be somewhat ellipsoidal (Fig. 5), the longest axis lying in the galactic plane and passing the Sun at a distance of some 3,000 parsecs. Its nearest point is in galactic longitude 240°, approximately coincident with the direction of the center of the local system of stars.

10. The center of the complete galactic system, including globular clusters, is in the general direction of (a) the richest star clouds of the Milky Way; (b) the most numerous open clusters, planetary nebulae, O-type stars;[5] (c) the vertex of the second star stream; (d) the region most conspicuously avoided by spiral nebulae, and in which lies the roughly determined antapex of their radial velocities.

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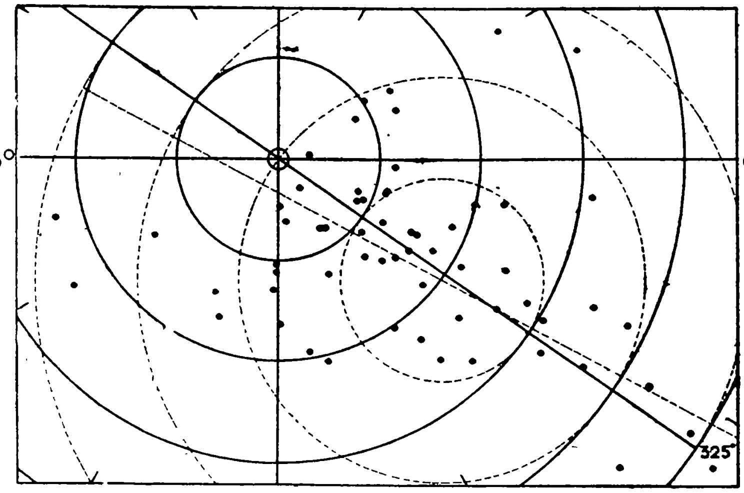

FIG. 5. The system of globular clusters projected on the plane of the galaxy. The galactic longitude is indicated for every thirty degrees. The "local system" is completely within the smallest full-line circle, which has a radius of a thousand parsecs. The larger full-line circles, which are also heliocentric, have radii increasing by intervals of 10,000 parsecs. The broken line indicates the suggested major axis of the system, and the broken circles are concentric about its center. The dots are about four times the actual diameters of the clusters on this scale. Nine clusters more distant from the plane than 15,000 parsecs are not included in the diagram.

11. With the plan of the sidereal system here outlined, it appears unlikely that the spiral nebulae can be considered separate galaxies of stars. In addition to the evidence heretofore existing the following points seem opposed to the "island universe" theory: (a) the dynamical character of the region of avoidance; (b) the size of the galaxy; (c) the maximum luminosity attainable by a star; (d) the increasing commonness of high velocities among other sidereal objects, particularly those outside the region of avoidance. In favor may be urged the suggestive ratio of width to extent for the equatorial segment of the galactic system. The matter can not be discussed in this summary, but we may state that the cluster work strongly suggests the hypothesis that spiral nebulae, while not closely related in history or dynamical development to the average star, are, however, members of the galactic organization, appearing to avoid the regions of enormous masses and forces more widely than do the globular clusters. The most generally accepted explanation of galactic novae is the penetration of nebulosity by a star with considerable velocity. Inverting this, the novae in spirals may be considered as the engulfing of a star by rapidly moving nebulosity; and the frequency of novae in spirals becomes a function of the dimensions of the nebula, its velocity in space, and the stellar density of its neighborhood—that is, the distance from the galactic plane.

12. The Sun is very eccentrically situated in the general system, being some 20 parsecs north of the plane and about a hundred parsecs from the center of a very open, perhaps ill-defined, local aggregation. The local group is about half way from the center to the edge of the galaxy, the thinnest part of the Milky Way lying between galactic longitudes 90° and 180°.

13. Throughout the whole extent of the region of avoidance the star density probably averages as great as near the Sun. The rich galactic clouds possibly represent depth more than star density. Stars of the 15th apparent magnitude are at the distance of the center if they have absolute magnitudes as bright as -1.5. A few blue stars of this apparent magnitude are already recorded from the neighborhood of Messier 11. Ultimately we may derive a check of the extent of the system from such stars.

14. Globular clusters supply a valuable "base line in time" for the observational study of the speed of the evolution of stars. Eddington's computations show that the duration of the total giant stage of a star, if contraction is its source of energy, can scarcely exceed 100,000 years. From the study of light that left the nearest clusters some twenty or thirty thousand years ago, we find for giant stars a well-known relation of color to luminosity. The light from the most distant globular cluster left its source nearly 200,000 years earlier. But the color-luminosity relation, so far as present results show, is identical.

Mount Wilson Solar Observatory,
December, 1917.

References:

[1]Bailey has called attention to the important fact of the apparent completeness of the lists of globular clusters. Notwithstanding great increases in telescopic power and in the numbers of stars and nebulae, there have been but one or two globular clusters discovered during the last fifty years.

[2]Adams and Strömberg, *Mt. Wilson Contr.*, No. 131, 1917.

[3]From a letter of Nov. 13, 1917.

[4]See Fig. *1b* of this summary and Fig. 1 of *Mt. Wilson Contr.*, No. 115, 1915.

[5]Hinks, *Monthly Notices*, **71**, 693, 1911; Hertzsprung, *Astronomische Nachrichten*, **192**, 265, 1912.