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THE SIZE OF THE UNIVERSE[1]

THE century in which we live promises to make an incalculable advance in man's power of exact measurement. "Nearly all the grandest discoveries of science," says Lord Kelvin, "have been but the rewards of accurate measurement and patient, long-continued labor in the minute sifting of numerical results." The opening decades of the century have witnessed the emergence of a number of fundamental natural phenomena, the explanation of which defies all the mighty power of Newtonian mechanics. The Newtonian laws have hitherto been found adequate to explain large-scale phenomena; but there seems convincing reason for grave doubt as to their applicability to small-scale phenomena. "The old laws," as Jeans observes, "are not, so to speak, fine-grained enough to supply the whole truth with regard to small-scale phenomena." Nor are they exact enough to explain very minute changes in large-scale phenomena. Conspicuous among contemporary theories which throw grave doubt upon the universal applicability of the Newtonian mechanics are the electron theory of Lorentz, the quantum theory of Planck and the relativity theory of Einstein. The Lorentz transformation, basic in the electron theory, belies Newton's ideas of absolute space and time. Crucial in the quantum theory is the phenomenon that "the total radiant energy per unit volume of ether in temperature-equilibrium with matter is finite"; and to explain the facts of radiation according to Planck's law the Newtonian mechanics are inadequate. The remarkable explanation of the observed discrepancy in the advance of the perihelion of Mercury, and the phenomenal accord of observation with theory in the matter of the light-ray deflection announced by W. W. Campbell a few weeks ago, thitherto unexplained by the Newtonian mechanics, constitute supreme triumphs for Einstein's relativity theory.

To-day are going forward profound investigations, at each end of the scale of magnitudes—towards the infinitesimal and towards the infinite. Methods of almost incredible refinement are being devised for determining the scale of the atom and the scale of the universe. The investigations of Rutherford have virtually set it beyond doubt that the atom consists of a central nucleus of almost infinitesimal dimensions, and of electrons revolving in planetary manner

[1] Presidential address before the North Carolina Academy of Science, Greensboro, N. C., May 5, 1923.

around the nucleus. The hydrogen atom consists of a negative electron revolving in an orbit round a positive nucleus of equal charge, while the helium atom consists of two electrons revolving in orbits round a nucleus with a positive charge equal in amount to twice that of an electron. The scale of the universe to the atom is believed to be 10^{22} to 1. The radius of the solar system is 10^{14} centimeters. This, on dividing by 10^{22}, becomes 10^{-8} centimeters, the radius of an atom. As Aston recently pointed out, "the atom, like the solar system, is *empty;* and what we measure as its spherical boundary really only represents the limiting orbits of its outermost electrons." An atom of hydrogen, on being enlarged by the factor 10^{22}, would become of the same size as the solar system; and its two planetary electrons would closely resemble Uranus and Neptune as regards size, distance from the sun and period of revolution. If in the atom of helium, for effective comparison of size and distance, the nucleus were represented by a rather large pea, its planetary electrons would be represented by two somewhat smaller peas revolving around it at the distance of a quarter of a mile.

These investigations of the atomic microcosm have concentrated attention upon the fundamental structure of the universe. It would seem that aggregations of matter, ranging from the infinitesimal to the infinite, possess the features of the solar system. Each particle of the atom may be a little world after analogy with this world now rotating beneath our feet at the rate of 1,000 miles per second. Our solar system is one among countless many others of the Milky Way; and perhaps the Milky Way is but one of countless giant nebulae whirling in spiral form through a space that may be infinite. While the mathematicians and the physicists, Lorentz, Planck, Poincaré, Thomson, Rutherford, Millikan, Soddy, have been turning their brains, their microscopes and spectroscopes to a study of the atom, the astronomers, Shapley, Kapteyn, Russell, Hertzsprung, Eddington, DeSitter, Curtis, have been utilizing their telescopes, interferometers and coelostats in the study of the new heavens revealed by the epochal advances in photography and spectroscopy. Until the time of Galileo, the "crystalline lens of the human eye, limited by the iris to a maximum opening about one quarter of an inch in diameter," was the only collector of starlight. Galileo's telescope, of 1610, with a lens-area about eighty-one times that of the pupil of the eye, vastly extended for the astronomer the boundaries of the visible universe, bringing to view stars down to the magnitude 10.5, of which nearly half a million are known to exist. Through the development of the photographic telescope and the use of the spectroscope, within recent years, astronomers have caught hundreds of millions of star-images upon the photographic plate and for the first time through spectral images and luminosity curves began to make some credible computations regarding the scale of the universe. In his presidential address before the British Association for the Advancement of Science, Eddington recently remarked: "Probably the greatest need of stellar astronomy at the present day, in order to make sure that our theoretical deductions are starting on the right lines, is some means of measuring the apparent angular diameter of stars." Recent observations at the Mt. Wilson Observatory, with the use of the Michelson interferometer, have greatly increased our knowledge of the apparent angular diameters of giant stars, and given us a new and enlarged conception of the magnitude of the visible universe. On December 13, 1920, by the use of the Michelson interferometer, Pease found that the angular diameter of Betelgeuse, Arabic for the "Giant's shoulder," the conspicuous red star in the right shoulder of Orion, was $0''.047$; and assuming a parallax of $0''.018$, the linear diameter of α Orionis turned out to be 240,000,000 miles. To help us to understand what this means, we may say that the angular diameter of Betelgeuse is that of a ball one inch in diameter, seen at a distance of seventy miles. This giant star, which is but a tiny point of light to the naked eye, would completely fill the orbit of Mars; and if placed in the position of our sun would shoulder out the sky and we should see only a blazing firmament of fire. If a boy of fourteen were to fire around Betelgeuse a bullet with the unchanging velocity of 2,800 feet per second, the highest known velocity for a projectile, the bullet would not complete the circuit until he had reached the Biblical age of threescore years and ten. A ray of light from Betelgeuse, traveling at the rate of 186,330 miles per second, would take 160 years to reach us; which means that Betelgeuse is distant from the earth about one quadrillion miles.

In any attempt to measure the sidereal universe, it is necessary to increase enormously our units of measurement. In ordinary mensuration upon the earth, we employ the units: inches, feet, yards. In measuring the moon, on account of the great magnifying power of the modern lens, it is possible to use the mile as a unit. The next unit we resort to is the diameter of the earth—say some 8,000 miles. But in order to measure the distances from the sun to its attendant planets, it is necessary to use a unit 12,000 times the diameter of the earth—the *astronomical* unit —93,000,000 miles, the distance from the earth to the sun. But in order to measure the very great distances from star to star, which are as remote from each other in some cases as a thousand million astronomical units, it is necessary to use a still greater unit, the *light-year*. As light travels with the velocity of about 186,000 miles per second, it is easy to compute the distance light travels in a year, which is something less than six million million miles. It is only by the use of such a yardstick as the light-year that one can satisfactorily take the scale of the sidereal universe.

While stars of the magnitude of Betelgeuse and Antares can be studied by the use of parallax methods, the globular clusters of the type of Omega Centauri and Hercules are so remote as to defy the astronomer in the attempt at determination of their distance from us by the geometrical measurement of parallax. By observing that, in each of the clusters where variable stars appear, the brightest stars of the cluster are, on the average, three times as bright, photographically, as the variables, Shapley has computed the distances from us of the principal globular clusters. Measuring the brightness of the brightest stars in any cluster, Shapley obtained results for some 30 clusters which are truly amazing. He found that the nearest of the globular clusters—Omega Centauri and 47 Tuscanae, both in the southern hemisphere—are distant from us about 22,000 light-years. The great cluster in Hercules is about 35,000 light-years away; and the remotest cluster, No. 7006, is at the enormous distance of 220,000 light-years—at least fifty times as far away as the remotest star whose distance can be measured by other methods.

Now our galaxy, delimitated for us by the projected contours of the Milky Way, is shaped much like a lens or a thin watch, the thickness being probably less than one sixth of the diameter. Astronomers are agreed that within this galaxy, which contains possibly a billion suns, the stars are not infinite in number nor uniform in distribution. Twenty years ago Newcomb remarked that the "sun *appears* to be in the galactic plane because the Milky Way is a great circle—an encircling band of light—and that the sun also *appears* near the center of the universe because the star density falls off with the distance in all directions." And yet he confesses: "Ptolemy showed by evidence which, from his standpoint, looked as sound as that which we have cited, that the earth was fixed in the center of the universe. May we not be the victim of some fallacy, as he was?" This very week, Painlevé, the distinguished French mathematician, made this extraordinary statement: "Under the old teachings it was explained that the world turned on its axis and in space. Of course, this is mere talk for children; no such thing occurs, but such explanations must be given so the ignorant can have a mental picture of what the universe is like. Neither the earth nor the stars whirl in space." Are we *all,* indeed, the victim of some strange fallacy?

To primitive man, the physical universe was anthropocentric. Eventually, with Ptolemy, came the conception of the geocentric universe. Since the time of Copernicus, astronomers have believed in a heliocentric universe—a universe in which the sun was considered to be at or near the center of the stellar universe. Shapley's investigations lead us to believe that the sun is at least 50,000 light-years from the galactic center. His study of the Cepheids—variable stars of short period named from the star Delta Cephei—have led to truly remarkable conclusions regarding the size and remoteness of these variable stars. They vary considerably in brightness from time to time, and also show corresponding alterations in color, being redder when faint, whiter when bright. Since spectroscopic observations of their motion in the line of sight show that the "peculiar" motions of these stars are unusually small, it was possible to devise trustworthy values for the average distance of these stars by considering their "parallactic drift" due to our motion in space past them. As the result of the observations of Russell, Hertzsprung and Shapley, it has been found that the average brightness of a Cepheid of period six days, is 750 times that of the sun; that a Cepheid with a period of 100 days is 23,000 times as bright as the sun; and that a Cepheid at maximum brightness is 30,000 times as bright as the sun. Computation on this basis shows that the Small Magellanic Cloud, one of the two remarkable outlying patches, similar to the Milky Way but remote from it, in the southern hemisphere, is at a distance from us of 62,000 light-years. A Cepheid of 100 days period is 800 times the sun's diameter—700 millions of miles—big enough to include all the inner planets of the solar system within its bulk, and almost as large as the orbit of Jupiter.

Shapley has calculated the actual positions in space of the 69 clusters definitely recognized as globular; and he finds that they, themselves, form a huge flattened cluster, probably 300,000 light-years in diameter, and about 100,000 light-years in thickness. "Since the affiliation of the globular clusters with the galaxy," says Shapley, "is shown by their concentration to the plane of the Milky Way and their symmetrical arrangement with respect to it, it also follows that the galactic system of stars is as large as this subordinate part. During the past year we have found Cepheid variables and other stars of high luminosity among the fifteenth magnitude stars of the galactic clouds; this can only mean that some parts of the clouds are more distant than the Hercules cluster. There seems to be good reason, therefore, to believe that the star-populated regions of the galactic system extend at least as far as the globular cluster."[2]

[2] *Bulletin of the National Research Council,* Vol. 2, part 3, No. 11: "The scale of the universe" by Harlow Shapley and Heber D. Curtis, 1921.

The center of this colossal globular star system is, according to Russell, some 70,000 light-years from the sun. The final conclusion, to which I would especially call your attention, is that, according to these truly arresting investigations, the diameter of the whole system of globular clusters is about the same as the diameter of the galactic system, namely, 300,000 light-years. This figure will, later on in this paper, furnish comparison with a remarkable investigation of Einstein regarding the size of the universe.

The largest figure hitherto given for the diameter of the galaxy was 60,000 light-years, advanced by Kapteyn. Other figures are Wolf, 14,000 light-years; Eddington, 15,000 light-years; Newcomb, 30,000 light-years. The new methods and the recent computations of Shapley, Hertzsprung, Russell and Miss Leavitt indicate a diameter for the galaxy some 10 times the figure ordinarily accepted by astronomers in the past. There appears, however, to be a definite limit to the size of the stellar universe. Stars of the second magnitude are 3.4 times as numerous as those of the first, those of the eighth magnitude are three times as numerous as those of the seventh, while the sixteenth magnitude stars are only 1.7 as numerous as those of the fifteenth magnitude. "This steadily decreasing ratio," says Hale, "is probably due to an actual thinning out of the stars towards the boundaries of the stellar universe, as the most exhaustive tests have failed to give any evidence of absorption of light in its passage through space."

Poets, philosophers, scientists throughout all the ages have regarded the universe as infinite. The book of Job gives us that awful image of an infinite void in the words: "He stretcheth out the north over the empty space, and hangeth the earth upon nothing." In propounding his doctrine of the infinity of the worlds in space, Giordano Bruno thunders out the mighty lines:

> Now unconfined the wings stretch out to heaven,
> Now shrink beneath a crystal firmament
> Aloft into the aether's fragrant deeps,
> Leaving below the earth-world with its pain,
> And all the passions of mortality.

On metaphysical grounds alone, Kant affirmed that space is infinite and is sown with similar stars in all parts.

Is the universe infinite? If a voyager of the skies travels in a straight line deep into the inter-stellar spaces, past the great blue helium stars of Orion, past Betelgeuse and Antares, beyond the white variable Cepheids, the gaseous red and yellow giant-stars, the colossal globular clusters, and beyond even the faintest of the super-nebulae whirling in fiery spirals in the dim void of remoter space—will he ever reach a limit of the sidereal realm? That is the profound and provocative query which has recently been raised anew by Einstein. In the Milky Way there are perhaps as many stars as there are now human beings living upon the earth. Beyond those dense masses of stars, such as the Magellanic Clouds, and beyond the great globular clusters which hover about the fringes of the Milky Way, lie vast wastes of desert space, devoid of stars over incalculable expanses. Beyond this, says Nordman, lie those strange bodies, the spiral nebulae, "lying like silver snails in the garden of the stars." Astronomers are divided in opinion to-day in regard to these spiral nebulae, of which there are known to be more than a million—whether to regard them as "island universes," systems like that of the Milky Way and comparable to it in their dimensions, or merely as annexes of the Milky Way, reduced models of it. These spiral nebulae have the enormous average space velocity of 1,200 kilometers per second; and their radial velocities and distribution, the maximum luminosity attainable by a star, the dimensions of our own galactic system, incline certain contemporary investigators to the hypothesis that the spiral nebulae are members of the galactic organization. Poincaré's calculation of the number of stars in the Milky Way agreed fairly closely with the number counted, which, taken together with other considerations, was opposed to an indefinite extension of the stellar universe.

What answer does the Newtonian mechanics give to the query: Is the stellar universe infinite? According to this theory, if there were an attenuated swarm of fixed stars of approximately the same kind and density, however far we might penetrate the interstellar spaces, then matter would have a finite mean density; and the intensity of the gravitational field at the boundary of the universe would be *infinite*—which is impossible. According, then, to the Newtonian theory, the mean density of matter must be infinitesimally small; and the cosmos must present the picture of an island of finite extent surrounded on all sides by infinite empty space. Such a view is repugnant to our minds, since the light of the stars and isolated stars themselves would drift away into the infinite, and this ephemeral cosmos would gradually melt away and disappear. Astronomical observation does not support the view that the energy of the cosmos is gradually being dissipated. To obviate these inevitable but incredible consequences of the Newtonian theory, it is necessary: either to assume with Seeliger, which is a purely *ad hoc* hypothesis, that the attraction of masses decreases at great distances somewhat more rapidly than in inverse proportion to the square of the distance; or else to assume that the number of stellar systems and stars is finite.

In a famous paper, "Cosmological Observations

Concerning General Relativity," published in the *Report of the Berlin Academy of Science,* February 8, 1917, Einstein advanced the view that the universe is finite, but unbounded. This statement sounds paradoxical, but brief reflection will show that a thing may be unbounded without being infinite. A being which moves on the surface of the earth, or indeed of any sphere, may travel over it indefinitely without ever reaching any boundary or limit. Similar considerations, extended to three-dimensional curved space, enable us to see how the universe may be at the same time finite and unbounded. Einstein assumed that the matter of the universe was distributed with uniform density; and that the stellar system is approximately at rest, since the velocity of the stars is very small as compared with the velocity of light. Assuming further the existence of pressure inside the electrically charged particles of matter in the universe, Einstein showed by elaborate calculations based on general relativity that space is "spherical" in structure, in the Riemann sense. In reality this means that space is "quasi-spherical" in the Riemann sense somewhat as the earth is quasi-spherical in the Euclidean sense, because of local corrugations. The Einstein universe is quasi-spherical, since matter does not actually occupy space uniformly and is not really at rest, but only shows the same density of distribution as a mean and has a very low velocity as compared with the velocity of light.

The "spherical" space here referred to is curved space—which means that according to Einstein the geometry of our universe is not Euclidean. The universe, moreover, does not have the shape of a sphere. It is not a three-dimensional space cut out of four-dimensional space—as is a sphere a two-dimensional space cut out of a three-dimensional space. It possesses the following properties: All lines starting from a point intersect again in the antipodal point measured along any of these lines. These straightest lines are closed and have a total length of $2\pi R$ where R is the "radius" of the universe. The greatest possible distance between two points is πR; and there is only one point, the antipodal point, at this distance from a given point. If a stellar body move through spherical space, its size gradually increases until it reaches its maximum at the universe's outer verge; and there, as it were, re-entering the universe it gradually diminishes in dimensions until it ultimately reaches its original size and position. Every point stands in the same relation to the rest of space as does every other point. There is no boundary to spherical space, and no center. The formula for the total volume of this spherical space is $2\pi^2R^3$.

Another extraordinary feature of this spherical space is that, neglecting the absorption of light, we should see a star-image of a given star at the opposite point in the heavens. If we look at some faint star in the Milky Way, the radiant pulses of energy give us a vision of the star, not as it is now, but as it was in the days of Tut-ankh-amen; and at the opposite point of the heavens we shall see an image of this same star—not as it was when the Egyptians were building the pyramids, but as it was perhaps in the prehistoric days of ancient Phoenicia. Who knows but that many of the stars we see in the firmament are not real but only ghosts of stars haunting the heavens from the days of remotest antiquity?

In this spherical space, according to Helmholtz, "we imagine the more distant objects to be more remote and larger than they are. But we find on approaching them that we reach them more quickly than we expected from their appearance. But we also see before us objects that we can fixate only with diverging lines of sight, *viz.,* all those at a greater distance from us than the quadrant of a great circle. . . . The strangest sight in the spherical world would be the back of our own head, in which all visual lines not stopped by other objects would meet again, and which must fill the background of the whole perspective figure." To those inclined to be sceptical of the existence or even of the conceivability of such a world, I need only suggest that you can see a world of spherical space by looking out at our own world through a slightly prismatic glass with the thicker side towards the nose.

In the graduate mathematics seminar at the University of North Carolina, we have made this year a thoroughgoing study of spherical space and the universe, according to Einstein's general relativity theory. The volume of this universe, expressed in grams, is 7 followed by forty-one ciphers, divided by the mean density of matter to the 3/2 power; and the mass of this universe is 7 followed by forty-one ciphers divided by the square-root of the mean density. If we assume that the average density of matter in the universe is the same as that of the Milky Way, we find that the radius of the universe is at least 150 million light-years; or, since the distance from the earth to the sun is 93,000,000 miles, the radius of the universe is 1 million times 10 million times the distance from the earth to the sun. Choosing the Milky Way as yardstick, of 30,000 light-years, according to the figure of Curtis, it will take 10,000 Milky Ways, laid end to end, to arrive at the diameter of the universe. The greatest sphere of water which could be included in the universe would have a radius of 300 million kilometers. Using the diameter of the earth's orbit as a measuring rod, we shall need 10 trillions of these units to take the measure of the diameter of the universe.

The weight of the universe, in grams, would be 1 followed by fifty-four ciphers—which would carry us into the nonillions of grams. The weight of the Einstein universe bears the same relation to the weight of the whole earth as the latter bears to a kilogram. The weight of the earth to that of the sun is as 1 to 324,000. Hence we should have to take a trillion suns to get the weight of the universe.

It would take a ray of light, traveling at the rate of 186,000 miles per second, one billion years to go around the universe. To go around the universe it would take the fastest aeroplane 3 quadrillion years; the fastest automobile five and one half quadrillion years; and an express train, traveling at the rate of 60 miles an hour, 11 quadrillion years.

In conclusion, I wish to call your attention to the fact that the dimensions of this finite universe of Einstein are more than ample to include the spiral nebulae—whether regarded as galactic phenomena or even as island universes. On the assumption of approximate equality of size for celestial objects of the same class, which has been used by Shapley and other investigators, the extreme distance of the most remote of the spiral nebulae, considered as galactic phenomena, would be of the order of 10 million light-years; and, considered as island universes, would be of the order of 100 million light-years. Thus, even the most remote spiral nebulae would fall far within the bounds of the Einstein universe with its super-diameter of 300 million light-years.

Descartes, confronted with the question "What lies beyond?", always affirmed that a finite universe was impossible. This question has no meaning for Einstein because the foundation of general relativity is the doctrine that there is no space without matter or energy. If all the heavenly bodies we know belong to our galactic system, it is possible, says Einstein, that "other universes exist independently of our own." They may remain forever optically isolated from us by the phenomenon of the cosmic absorption of light. While other universes may palpitate beyond our own, no ray of knowledge, says Nordman, "could ever reach us from them. Nothing could cross the black, dumb abysses which environ our stellar island." We are doomed to dwell within a finite universe a thousand million times greater than the region now accessible to astronomical observation. Our glances are confined for ever within this giant—this all too minute—monad.

Archibald Henderson
The University of North Carolina

A NEW ERA FOR AMERICAN MUSEUMS

On March 30, it was announced in Science that a grant of $30,000 had been made to The American Association of Museums contingent upon the raising of $55,000 more, and that the campaign for funds was expected to continue through the autumn of 1923. It is therefore a matter of pride to the association that announcement can be made now of the success of its project and of the consequent establishment of national headquarters at Washington, D. C.

This development signals the beginning of a new era for the association, of course, but much more than that, it is believed to mark the beginning of a new era for the museums of America.

Organization on a national scale to the end of maintaining a staff to work for a common cause has been found highly advantageous by local units in many fields. Most wide-spread interest has attached to industrial and commercial developments along these lines, but the same methods have been equally successful in fields of social, civic, religious and educational endeavor. The recourse by museums to organized cooperation is therefore not surprising, but it is a clear indication of the hopeful trend in museum affairs.

The funds now available have been contributed in part by individuals, many of whom are members of museum boards. Unfortunately no more than a dozen museum corporations have shared to any considerable extent in the financial burden, but it is hoped that the three-year demonstration, which is now assured of support, will bring about more general participation by museums. It is felt that the responsibility will have to be shared in equitable fashion by a majority of active museums before the movement can enter upon the road to permanent success. However, the work is now afoot, and the future will depend upon the success of activities during the next three years. For those who are most closely associated with the project, there is a great responsibility.

Fortunately there is no lack of interest and moral support on the part of museums—at least so far as official attitude can be judged by the consensus of opinion among some five hundred museum employees and trustees, who make up the active membership of the association.

The program which has been drafted looks far into the future, and there is no thought that more than a few of the most important projects can be initiated within the near future.

The Program

I. Propaganda Service for Museums.
To acquaint the American public with the work and aims of museums.
A. Press publicity—news items, articles and special departments in newspapers, magazines, trade papers and house organs.
B. Screen publicity—production and circulation of films and slides showing the value of museums; efforts to induce producers of educational films to utilize museum material.