SIXTY YEARS' PROGRESS IN ASTRONOMY

Adapted from an address given to Section III of the Royal Society of Canada at Ottawa on May 25th, 1927.

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As it is quite impossible to review the progress of any science for the past sixty years in the short time allotted, I must confine myself mainly to one aspect of astronomy and propose to contrast and compare present day ideas of the dimensions and form of the universe, one of the fundamental problems of astronomy, with those held at the time of the Confederation of Canada.

In 1867 astronomers had only a very limited idea of the dimensions and a vague notion of the form of the universe. Less than thirty years previously, in 1838, the first reliable measure of the distance of any star was obtained by Bessel, who found the parallax of 61 Cygni to be about a third of a second, corresponding to a distance of ten light-years, and by 1867 the parallaxes of less than a dozen stars were reliably known and no definite or adequate idea of the dimensions of the sidereal system was extant. The conception of the simple disc-like form of the universe, introduced by Wright a century earlier, was elaborated and confirmed by Sir William Herschel's early star gauging methods. Although the views of the latter were somewhat modified in the beginning of the 19th century, it cannot be said that there had been any particular progression in the prevailing ideas of the form of the universe by 1867. So far as the motions of the stars were concerned only a few hundred proper motions were roughly known at the time of Confederation, while the method of determining radial motions, another important factor in the problem, had not yet been developed. In the accompanying series of illustrations, especially drawn to give a graphic representation of the scale of the universe with linear dimensions increasing by a factor of 100, the certain knowledge of 1867 did not go beyond No. 7, the sun and the nearer stars.

It thus seemed almost a time of stagnation in the science. But this was only apparent as great developments, fated to change the whole aspect of astronomy, were even then in progress. The centre of attention of astronomers was being diverted from the solar to the sidereal system, to accurate measures of the positions and motions of the stars. While progress may have seemed slow, this was due to the large numbers requiring observation, to the meticulous care required to obtain reliable values, and to the long intervals that must elapse between successive measures of position before reliable proper motions could be obtained. While we may have had to wait until the third decade of the twentieth century to reach, even provisionally, any generalization on the form and dimensions of the universe, we are now reaping the fruits of the advances initiated, the new methods of attack developed and of the preparatory work so carefully and accurately done in the past sixty years. The most striking result of these advances has been to extend outwards into space our conceptions of the dimensions of the universe as greatly as physics in the modern atomic theory has travelled in the opposite direction.

Probably the most important factor in this extension of the bounds of the universe has been the increase in the number and precision of the determinations of stellar parallax, and the development of new methods for obtaining the distances of celestial objects. The scant dozen stellar parallaxes of 1867 had barely reached a hundred, all visually determined, by 1900. The application of photographic methods and the coöperation of many observatories in this important problem has resulted in a rapid increase in numbers so that now the parallaxes of over 2,000 stars have been trigonometrically determined with a probable accuracy of one hundredth of a second of arc. But it is obvious that, valuable as it is for the nearer stars and important as forming the basis for less direct methods, the trigonometric method cannot usefully be applied to stars with a parallax approaching the hundredth of a second, or at a distance greater than two or three hundred light years from the sun. For more distant objects new methods of attack had to be developed and these methods with the results derived from their use, have constituted perhaps the most important advances in the aspect of astronomy under consideration.

The two most important additional methods of deriving stellar distances, the statistical method and the luminosity method, both require in their use applications of stellar spectroscopy and before they can be intelligently discussed it seems necessary to interpolate a paragraph on the application of the spectroscope to astronomy. This has signalized probably the greatest advance in the history of the science, indeed marking the development of the sister science of astrophysics.

Spectroscopy was effectively only eight years old and was applied practically to the stars by Huggins only one year before the time of Confederation. That time may hence be said to mark the birth of astrophysics, which has given us a new and marvellous knowledge of the physical and chemical constitution of the heavenly bodies, as well as indicating, partially at any rate, the plan of evolution of the universe. One of the early applications was in the determination of the radial velocities of the stars, essential in the statistical method of obtaining stellar distances and in the discussion of stellar motions. Even more important perhaps have been the theoretical advances based primarily on experimental and observational spectroscopy and developed principally by the great school of English mathematical physicists. From the mere conjectures of sixty years ago, when any definite knowledge of the constitution of these forever inaccessible bodies was an undreamed of possibility, we now have a clear conception of the constitution, temperature, pressure and other physical properties of the external atmospheres of the stars. As a practical development of this advance, even though obtained empirically, the luminosity or absolute magnitudes of many of the stars can be obtained by the comparison of the relative intensities of certain lines in their spectra and hence, as will be seen later, their distance immediately follows. What seems even more incredible than knowledge of the external constitution of the stars, are the calculations now available of the conditions in the interior where the temperatures rise to millions of degrees,—forty million at the centre of the sun. The stable radiating mechanism we call a star is an example of the remarkable balance of forces in the interior, the force of gravity acting inwardly being opposed by the gas pressure due to temperature and by the radiation pressure against the opacity, acting outwardly. The calculation of the conditions necessary for such a balance, beautifully developed by Eddington, have resulted in the very important relation, amply confirmed observationally, that the total brightness, "absolute magnitude", of a star is practically independent of its external temperature and is a simple function of its mass. The application of this relation to the determination of luminosity and hence of distance, when the mass is known, is obvious. While our knowledge of the constitution of the clusters and nebulæ is not so definite as in the case of the stars, great progress has been made and there can now be presented a picture, imperfect and incomplete though it may be, of the constitution and evolution of the universe, thus supplementing that of its form and dimensions now being considered.

The statistical and luminosity methods of obtaining stellar distances, after this necessary digression, can be now effectively described. Although the statistical method cannot be applied to individual stars, the average distance of a group of stars, its mean parallax, at distances beyond the range of the trigonometric method, can be reliably determined. Accurate values of the proper motions and radial velocities of the stars are required and it is of interest to note that in the sixty years the number of reliable proper motions has increased from some 300 to over 10,000 and of radial velocities from 0 to over 3,000. As is well known and determined from the radial velocities, the sun is moving through space towards Lyra with a velocity of about 20 km. per second. In consequence, the stars appear to move in general in the opposite direction. This parallactic motion, as it is called, being the component of the proper motion in that direction, will obviously be greater the nearer the stars, and from it, with the known velocity of the sun, the average distance of a group of stars can be easily calculated. Other methods of a similar nature, using both the proper motions and the radial velocities, give also the mean parallax of groups of stars and these statistical methods have been widely applied in studies of stellar distribution and other investigations.

The luminosity method of obtaining stellar distances has, however, been by far the most fruitful in extending the known bounds of the universe. While the trigonometric method is limited to distances of two or three hundred, and the statistical to distances of a few thousand, the luminosity method has been successfully applied to celestial objects at distances of about a million light years. It is based on an application of the well known law of the decrease of brightness as the inverse square of the distance. It is known from careful measures that the sun would shine as a star of about the fifth magnitude if removed to a distance of 33 light years, corresponding to a parallax of one tenth of a second. If the apparent magnitude of any star is known, and this is a readily measurable quantity, and its luminosity or relative brightness compared to the sun can be determined, it is evident that its distance can be easily calculated. A fruitful method of obtaining the luminosities of stars from their spectra, which has already been applied to over 2,000 stars, and a second method, from the relation between luminosity and mass, have been referred to in the paragraph on spectroscopy. The most important method of deriving the luminosity of stars, however, is the relation between the period and the luminosity of Cepheid variables, first noted by Miss Leavitt and later developed and extended by Shapley. As will be seen later, our knowledge of the clusters and nebulæ and of the dimensions of the universe depends upon the use of this relation in deriving stellar distances.

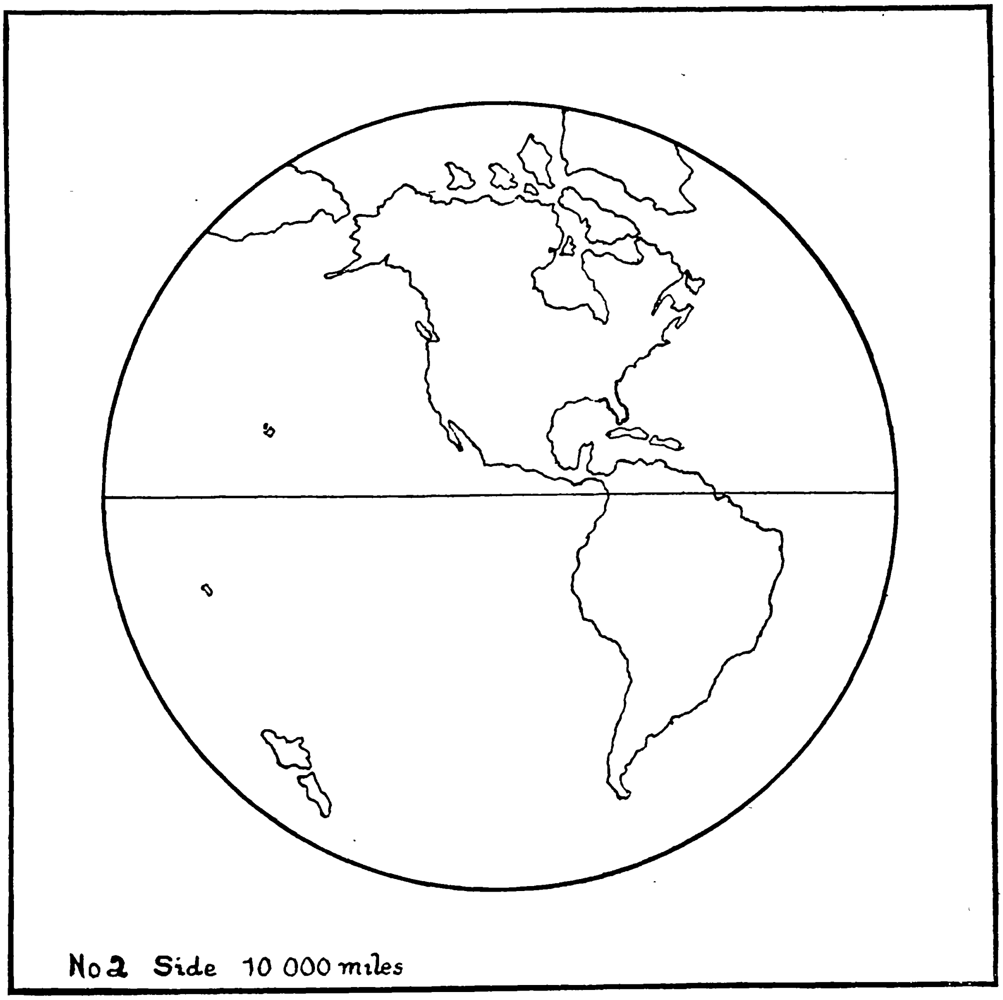
With this brief description of the methods used for gauging the dimensions, we are now in a position to review the progression in our conceptions of the dimensions of the universe for the last sixty years and the present state of knowledge on the subject. In 1867 and for two or three decades later, little was known, outside the general conception of the disc-shaped form and complex structure of the sidereal system, as to its dimensions and extent. It was not until the twentieth century that increasing knowledge of the distances and motions of the stars made estimates of the dimensions possible. In 1905 Newcomb and Seeliger estimated the diameter of the watch-shaped sidereal system as about 7,000 light years, a similar estimate being reached Hertzsprung a year later. This was extended by Walkey in 1914 from added data to some 10,000 light years and was further extended from considerations of a general nature by Eddington to perhaps 15,000 light years. The most general and complete investigation of the dimensions and structure

	SCALE OF	UNIVERSE.	
-9	.000 000 000 000 06 in.	$1.6x10^{-13}$cm.	Electron.
-8	.000 000 000 006 in.	$1.6x10^{-11}$	
-7	.000 000 000 6 in.	$1.6x10^{-9}$	
-6	.000 000 06 in.	$1.6x10^{-7}$	Atom.
-5	.000 006 in.	$1.6x10^{-5}$	Soap Bubble.
-4	.000 6 in.	$1.6x10^{-3}$	Tissue Paper.
-3	.06 in.	$1.6x10^{-1}$	
-2	6.3 in.	1.6x10	
-1	.01 m.	$1.6x10^{3}$	
0	1 mile	$1.6x10^{5}$	
1	100 m.	$1.6x10^{7}$	
2	10 000 m.	$1.6x10^{9}$	Earth.
3	1 000 000 m.	$1.6x10^{11}$	Earth Moon.
4	100 000 000 m.	$1.6x10^{13}$	Earth Sun.
5	10 000 000 000 m.	$1.6x10^{15}$	Solar System.
6	1 000 000 000 000 m.	$1.6x10^{17}$	
7	17 light years	$1.6x10^{19}$	Nearer Stars.
8	1700 l.y.	$1.6x10^{21}$	Local Cluster.
9	170 000 l.y.	$1.6x10^{23}$	Galaxy.
10	17 000 000 l.y.	$1.6x10^{25}$	Nearer Spirals.
11	1 700 000 000 l.y.	$1.6x10^{27}$	6 times Range 100 in.
12	170 000 000 000 l.y.	$1.6x10^{29}$cm.	Einstein Universe.

No. 1. Table of Dimensions of the Universe.

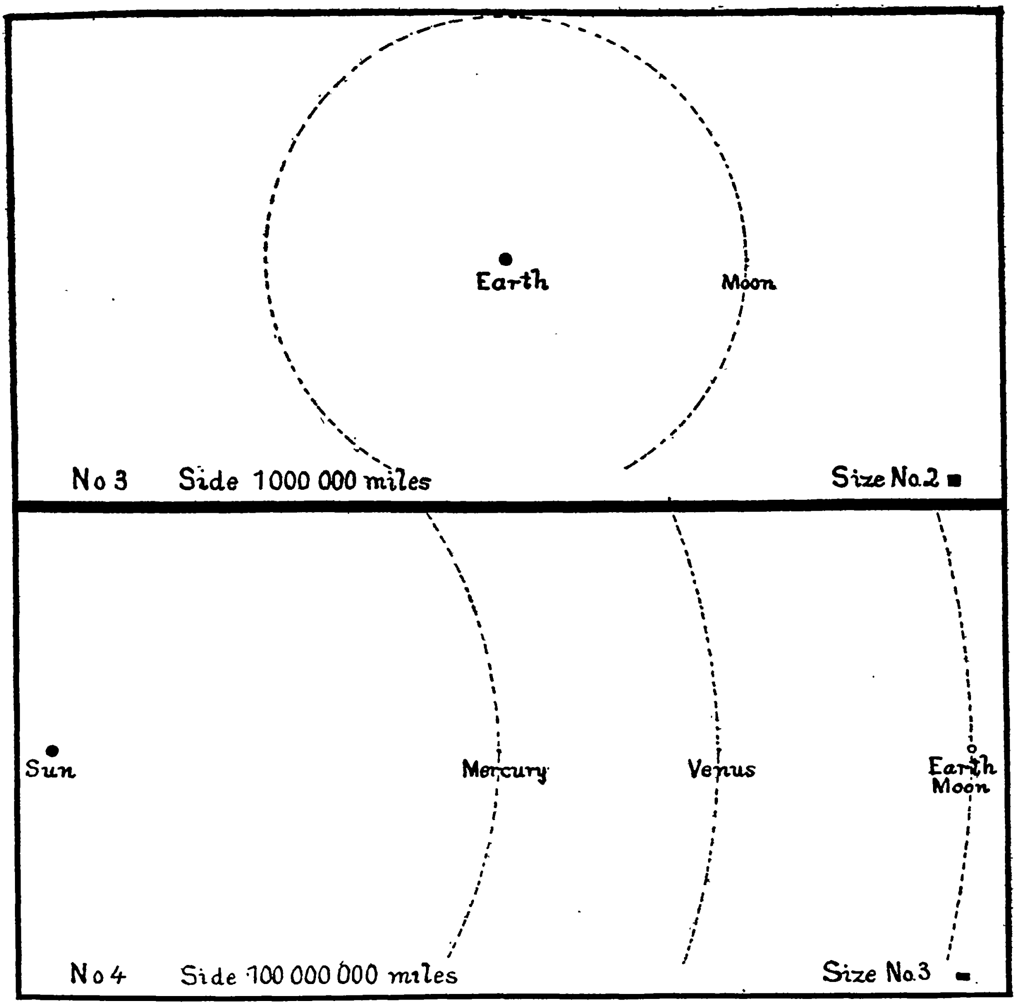
of the sidereal system is, however, due to Kapteyn, who, from investigations of the distribution, distances, motions and brightnesses of the stars, covering practically his whole lifetime, finally reached a provisional conclusion about 1920 as to the density distribution of the stars in space. The gradual thinning out of the stars with increase of distance from the sun proceeds in a fairly regular manner, the diameter corresponding to a density of one tenth that of the solar neighbourhood being about 18,000 light years with a thickness about 3,500. For a density one hundredth of that near the sun, which may perhaps be considered as the limit of the system, the diameter was found to be about 55,000 with a thickness about 11,000 light years.

It must not be forgotten, however, that all the above investiga-



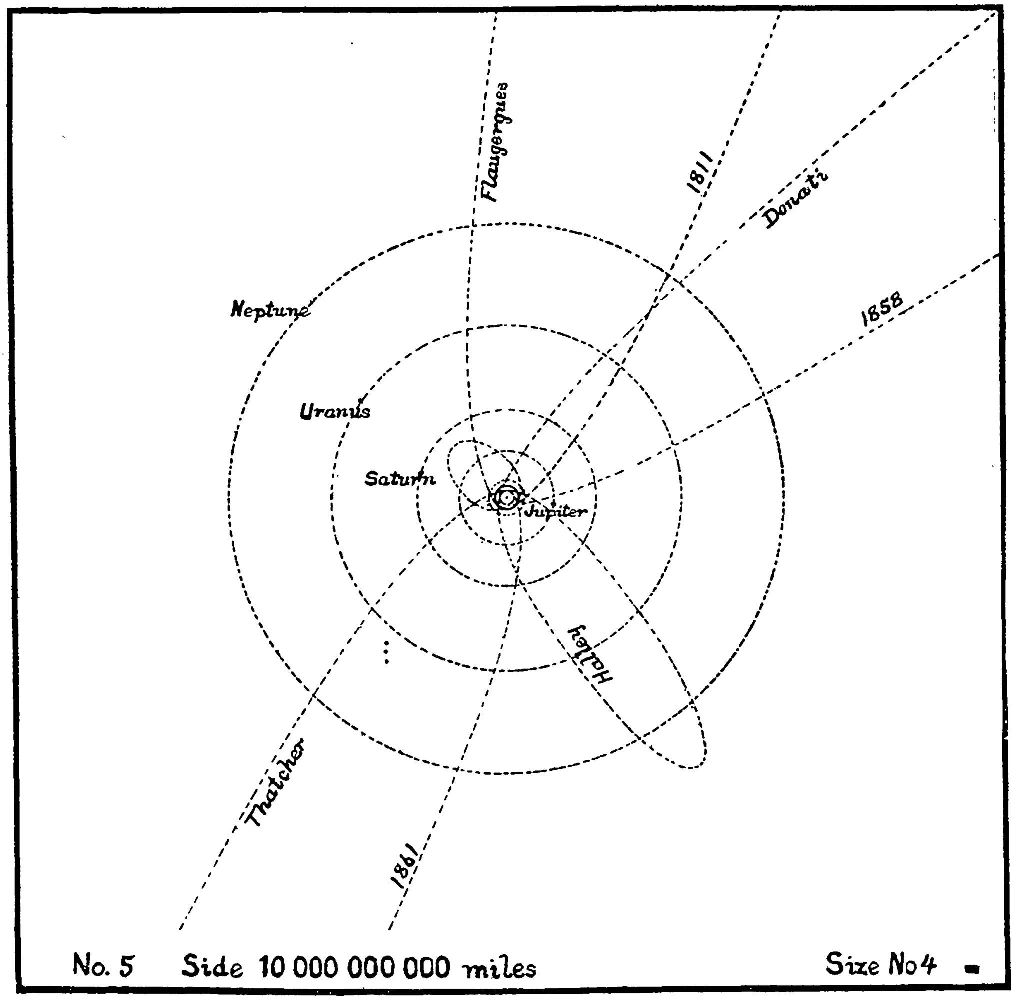
No. 2. The Earth

tions refer to a simplified or ideal form of the stellar system, and attack the problem indirectly through a determination of the density, luminosity and velocity functions from limited observations of the brighter stars only. They take no account of the obviously complex star clouds and clustering in the Milky Way, of whose distances practically nothing is known, and are admittedly incomplete and uncertain. However, a new method of attacking the problem and a further stride in the progression of increasing distances was given by Shapley at Mt. Wilson about 1918 who, from determinations of the distances of the globular clusters, assigned to the Galactic System a probable diameter of 300,000 and a thickness of 12,000 light years. Shapley's work was epoch-making on account of the enormously greater depths of space reached and because of the application of



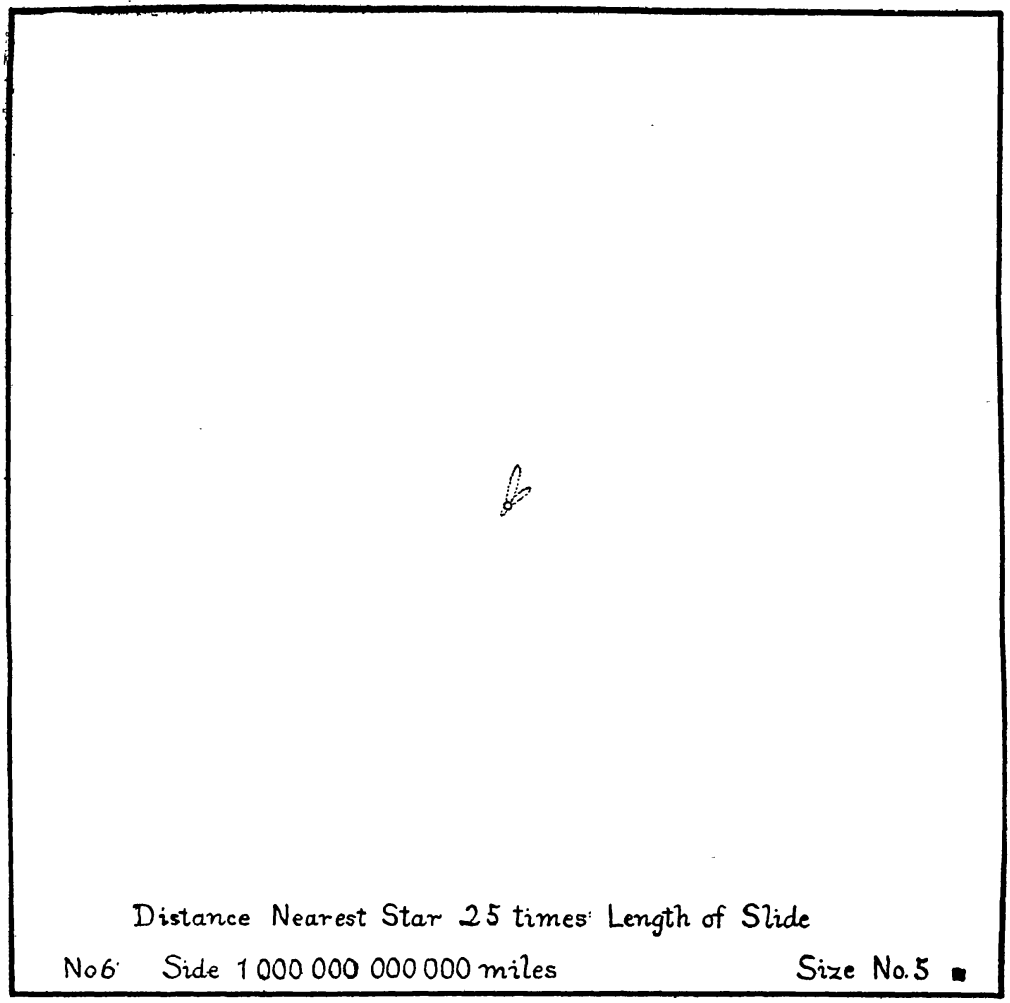
No. 3 and 4. The Earth-Moon and Sun-Earth Systems

the luminosity method to this purpose. Miss Leavitt had earlier shown, from the study of variable stars in the Magellanic Clouds, that increase of period in the Cepheid variables was accompanied by increased brightness in a definite way, and Hertzsprung applied this to derive the distance of the Lesser Cloud. Shapley, however, by an elaborate investigation of the Galactic Cepheids and by correlation of the latter with Cepheids in the clusters and Magellanic Clouds, accurately determined the form and zero point of this important relation, generally called the Luminosity Period Law, and applied it to obtain the distances of the globular clusters. In a masterly and laborious investigation he determined the distances of the 86 known globular clusters and found them to range between 20,000 and 200,000 light years from the sun. Plotting their distribu-



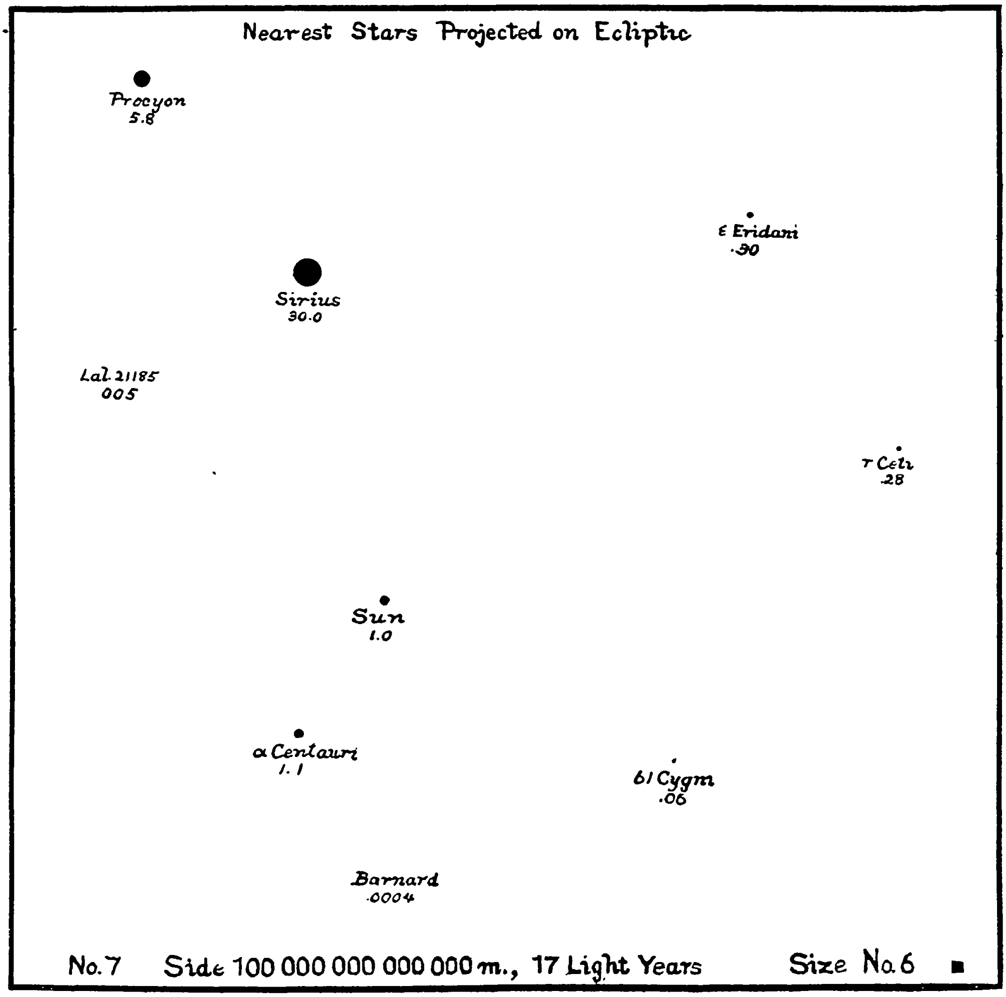
No. 5. The Solar System

tion with respect to the Galaxy, he found they were symmetrically distributed, 43 on each side, in a roughly ellipsoidal form about the galactic plane as seen in No. 9 of the illustrations. Although their motion is generally towards the Galaxy, he found that none of the globular clusters were nearer than 5,000 light years to the central plane, in contrast to the open clusters, almost exclusively within the system. This led him to the theory that the dynamical forces encountered when a globular cluster penetrated the Galaxy were sufficient to destroy its equilibrium and dissipate it into an open cluster, and to the assumption that the Galactic System, composed as it is of star clouds and open clusters, may have been partly constituted in this way. From the symmetry of the globular clusters to the Galaxy and the presence of open clusters within it, Shapley



No. 6. The Emptiness of Space.

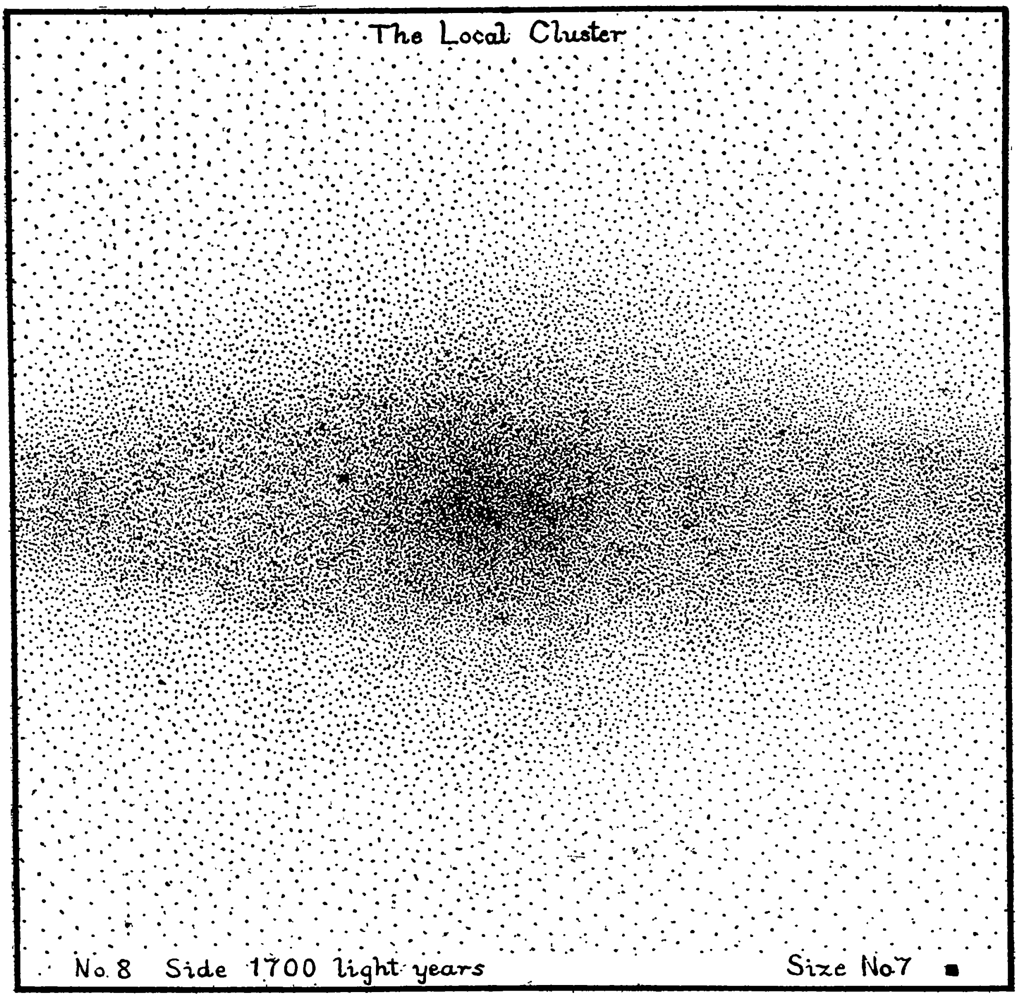
reasonably concluded they must be dependent members of the Galactic System, which must hence be co-terminous with the Globular Clusters, some 300,000 light years in diameter and 12,000 thick. He found that the sun is situated somewhat eccentrically within a watch-shaped star cloud about 5,000 light years in diameter and that this cloud, generally called the "local cluster," is inclined about 12 degrees to the galactic plane. A probable representation of the local cluster is shown in No. 8 of the illustrations with the position of the sun represented by a cross. The scale of this figure could not include the whole of the cluster which extends longitudinally considerably beyond the sides. This "local cluster" is quite eccentrically situated, however, as the centre of the whole Galactic System is about 60,000 light years from the sun in the direction of Sagittarius where, as is



No. 7. Our Nearest Neighbours in Space in Their Relative Brightness.

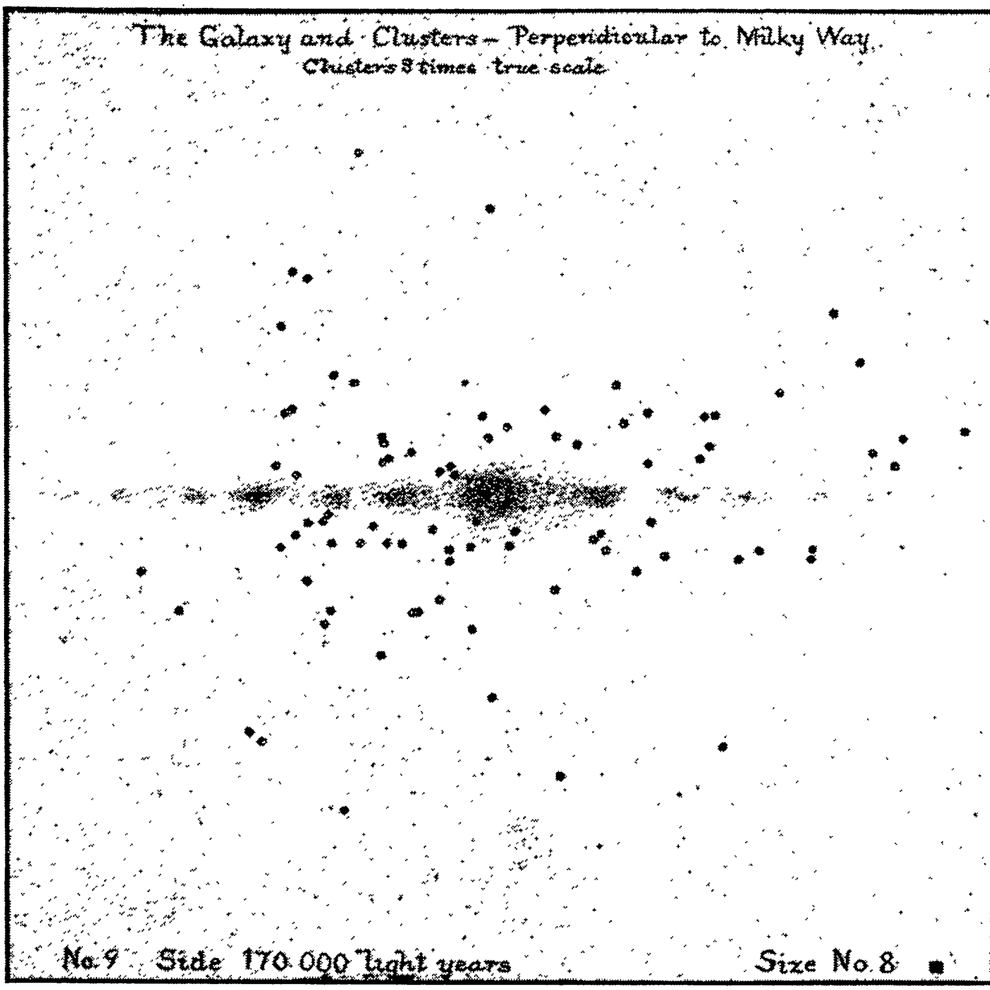
known, the star clouds appear exceptionally dense. This eccentric location of the sun should effectively shatter any belief in its importance or its central position in the Cosmos.

This is truly a magnificent and impressive picture of the Galactic System, containing several thousand million stars, and including within its confines not only the great star clouds of the Milky Way and the planetary and diffuse nebulæ but the open and globular clusters. While more recent work has tended to reduce Shapley's cluster distances and hence the scale of the Galaxy by some thirty per cent, the question is not yet finally settled, and it can be safely said that his general conclusions have not been seriously contested. While it is conceded that we have no direct evidence of galactic stars at a greater distance than 20,000 light years, that is probably



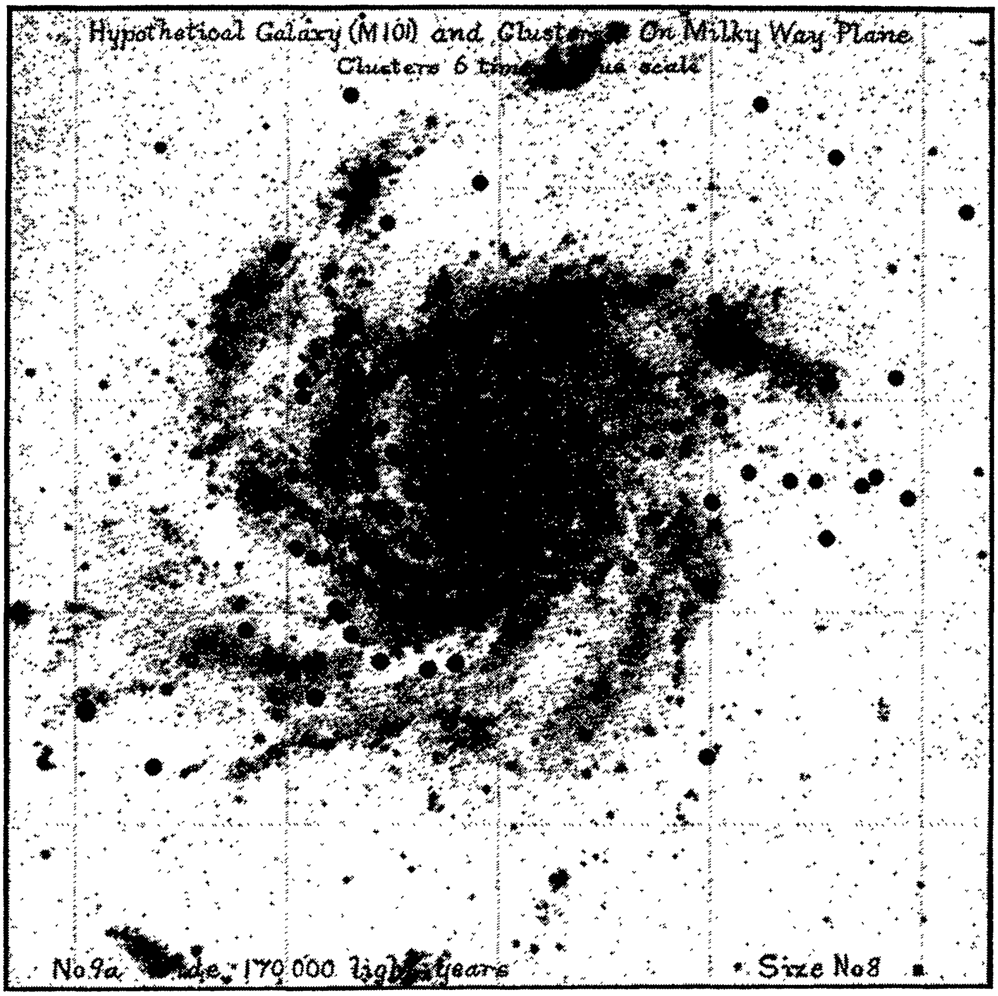
No. 8. The Local Cluster.

because no concerted search has yet been undertaken for such distant objects. It will be of interest to refer to the accompanying illustrations depicting the scale of the universe. No. 9 and No. 9*a*, in which the position of the sun is represented by a cross, must not be taken too seriously as they represent a purely imaginative conception of the form of the Galactic System. Nevertheless, this conception is not improbable from analogy with the nearer spirals, the base of 9*a* being a photograph of M101, which, as will be seen below, are now considered as outside galaxies of a similar constitution and order of dimensions. The scale attached was reached, obviously, from the starting point of 1 mile and must be taken as approximate only as the diameter is probably greater than 200,000 light years.



No. 9. Relation of the Globular Clusters to Galaxy; Perpendicular to Plane.

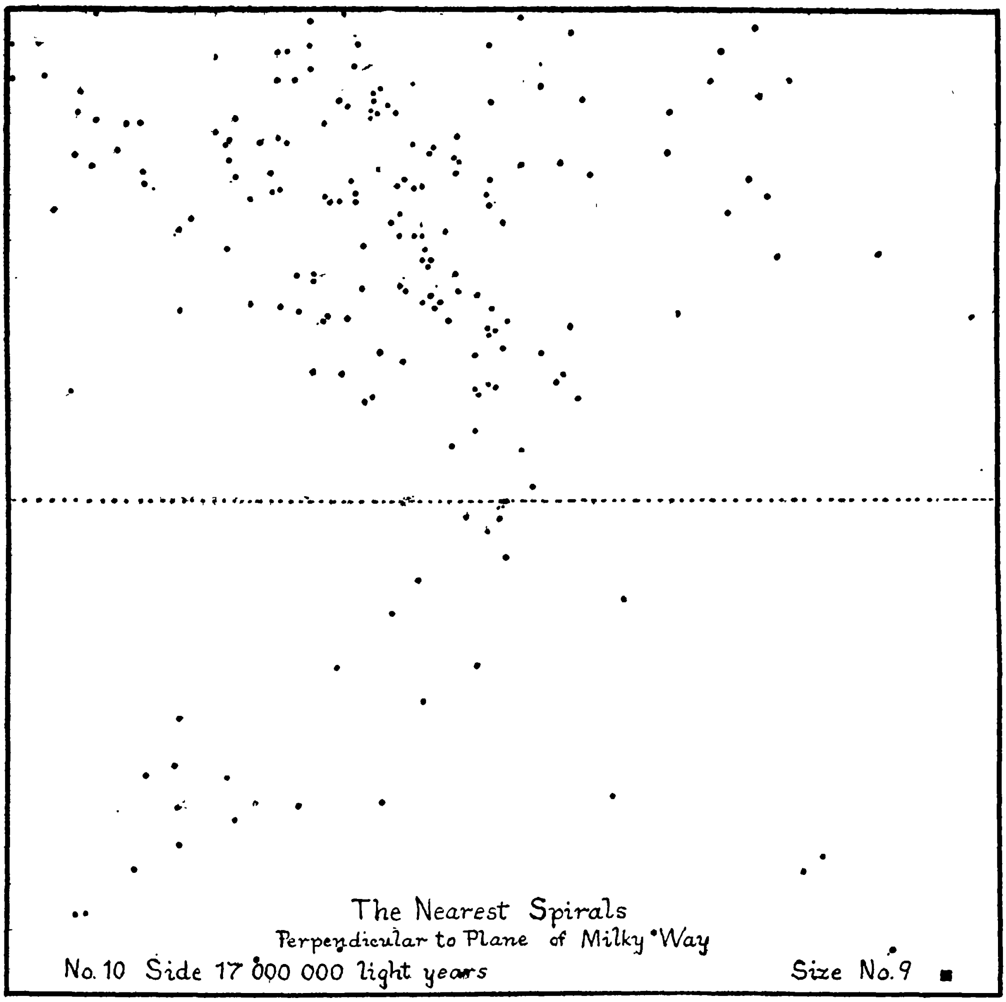
Shapley's conception of the Galaxy included the clusters and the diffuse and planetary nebulæ but avoided definite consideration of the place of the spiral and other extra-galactic nebulæ, probably because no reliable information as to their distance was then available, although he tentatively considered them as subsidiary to the Galaxy. The place and position of the spirals in the Cosmos has been hotly debated for many years and has been the subject of two opposing schools of thought. The earlier school, which prevailed generally until some ten years ago and has had strong advocates throughout, considered the spirals as outside galaxies or "Island Universes"; with distances of the nearer ones of the order of a million light years. The other school, based on the measures of



No. 9a. Relation of the Globular Clusters to Galaxy; Projected on Plane.

proper motions in some of the spirals by van Maanen and the theoretical work of Jeans, estimated the distance as of the order of 10,000 light years, hence making them subsidiary to our Galactic System. This view commanded fairly general acceptance for a few years, but the pendulum of opinion has again swung back, in the last year or two, to the Island Universe theory.

This last stage and the most recent extension of our views of the dimensions of the universe is due to Hubble of the Mt. Wilson Observatory, who has recently discovered several Cepheid variables in some of the brighter spirals and has carefully determined their periods. The application of the Luminosity Period law derived by Shapley has enabled the distances of these objects to be reliably



No. 10. Distribution of the Nearer Spirals; Perpendicular to Galactic Plane.

determined. As the same luminosity standards were used as by Shapley, there seems no question, however conflicting the views on the correction to Shapley's scale, that the relative values of the size of the Galaxy and the distances of the clusters and nebulæ are substantially correct. Thus Hubble was able to show that the Andromeda Nebula had a diameter of 45,000 and was at a distance of 900,000 light years and that the corresponding figures for the spiral in Triangulum were 16,000 and 870,000 light years, thus indicating systems which, though not so large, are of the same order as Shapley's dimensions of the Galaxy and justify by their size and importance the designation of "Island Universe."

Hubble, by means of assumptions of a fairly probable character as to comparability of diameter and brightness of the spirals, was able to deduce that the average separation of the spiral and other extra-galactic nebulæ from one another was of the order of 1,700,000 light years and that the average mass was equivalent to 260,000,000 suns. The average density of space corresponding to these dimensions is 1.5×10^{-31} grams per cubic centimetre, equivalent to 1 lb. of matter diffused uniformly over a cube of space with sides 1,000,000 miles long. This exceedingly small average density, however, is several million times less than Eddington's recent value for the diffuse matter in the Galaxy. From this density, Hubble, by applying Einstein's equations for a spherically curved space, obtains as the radius of this particular hypothetical space 85,000,000,000 light years. He estimates this distance as about 600 times the possible range of the 100-inch telescope, thus leaving an ample margin of unexplored and apparently unexplorable space for the imagination. While the tendency of the past sixty years, as we have seen, has been vastly to extend our conceptions of the size of the universe, it seems reasonably certain that a proportionate increase can hardly be expected in the future. The distribution of the nearer spirals, showing their peculiar arrangement with respect to the Galaxy and their complete avoidance of the galactic plane, the latter being represented on proportionate scale, is shown in No. 10 of the illustrations which is plotted from data obtained from Hubble's tables. The tremendous extent of the spherical relativity universe can be better imagined when it is realized that two additional figures on the same hundred-fold ratio would be required to reach the boundary.

It should be of interest to Canadians to learn, in concluding this review of the progress made in our conceptions of the universe since Confederation, that Canada's contribution to modern astronomical research is one of which every Canadian has good reason to be proud, as to the best of my knowledge, it is unequalled relatively, so far as Government support is concerned, by any other country. Canada with its small population and its relatively short span of national life has established and supports two national observatories of the first rank, one of these having the second largest telescope in existence, and both making important contributions to science.

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