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THE HARVARD PROGRAM OF GALACTIC EXPLORATIONS

By Dr. HARLOW SHAPLEY
DIRECTOR OF THE HARVARD OBSERVATORY

THE work carried on at the Harvard Observatory for the past ten years has included the systematic survey of various parts of the stellar universe. Recently we have been able to inaugurate active studies in the whole range from the nearest stars to the groups of galaxies at distances of the order of a hundred million light years. For convenience of operation and discussion the program of exploration and measurement has been divided into eight major sections, each concerned with a separate territory and employing in general a special method and equipment. Ten photographic telescopes and approximately thirty observers and investigators are involved in the program. In the following paragraphs I shall outline briefly the progress in the eight territories, of which five lie within the galactic system and three in the extragalactic universe.

(1) THE SOLAR NEIGHBORHOOD

A large majority of the stars within fifty light years of the sun are of less than solar luminosity, and most of them are below naked-eye visibility. Thus a recent compilation of those stars known to be nearer than sixteen light years shows but 40 per cent. brighter than the sixth magnitude. The exploration of the solar neighborhood is therefore a search for dwarf stars among telescopic objects.

It is important to have as complete a census as possible of the solar neighborhood—the most useful sample we have of a volume of space. A thoroughly observed frequency distribution of stellar luminosities and a knowledge of the density-in-space laws for the stars within fifty light years of the sun are fundamental in the analysis of stellar development and the structure of stellar systems.

The Harvard work on the space distribution of nearby stars is at present confined to the southern hemisphere and consists in the detection of these stars, not through parallax measures, but through their large proper motions. Photographs made with the 24-inch Bruce doublet at the southern station (now near Bloemfontein, South Africa) cover practically all the southern sky for stars to the seventeenth magnitude and about one fourth of the southern sky for stars to the eighteenth magnitude. Many of the plates were made more than thirty years ago. A comparison of these plates (scale $1' = 1$ mm) with the plates made currently on the same fields with the same telescope will provide much material on the number and on the distribution in space and in luminosity of the stars in the circumsolar region. At present approximately 40 per cent. of the telescope's working time is devoted to proper motions, and already a large number of conspicuously moving stars have been found on the Bruce plates by Dr. Luyten, who continues at the University of Minnesota the study begun at Harvard.

(2) The Region of the Brighter Stars

The great majority of naked-eye stars lie between the distance limits of fifty and five hundred light years, though some of them with unusually high intrinsic luminosities are farther away. Within the same limits of distance are probably half a million telescopic stars. Their distribution in space and the general structure of the stellar system which they compose can be determined in part from studies of proper motion and trigonometric parallax. The naked-eye stars of the region can probably be most effectively studied, however, through those methods of distance measurement that depend on knowledge of the absolute magnitudes (intrinsic luminosities) of the stars as estimated from their spectra. With the absolute magnitudes known and apparent magnitudes measured, distances are readily computed.

Our own explorations of this territory are very largely based on spectroscopic parallaxes. For several years at both the southern and the northern stations we have systematically accumulated spectrograms suitable for the work; methods of using the various classes of spectra are under study at Harvard and elsewhere and it appears probable that good criteria of absolute magnitudes will soon be available for many of the spectral classes. We can use in this survey not only the plates specially collected for the purpose but also the tens of thousands of short dispersion spectrum plates in the Harvard photographic collection. The analysis can thus go several magnitudes below the naked-eye limit, extending the territory to the distance of a thousand light years or so, and making possible a much more complete census of the dwarf stars within a few hundred light years of the sun.

(3) The Local System

We have good but not incontrovertible evidence of the existence of a localized star cloud in our part of the galaxy. Its diameter is several thousand light years, its population is in the tens or hundreds of millions of stars. I believe that this local system may be comparable in dimensions and composition with the Magellanic clouds or with a typical spiral nebula. But it will take long and laborious study to unravel the complications of stellar structure in this third territory which, we assume, extends out to a distance of approximately five thousand light years.

The Henry Draper Catalogue gives the spectra of 225,000 stars as classified by Miss Cannon, and affords material for the statistical discussion of their space distribution. Most of the stars, however, to the magnitude limit within which the catalogue is essentially complete, are not more distant than one or two thousand light years; they do not represent satisfactorily the local system.

Nearly ten years ago we began an extension of the Henry Draper Catalogue to the fainter stars, paying special attention to the rich regions in low galactic latitude. The new spectrum plates required for the work were made at the southern station, mainly with the Metcalf 10-inch camera. A hundred thousand faint spectra have now been classified for the Henry Draper Extension. The limiting photographic magnitude of completeness is approximately 11.5, corresponding to a fourfold extension in distance over the Henry Draper Catalogue. The distance limits are, of course, quite different for the various spectral classes, because of the diversity in absolute magnitude from class to class.

Scarcely one fourth of the Milky Way has been covered at the present time by the Extension, but preliminary analyses have already shown that the new work will be of much value in advancing our knowledge of that nearer part of the Galaxy which we call the Local System. An equally useful result of the program will be the determination and the publication of spectra and magnitudes of great numbers of individual faint stars, thus giving the students of positions, motions and luminosities basic data for their investigations.

For the work on spectral classification, as for the projects in several of the other territories under exploration, the measurement of the stellar magnitudes is fundamental. To provide the necessary standards of photographic brightness, the Harvard photometric program has been taken up actively again after an interruption of several years.

(4) THE MILKY WAY

The stars within five thousand light years of the sun constitute a trifling proportion of the galactic system as outlined by globular star clusters and the Milky Way clouds. The faint stars of the Milky Way are so remote that spectroscopic methods of determining their distances are as yet quite impossible, and trigonometric and proper motion measures are hopelessly inadequate. Statistical analyses, based on the counts of stars of various magnitudes, assist in discovering the structure of the nearer parts of the Milky Way; but perhaps now the most satisfactory attack on its extent and structure can be made through the study of the periods and light curves of variable stars. The methods of using eclipsing binaries, long period variables, novae, and Cepheid variables in the measurement of stellar distances are well known to the students of stellar astronomy. The Cepheid variables are especially powerful in measuring space, through the fortunate circumstance that the lengths of their periods of variation are closely correlated with their absolute magnitudes. The period-luminosity relation for Cepheid variables is the key to the measurement of practically all distances greater than a few thousand light years.

About seven years ago a program for the systematic photography of Milky Way variable stars was inaugurated at our northern and southern stations to supplement the plates of the Harvard sky patrol, which had been in operation for approximately thirty years. The regular patrol furnishes ample material for the three or four thousand variable stars brighter than the twelfth magnitude, but it contributes little for the fainter variable stars associated with the Milky Way star clouds. In the new observing program, which is carried on with the larger telescopes at Cambridge and Bloemfontein, several thousand photographs have been taken. The whole of the galactic belt is covered systematically. In three lines along the galactic circle 196 regions have been chosen, so centered that adjacent fields overlap. For purposes of comparison seventy-two variable star fields in various high galactic latitudes have also been selected for study. Particular attention is given at present to the southern Milky Way, not only because of its greater richness in variable stars and in other objects of interest, but because the northern sky is being more actively studied than the southern by other observatories.

The photographs of ten of the Milky Way fields have been examined by the workers in Cambridge, who have found nearly two thousand new variable stars and have determined the periods and light curves of several hundred. The photographs extend to the sixteenth magnitude and fainter, and many of the new variables are more than thirty thousand light years distant. The work shows conclusively that the variable stars provide an easy entry into the Milky Way star fields in which they are imbedded; but the labor of discovery and analysis is very great, and it will be ten or fifteen years before a sufficient number of the Harvard Milky Way fields are studied fully enough to outline the arrangement and dimensions of the star clouds composing the Milky Way system.

The regions so far studied are mainly in the Milky Way between Carina and Aquila. One of our first results on this program was the discovery that the dense star clouds in Sagittarius and neighboring constellations are at a distance of forty or fifty thousand light years. Apparently they form a nucleus of the Milky Way system, near the gravitational center of the surrounding system of globular star clusters. They indicate a center that agrees both in direction and in distance with the galactic center found ten years before from the study of the space distribution of individual globular clusters.

Concurrently with the systematic work on faint variable stars in the Milky Way, which is under the supervision of Miss Henrietta Swope, we have undertaken several special studies of the nearer variable stars: (a) With the help of a grant from the American Academy of Arts and Sciences an investigation of the photographic brightness of eclipsing stars has been made, providing the first extensive material available on photographic light curves of a type of variable star important to our knowledge of the shapes, surface brightnesses and mean densities of stars in binary systems, and significant therefore for theories of stellar evolution. (b) Harvard patrol plates have been used by Dr. L. V. Robinson to determine from about fifty thousand observations the photographic light curves of one hundred of the brighter Cepheid variables in an attempt to learn more of the characteristics of these stars on the basis of homogeneous material. (c) Participation by the Harvard Observatory in an international study of Cepheid variables in selected regions during the past two years has involved the measurement of sixty-two magnitude sequences, the accumulation of a thousand new photographs of the "international" Cepheids, the study of their spectra and the detailed investigation of their periods and mean photographic light curves. (d) The study of faint variables in three large fields in high galactic latitude has revealed an abundance of cluster type Cepheids and of eclipsing binaries but relatively few long period variables and no classical Cepheids, indicating the thinness of the Milky Way system.

(5) THE SYSTEM OF GLOBULAR CLUSTERS

The diameter of the Milky Way is not less than a hundred thousand light years; probably it is much larger. Undoubtedly the globular star clusters which are observed along the borders of the Milky Way and sparingly in high galactic latitudes extend throughout a region more than two hundred and fifty thousand light years in diameter. The galactic system may be coextensive with this system of globular clusters; and it may be that the globular clusters, with the star clouds of the Milky Way, the local system and the Magellanic clouds, form a complex system of higher order than a simple galaxy. In time we should know much about these matters. It is convenient for the present to consider that the supersystem of a hundred globular clusters constitutes the fifth stage in our explorations and marks the point where we pass from considering various parts of the galactic system to the treatment of external galaxies.

The discovery and study of variable stars in globular clusters by the late Professor Bailey at Harvard was followed by the extensive investigations of such systems with the Mount Wilson reflectors and by further photometric researches at Harvard. At the present time we know more about this territory than about any of the others. The results are summarized in a recent monograph.[1] To extend the work on these systems and on other extra-galactic objects in the southern hemisphere, a 60-inch reflecting telescope has been obtained for the station at Bloemfontein. Within a year it should add greatly to our information about the luminosity curves, variable stars, density distribution, and internal structure of globular systems, since the nearer and brighter examples of the class are too far south for analysis with northern telescopes.

Current studies of globular clusters at Harvard include a new determination of the period-luminosity relation, investigation of the small amplitude variations for stars in Messier 3 of the same luminosity and color as cluster type Cepheids, derivation of luminosity curves of the giant stars in northern clusters and the construction of contour maps of the luminosity distribution for a few of the brighter systems.

(6) THE CLOUDS OF MAGELLAN

The present and forthcoming work on the spectra, light variations, and distribution and motions of the stars in the Magellanic clouds, and the study of their clusters and nebulae, will reflect on the problems of our local system and of the similar star clouds in the Milky Way. But as the nearest of isolated external galaxies, the clouds of Magellan should serve primarily as leads to knowledge of the millions of extragalactic systems, for these large and complex stellar organizations in the southern sky are immediately related to spiral and spheroidal nebulae. Studies of the clouds have, in the past, included the detection of peculiar spectra, the determination of the period-luminosity relation by Miss Leavitt, the measurement by R. E. Wilson and others of the radial velocities of the included gaseous nebulae, studies of motions by Hertzsprung and Luyten, and the discovery and cataloguing of variable stars, gaseous nebulae and star clusters by various Harvard investigators.

Current Harvard work on the Magellanic clouds includes the following studies:

(a) An analysis of the number and distribution of giant and supergiant stars in the Large Magellanic Cloud, which has become possible (for the first time in any galaxy) through the establishment of standard magnitudes in the cloud.

(b) The classification of spectra of supergiant stars in the Large Cloud, including those of peculiar types with luminosities of more than ten thousand times that of the sun; Miss Cannon has classified more than three thousand of the faint spectra, most of which, however, are foreground stars in our own galaxy.

(c) The determination of the magnitudes of the brightest individual stars in one hundred and sixty open star clusters in the Large Cloud.

(d) The discovery of several hundred new variable stars in the Large Cloud, in which Miss Leavitt had previously found eight hundred; on the basis of the new discoveries, which were made on recent plates from Bloemfontein, I estimate that the total number of Cepheid variables in the Large Cloud is not less than three thousand.

(e) The determination of periods and light curves of about seventy-five Cepheid variables in the two clouds, showing that the period-luminosity relation holds for the Large Cloud as for the Small, and that the Cepheids in external galaxies are similar in amplitude of variation and in form of light curve to those in our own galactic system.

Future work on the Magellanic clouds will include an analysis of globular clusters within them, studies of the variable stars in these clusters, classification of the spectra of the highly luminous stars in the open clusters, further studies of the velocities in the line of sight—not only of the easily measured gaseous nebulae but also of the stars themselves, studies of variable stars fainter than those now attainable and the extension of the luminosity curves toward the dwarf stars for each spectral class separately. All of these researches should be carried forward rapidly with the aid of the new 60-inch reflector.

[1] Harlow Shapley, "Star Clusters," Harvard Observatory Monograph No. 2, McGraw-Hill Book Company, New York, 1930.

In the investigations of the clouds of Magellan we take full advantage of our position as external observers; future studies will still further exploit this advantage of objectivity.

(7) The Supergalaxies

The clouds of Magellan are serviceable representatives of the numerous external galaxies that lie within two or three million light years of the earth. To explore more remote regions satisfactorily we can take advantage of the tendency of external galaxies to form higher systems. These supergalaxies, or clusters of extragalactic nebulae, yield to the same type of analysis that we have used for star clusters. The use, for individual galaxies, of relative diameters and relative brightness as criteria of relative distance is unsafe, but the method can be employed with some success when mean values are obtainable for the several members of a supergalaxy.

Approximately forty clusters of galaxies are now distinctly shown on the Bruce plates at the Harvard Observatory. Their distances range from a few million to a hundred million light years. The current studies of these higher systems include the measurement of magnitudes, dimensions, positions and orientations of the individual members. The extension of the survey with long-exposure photographs to all regions of the southern sky will undoubtedly increase the number of known supergalaxies and add to our information of their distribution in space.

The most conspicuous supergalaxy under study at the present time is Coma-Virgo Cloud A, which is a stream of several hundred bright spiral, spheroidal and irregular galaxies extending over about sixty degrees of the sky. Its distance from the earth is approximately ten million light years, and its greatest length at least half as much.

(8) The Metagalaxy

Two systematic surveys of external galaxies which are now in progress at Harvard concern the all-inclusive order which we call the metagalaxy. Of the two, the less ambitious is a catalogue of the photographic magnitudes of all external galaxies brighter than magnitude 13.0. This survey will include something less than a thousand objects. The magnitudes are based on numerous small scale photographs. The second systematic survey reaches to the eighteenth magnitude and fainter, and will probably require at least ten years for completion. It will involve the finding and the study of tens of thousands of heretofore uncatalogued objects, the measurement of their positions, approximate magnitudes and diameters, and their classification on a system peculiarly suited to the scale of the Bruce photographs.

The survey of bright objects may be assumed to extend five million light years into space, though undoubtedly many of the intrinsically fainter galaxies within that limit of distance are not recorded, and many of the high luminosity galaxies will appear in the catalogue though lying considerably more than five million light years distant. The second survey will extend to objects five magnitudes and more fainter and will reach, we may assume in a first approximation, to an average distance of fifty million light years. We are sure, however, that several of the supergalaxies found among the faintest objects are more than a hundred million light years away.

Approximately one sixth of the whole sky has been covered in the eighteenth magnitude survey. More than twenty thousand new systems have been found. For 75 per cent. of them positions have been determined and for 58 per cent. classifications have been made on the Harvard system. The number of galaxies per square degree has been counted on a large number of Bruce plates, and conspicuous deviations from uniform distribution are revealed (in addition to the well-known apparent avoidance of low galactic latitudes which is the result of obscuration by dark nebulosity). Equally distinct dissimilarities from field to field are found in the magnitude distribution, indicating that along the line of sight as well as on the surface of the sky the distribution is far from uniform. Taking the whole sky we find, in agreement with Hubble's results with the Mount Wilson reflectors, that the increase in numbers with decreasing brightness is approximately of the order of magnitude appropriate to uniform density in space, though for various large sections of the sky the uniformity criterion fails conspicuously.

As a whole, our surveys of the metagalaxy, which cover large and representative sections of the sky, give no evidence that we have measurably approached the limits of the galaxy-populated universe; we have no indication that the systems are falling off in number as we go out from our galaxy. On relativistic grounds the red shift in the spectra of distant objects can be taken as an observational indication of an expanding universe that is finite; but so far as the present census of the metagalaxy goes, the total number of galaxies and the radius of space may both be infinite.

The studies of the various territories in which our explorations proceed are closely interwoven. For instance, the luminosity curves for the solar neighbors will be of direct application in work on the integrated luminosities of the Magellanic clouds and of other external galaxies; the frequency of Cepheids in the Magellanic clouds will bear on the interpretation of results in the Milky Way; variable star fields a comparison of the structure of the local system with that of external galaxies will eventually determine whether our galaxy is a unit organization or a supersystem; and the researches on the anatomy of bright southern globular clusters, throwing light on the nature of the faintest spheroidal galaxies, will aid in the measurement of the metagalaxy.

OBITUARY

FRANK WIGGLESWORTH CLARKE

On May 23, 1931, Frank Wigglesworth Clarke, one of the most widely and favorably known of American chemists, quietly passed away at his home in Chevy Chase, Maryland, at the age of eighty-four years.

Dr. Clarke was born in Boston, March 19, 1847. He was the great-great-grandson of Robert Clarke, of the Scotch colony near Londonderry, Ireland, who came to this country about 1725.

Dr. Clarke's early education was obtained in schools in and near Boston, and in March, 1865, he entered the Lawrence Scientific School of Harvard University where he took up the study of chemistry under Wolcott Gibbs. Receiving the degree of Bachelor of Science in 1867, he remained at the School for another year, and published his first scientific paper, "A New Process in Mineral Analysis," in the *American Journal of Science* in 1868. In January, 1869, he went to Cornell University as assistant to Professor J. M. Crafts and, leaving that position at the close of the academic year, he returned to Boston where for the next four years he lectured on chemistry in the newly established Boston Dental College and eked out his small income by lecturing in other schools and by journalistic work.

From early boyhood he had a strong bent toward the preparation of collections—stamps, coins, flowers and especially minerals—and of tabulations of the facts that came to him through observation or reading. This characteristic of his orderly mind led him later to compile a "Table of Specific Gravities, Boiling Points and Melting Points of Solids and Liquids," which was accepted for publication in 1872 by Professor Joseph Henry, secretary of the Smithsonian Institution, who gave to the paper the general title "Constants of Nature, Part I." Further volumes under this title followed in 1876, 1882, 1888 and 1897.

After one year as professor of chemistry and physics at Howard University, Dr. Clarke accepted appointment in 1874 to the chair of chemistry and physics in the then new University of Cincinnati where he remained until, in 1883, he went to Washington as chemist of the United States Geological Survey and honorary curator of minerals of the United States National Museum, positions that he held until his retirement on December 31, 1924.

The investigations by Dr. Clarke and his associates in the Survey were of the most varied character, and the wide range of the topics of their many bulletins in the publications of the Survey affords abundant evidence of Dr. Clarke's striking ability as a director of research and as a chemist of unusual versatility and breadth of interest.

He early began the collection of data relative to the determination of atomic weights, and presented his first paper on the subject at a meeting of the Subsection of Chemistry of the American Association for the Advancement of Science, held at Saratoga in August, 1879. In 1882 there appeared from his pen a comprehensive monograph of 271 pages entitled "A Recalculation of the Atomic Weights," which attracted wide attention not only in this country but also in Germany and Norway, where similar revisions had been prepared. In 1892, the American Chemical Society requested him to prepare an annual report on the subject, and to compile annually a table of atomic weights for official use in this country. This he did until 1903, when an International Committee on Atomic Weights was created with Professor Clarke as chairman, a position that he continued to hold until 1922.

His article upon "The Relative Abundance of the Elements" appeared in 1889, and through all the following years it has stood as a classic on this subject.

One of his greatest services to chemistry in this country was in connection with the creation of the American Chemical Society. Up to 1873, chemistry had been given but scant attention in the meetings of the American Association for the Advancement of Science. In that year, at the meeting at Portland, Maine, four young men, C. E. Munroe, W. McMurtrie, H. W. Wiley and F. W. Clarke, presented a request that chemistry be more adequately recognized by the formation of a subsection of chemistry, now Section C. The request was granted, and the section held a successful meeting at Hartford in the following year. In 1876 the chemists of New York City organized a local society to which they gave the name American Chemical Society, and some eight years later another local society of chemists was formed in Washington. The American Association met at Cleveland in 1888, the chairman of the chemical section at that time being Dr. C. E. Munroe. Dr. Clarke wrote to him and suggested the formation of a really national Chemical Society. Dr. Munroe favored the idea, and after some three years of discussion of the project,