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DO WE LIVE IN A SPIRAL NEBULA?[1]

IN May, 1925, my colleague, Dr. Joseph H. Moore, and I determined anew the elements of the motion of the solar system, upon the basis of the radial velocities of 2,034 stars, as observed at the Lick Observatory and at the Chile Station of the Lick Observatory. The apparent solar motion was found to be toward a point in the heavens having right ascensions 268°.9 and declination +27°.2, with speed 19.0 km per second. These results are in good agreement with those obtained by me from 1,193 observed radial velocities, in 1911, as follows: right ascension 268°.5, declination +25°.1, and speed 19.5 km per second.

The direction in which we found the solar system to be moving makes an angle of 22° with the plane of the Milky Way. Moving with a speed of 19 km per second, the solar system travels 600,000,000 km per year, or four times the mean distance of the earth from the sun. We are doubtless showing high respect for the values of understatement when we say that our sun is at least many hundreds of millions of years in age. Clearly our solar system in its early youth did not have its present position in the stellar system, and its old age will find it in still other surroundings. We can not speak with confidence concerning the path upon which we are traveling, whether it is a great closed curve—an elongated ellipse, for example—which will suggest our return a few hundred millions of years hence to our present point of observation, or whether it is a path so curved that it does not return unto itself. If the stars were distributed in a system having spherical symmetry the center of the system should be the effective center of gravitational attraction and, neglecting minor perturbations, our sun should describe an ellipse about that center. But we know that our stellar system is not spherical either as to form, or as to the grouping of its component stars, and therefore the path followed by our sun probably differs somewhat from an ellipse. It is of interest to note that if our stellar system were spherical in form and the stellar materials were uniformly distributed through it, the revolutionary periods of the individual stars would all be equal, no matter what their distances from the center, no matter what their observed speeds at any instant, might be. A knowledge of the density of distribution of the star materials would at once tell us the com-

[1] Address of the retiring president of the American Astronomical Society, read at Rochester, New York, January 2, 1926.

mon period of revolution. Eddington has calculated that a density of distribution which assigns ten stars, each equal in mass to our sun, to every sphere of space 33 light years in diameter would mean a period of 300,000,000 years for the sun and all other stars around the center of mass of the system. But, let us repeat, our system is not spherical in form, nor as to its stellar distribution, and we do not know the density of mass distribution even in our own neighborhood.

But at this point many questions suggest themselves. We are constrained to ask: May not our stellar system be one of those mysterious objects which we call spiral nebulae? Easton of Belgium considered this subject seriously, and rather favorably, a generation ago. The memorable discussion of the probable dimensions of our stellar system, conducted by Curtis and Shapley in 1920, under the auspices of the National Academy of Sciences, bore here and there upon this question, as well as upon the related question, Are the spiral nebulae island universes? Aside from the studies mentioned, the subject of our stellar system as a spiral nebula has received only haphazard attention.

The spectrum of a typical spiral nebula closely resembles the spectrum of our sun; as if the spirals were great collections of suns. Some of the spirals are from their spectra observed to contain true nebulae, just as our stellar system has many nebulae distributed within it.

The spirals closely resemble our stellar system in general outline. Their major dimensions are many times as great as their thicknesses, ten times as great in some observed cases. From the days of Herschel's star counts—star gauges, he called them—we have known that our system is lenticular in form. Recent students of the subject incline strongly to the view that the ratio for our system is even much greater than 10 to 1.

Casual observation of spiral nebulae is sufficient to convince us that they are in rapid rotation—that is clearly the reason why they resemble lenses in form. The spectrograph has measured the rotational velocities of two or three spirals, with results about as might have been anticipated.[2] The observed rotational data, treated in accordance with the laws of celestial mechanics, tell us that these few spirals are each massive enough to supply materials for millions of stars equalling our sun in mass.

Hubble with the 100-inch reflector at Mount Wilson has recently resolved a few of the largest spirals into myriads of stars. He has shown that two of them—the two which have the largest angular diameters—are nearly a million light years[3] from us, and therefore that they have enormous linear dimensions. Expressed in light years their diameters are probably of the order of 40,000[3] in one case and 10,000 or 15,000 in the other.

When viewed edgewise, or nearly so, the spirals generally show the presence of absorbing or occulting matter on or near their peripheries. If we were near the center of one of the more or less irregular masses in one of the arms of a spiral, looking out through the supposedly starry heavens, might not the counts of stars show remarkable similarity to the star gauges of Herschel? Shouldn't we expect to observe a Milky Way? Would not such a Milky Way be irregular in outline and intensity, and show cloud forms? Might not absorbing or occulting matter in a spiral, apparently an attribute of many of them, produce a bifurcated structure, similar to that of our Milky Way as seen in the night sky of the northern summer? Might not the central thicker nucleus of the spiral be actually invisible, save as to its two outermost segments, just as in the double section of our Milky Way we may be seeing merely the outermost segments of its thickest part? Or, it may be that an observer in one of the distant spirals, by virtue of prevailing obstructions in his line of sight, would not see the spiral nucleus at all, as we may possibly, though not probably, be prevented from seeing the nucleus of our system. Astronomers know that the appearance of our Milky Way, as to its outlines and densities, is profoundly influenced by obstructing material which interferes with our view of it. The apparent division of our Milky Way structure at its widest parts is thought to be due to the presence of invisible obstructing materials, in vast quantities.

Curtis's Crossley-Reflector photographs of several dozens of spirals which are strongly inclined to the line of sight show what appear to be absorption or obstruction effects in essentially all cases. These effects in some spirals persist right up to the central nuclei: the halves of a few such nebulae, thought to be the halves nearest to us, are reduced in brightness, as if a considerable share of the radiations which would otherwise have come to us from those hemispheres were cut off by obstructing materials. If such an obstructing system, perhaps preferably an occulting system, prevails on and near the periphery of our stellar system, an occulting structure of considerable thickness existing not only in the plane of

[2] Considerable doubt seems to have existed, and possibly still exists, as to the proper assignments of the spectrographically observed rotational speeds to the apparently nearer or to the apparently farther edges of the spirals concerned.

[3] These distances and dimensions do not differ greatly from those arrived at several years ago, by Curtis and others, from the observed magnitudes of the novae discovered in the spirals.

the Milky Way but extending out at right angles to it considerably farther than the radiating stars extend—as seems to be the case in some of the oblique spirals referred to—then we should not be able to see faint objects, such as spiral nebulae, in the direction of the Milky Way, or on or near its borders. Now this is exactly in accord with the facts of observation. With the Crossley Reflector, Keeler showed that there are certainly many tens of thousands of nebulae in the heavens, which have the general form of spiral nebulae. Though Hubble's photographs with the 100-inch reflector of Mount Wilson have failed to show spiral structure in many of these nebulae, their spectra seem to resemble closely the spectra of spirals. They are extremely plentiful in a large region of the sky which contains the north pole of the Milky Way, that is, in the region farthest from the Milky Way, and they are plentiful in a very large region surrounding the south pole of the Milky Way; but as the sky areas photographed are closer and closer to the Milky Way, the numbers of spiral nebulae recorded grow smaller and smaller, and before the Milky Way structure is reached the spirals cease to show at all. In the direction of the Milky Way background, which covers a pretty large area of the sky, not a single spiral nebula has ever been observed.

Shapley's studies of the distances of many globular star clusters in the Milky Way, which are prevailing close to its central plane and may therefore be assumed to be component parts of our stellar system, have led him to the conclusion that even if the most distant clusters are on the actual periphery of the system the radius of our stellar system must be of the order of 150,000 light years.[4] The presumably nearest spiral nebulae are nearly a million light years away, and we have no apparent means of telling how far away are the ones with angular diameters so small that they are difficult to distinguish from single stars. Perhaps it is too much to expect that the greatest of the spirals should be our nearest neighbors; at any rate it is not difficult to imagine that some of the more distant spirals have linear diameters equaling or exceeding the diameter of our stellar system. Recalling, from the theological history of the world, that man always started out with the idea that his abode was the center of the universe, and later became more humble, it would be surprising if our stellar system should prove to be unique either in kind or in size. It would be astonishing indeed if our thin and flat stellar system had tens of thousands of spiral attendants to the right of it, and tens of thousands of spiral attendants to the left of it but none in front of it, none in or near any extension of its principal plane.

The motions of the spirals seem also to free them from the charge that they are retainers of our stellar system. Slipher has found them to have uniquely high radial velocities; from 300 km per sec. approach up to 1,800 km per sec. recession, for 43 observed nebulae not in our stellar system; 24 of them showing detailed spiral structure and the remaining 19 the general forms of spiral nebulae. Although other conditions than the radial velocity of the light source as a whole are known to displace spectral lines from their normal positions, there seems now to be no inclination to doubt that the large displacements observed by Slipher are chiefly and perhaps wholly Doppler-Fizeau effects.

Following the methods employed for determining the motions of the solar system from radial velocity data for the surrounding stars, Lundmark has determined the motion of the solar system with reference to the 43 spirals as a system. He obtained a velocity of 401 km per sec. Naturally the solution, depending upon very limited data, is of limited weight, but accepting the solution at its face value it says that with reference to the 43 spiral nebulae, considered as a system at rest, the sun and its group of neighboring stars comprising our naked-eye system, and perhaps representing fairly well our entire stellar system, is travelling with a speed of about 400 km per sec.—a speed of the same order of magnitude as the radial velocities possessed by many of the 43 spiral objects themselves. Even as to its speed our stellar system appears to conform to the spiral type. Should it appear in the sequel that the extremely distant spirals have actual radial velocities lower than those observed, because a curvature of space, conforming to the Einstein theory of relativity, would have the effect of adding to their apparent velocities of recession, the percentage of change required in the dimensions I have quoted should be low.

Referring to dynamical conditions within the spirals: why have they developed into their present state, and how do they maintain their strange forms in the face of strong central gravitational attraction? The comprehensive answer is, they are in rapid rotation. Jeans and others, making profound studies of these objects, have come to this conclusion. In fact, as noted above, one has but to look at the photographs of the brighter and larger spirals, including those viewed obliquely as well as those seen edgewise and in full face, to obtain the conviction that this is so.

[4] It is an interesting fact that whereas Shapley viewed with disfavor the island-universe interpretation of spiral nebulae, and Curtis was unable to accept Shapley's dimensions of our stellar system, Miss Leavitt's formula for the period-luminosity relationships in Cepheid variable stars, after modification of its constants by Shapley, was used by Hubble to establish the island-universe dimensions of the spiral nebulae.

The measures by van Maanen have appeared to show rapid motion outward along the spiral branches for the matter composing the branches. These van Maanen components of motion apparently include such other components as arise from the relatively rapid revolution of the several measured points around the centers of the spirals. But as my purpose is not to discuss the mechanics and dynamics of spirals, except in a most general and limited way, I do not attempt to interpret the measures made by van Maanen, in the light of apparently conflicting results obtained by Curtis, Ritchey, Lundmark, Hubble and others. My question is, assuming the composition of the spirals to be chiefly stellar, with each nuclear mass a group of stars widely separated, in what orbits do the individual stars move? Is it not possible that the stars in any one great group are not totally free to depart from their group, and are not free to describe elongated elliptic orbits around the center of mass of the spiral, except as fortuitous perturbations may free a star now and then from the serious and perhaps commanding influence of its group? The general form of orbit described by a star at a great distance from the center may resemble a circle, in response to the rotation of the entire spiral body; but it would be surprising if a great number of stars composing one of the nuclei in a spiral arm should not develop their own system of motions, in response to the conditions of equilibrium. If the principal dimensions of a spiral are a few tens of thousands of light years, the thickness of some of its more or less isolated masses may be several thousand light years, and the stars composing such a mass may well have their local system of orbital motions, very much as Jupiter and his three outermost moons have their local system of motions, though subject to large perturbations from the differential attractions of the sun, while revolving around the sun.

But to come back to our own system: How has it happened that our system, so enormous in its Milky Way dimensions, is relatively so thin and so flat? It is at least as thin, relatively, as any spiral thus far observed in an edgewise position. Must it not have developed with the accompaniment of high rotational speed? Or if formed, and in the absence of rotation, could its stellar cloud forms have avoided dissolving or collapsing? Answers in favor of a rotation of the system, now and throughout the history of its development, seem to me natural, and reasonable, and I am tempted to say necessary. We all incline to the opinion that the developments of the individual stars have covered several thousands of millions of years. For the Milky Way structure to form, to endure through long ages, and to present no recognizable signs of collapsing, it must be in a state of equilibrium; and equilibrium in such matters, to the best of our knowledge, means a rotation of the system around an axis through the effective center of mass of the system. For a system so vast as to its distances, and with so low a distribution of materials throughout its extent, an extremely slow speed of rotation would be called for: Poincare has estimated that an angular speed of a few tenths of a second of arc per century would suffice to maintain equilibrium. The observed proper motions of the stars have been utilized by half a dozen astronomers in efforts to uncover the first indications of a rotational effect. Out of eleven such results, six indicated rotation of the stellar system toward the east and five rotation toward the west, all being at exceedingly slow rates. We may therefore say that the evidence presented by them is negligible. Charlier has found that the line of intersection of the invariable plane of the solar system with the central plane of the Milky Way is apparently shifting easterly amongst the stars by 0.35 second of arc per century. A literal interpretation of this result favors a rotation of the Milky Way system westerly at the slow rate quoted. The subject is an extremely difficult one and the discovery is for the future to make.

We do not know, I must confess, that our stellar system is now a spiral nebula, or that it is the developed product of a spiral of ages past, but it does seem to have most of the known attributes of a spiral. The motions of our naked-eye stars are in such directions and of such speeds in general that their velocity components in the plane of the Milky Way are larger than their components at right angles to that plane, as perhaps we should expect, but the latter components are relatively much larger than we should expect, or have succeeded in explaining, on the supposition that we are dealing with motions in orbits which have the effective center of the great stellar system in or near their foci. There are many other perplexing facts brought to light when we attempt to determine the elements of the solar motion with reference to groups of stars having different spectral classes, or very different absolute magnitudes, or velocities of very different orders of magnitude. It is quite possible that the wide variety of results for the motion of the solar system with reference to the different groups of stars mentioned, as obtained by Strömberg and others, and likewise the fact that the velocity components at right angles to the plane of the Milky Way seem unduly large, will find easier explanation if the observed stellar velocities are in some degree local effects. Our sun and our naked-eye stars and our neighboring stars in general to the number of many millions may compose a veritable star cloud, with resemblances to those observed in our great Milky Way structure, and possibly such as the more or less isolated masses of stars which apparently go to make up a typical spiral nebula. We do not actually know that the density of distribution of stars in our region of the stellar system is less than it is in some of the distant Milky Way cloud forms. If our sun and our neighboring stars are members of a rich local group of stars the mass of the group as a whole may be sufficient to account for an appreciable component of the motions which we have observed; but I must confess that this is carrying the speculative spirit very far indeed. Fortunately such speculations need do no harm, and they have been known to do good.

I have speculated concerning our stellar system as a spiral nebula, partly as a guard against the assigning of undue weight to the deduced motion of our solar system. The speed and direction of the sun's motion, as here determined, may or may not hold good for the stellar system as a whole. If our local group of stars to which the solution refers composes but a small part of one of the isolated masses in a typical spiral, a knowledge of our motion with reference to the observed group of 2,034 stars may not tell us much concerning our motion with reference to the spiral as a whole. And if our stellar system is not a spiral, but on the contrary a non-rotating, fairly symmetrical system, we should likewise be modest in drawing conclusions as to where our tour amongst the stars is going to carry us, and when we may expect to return. Shapley may be approximately correct in his estimate of 300,000 light years for the diameter of our system, and there may be merit in his surmise that our present place of abode and travel is in a locality situated about 60,000 light years from the center of the system, which center, he suggests, is in the rich Milky Way region of Sagittarius. Now the 2,034 naked-eye stars upon which our solution for the solar motion depends are nearly all within a sphere of radius 500 light years having our sun at its center, and certainly there were no stars used in the solution which are as much as 1,000 light years away. If we represent the stellar system in its greatest dimension by a circle, assuming that its radius is 150,000 light years, and if at some point about two fifths of the way from the center to the circumference we draw with radius 1,000 light years, we shall find that this latter circle is little more than a dot upon the picture. If we represent the stellar system by a circle 300 inches, or 25 feet, in diameter, a circle within it only 2 inches in diameter would in effect contain the 2,034 naked-eye stars used in our solution, and the overwhelming majority of these stars would lie within the central 1 inch[5] of the 2-inch circle.

We know to a degree of accuracy quite satisfactory our sun's motion with respect to a system of 2,034 stars, nearly all giant stars, in our own neighborhood. The elements of the sun's motion as here determined may be, and probably will prove to be, also quite satisfactory with reference to a vastly greater group of stars. That remains to be determined. We can report progress and feel assured that future astronomers, equipped with more powerful instruments and probably with more effective methods, will carry on with stars continually fainter and more distant. It is by the taking of such successive steps that great problems of this kind eventually reach their solution.

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[5] Assuming, with Eddington, a density of 10 stars, each equal to our sun in mass, per sphere of diameter 33 light years, a sphere 1,000 light years in diameter would correspondingly contain 270,000 unit stars. A circular disk of space 300,000 light years in diameter and 10,000 light years thick, would similarly contain more than 300,000,000,000 unit stars! We do not seem to be in possession of any facts of observation suggesting that our most powerful telescopes, employed in the manner which enabled them to photograph the most distant star clusters used by Shapley in estimating the diameter of our stellar system, would record more than 3,000,000,000 stars in the system. Are there really good reasons for thinking that the star clouds, or the stars distributed with the same order of frequency as observed in the sun's neighborhood, extend out even to half the distance of the farthest globular clusters thus far observed?

WHAT IS THE SIGNIFICANCE OF TRANSPIRATION?

A LARGE number of research experiments have been carried on dealing with various phases of the subject of plant transpiration, and botanical literature on the subject is voluminous. Most of these experiments have been directed towards a determination of the amounts of water lost by plants and the factors, both internal and environmental, which affect the rate of this loss. It is rather surprising how relatively few have been performed to determine the possible function of transpiration or its influence on the various life processes of the plant. From an inspection of the literature and text-books in botany and allied subjects and from conversation with many teachers and advanced students of botany it is evident that many have given little thought to its significance or they have assumed certain functions without critical examination or thought. I have found that opinions as to the possible value of transpiration to plants vary all the way from those which assume that transpiration results in benefits on a par with those resulting from photosynthesis and respiration to those which ascribe to transpiration practically nothing but harm. Opinions obtained from a large number of advanced students in botany, students who have had their early botanical