COUNTING THE STARS AND SOME CONCLUSIONS[1]

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I

INTRODUCTION

Counting stars is not unlike counting people or sheep or pebbles on the seashore. The astronomer's difficulties are not in the counting, but rather in knowing when the counting must start and stop. With patience these difficulties may be overcome, but the conclusions to be drawn from the numbers of stars counted are a more delicate matter; some are indisputable, others less certain, still others highly speculative.

First of all, we are concerned with a census of the sky; and just as the census taker enumerates people in different ways—according to residence, race, occupation, for example—so the astronomer may count his stars differently; but, whatever the manner of counting, it has always the purpose of learning how the stars are scattered throughout space and how the great system which they form is constructed.

To keep clear of complexities and survey only the broad structural features of the system, he counts, at the start, in only two ways; to learn fundamental things, he considers characteristics which themselves are fundamentally different. At first, therefore, he observes only the direction of a star in the sky and its brightness as seen with the telescope. All other features in which stars differ, such as size, color, mass, motion, are left for subsequent study. It is as though the census taker were to count people according to their ages and the places in which they live, disregarding all other possible groupings, such as height, race, and occupation.

The sky has no naturally marked boundaries within which the stars may be counted and intercompared; but as far as di-

[1]An address delivered before the Pacific Division of the American Association for the Advancement of Science, at the Pomona meeting, June 14, 1928. A detailed account of the investigations here described, which were undertaken in part with the cooperation and assistance of Professor P. J. van Rhijn of the Kapteyn Astronomical Laboratory at Groningen, and of Miss Mary Joyner and Miss Myrtle Richmond of the Computing Division of the Mount Wilson Observatory, may be found in *Mt. Wilson Contributions,* Nos. 301, 346 and 347.

rection is concerned, it is easy to find how many stars there are, say per square degree of the sky, in different parts of the heavens. The counting of stars according to brightness, however, is another matter.

The practical difficulty, as already stated, lies in recognizing the limits of brightness within which the stars are to be counted. To overcome this, a scale of brightness is required, with which individual stars may be matched to determine their light; for example, a sequence of stars, progressing by known steps, from the most brilliant in the sky to the faintest seen in our telescopes. Whatever the procedure adopted, it is essential that the unit of measurement be known in terms of the intensity of star light, because the intensity of the light received by the eye depends partly on the distances of the stars, and distances we wish very much to know. Initially, no such scale existed, and one had to be constructed.

The earliest records of the brightness of stars, which go back 1800 years to the Alexandrian astronomer Ptolemy, represent rough eye estimates, expressed in a unit called a magnitude. To the brightest stars Ptolemy assigned the first magnitude; to those just visible to the unaided eye, the sixth magnitude; and to stars of intermediate brightness, magnitudes 2, 3, 4, and 5. When the invention of the telescope brought fainter stars into view, Ptolemy's scale was extended, still by simple eye estimates. At length, about a century ago, instruments for measuring the intensity of a star's light were devised, and then for the first time the physical equivalent of the unit of magnitude became clear. At this point it must be noted that magnitude is a measure of visual sensation—a very different thing from the intensity of the light which produces the sensation. On measurement it turned out that the intensity of Ptolemy's first-magnitude stars was about 100 times that of stars of the sixth magnitude, and for convenience the relation thus approximately satisfied by Ptolemy's magnitudes was adopted as a precise definition of the unit of magnitude. As now used, therefore, the unit is such that a difference of five magnitudes corresponds exactly to a ratio of 100 to 1 in the intensities, whence a difference in brightness of one magnitude corresponds to an intensity ratio of 2.512. A further detail is the beginning, or zero point of the scale of magnitudes, which must be the same everywhere in the sky, if measures of brightness in different parts of the heavens are to be comparable. Again for convenience, the early observations were taken into account by adopting a zero point such that the precisely defined magnitudes agree as closely as possible with the old values obtained by eye estimates.

Note now how this definition applies to faint stars. It means that a sixth-magnitude star is 100 times as intense as one of the eleventh magnitude, and hence, that the first-magnitude star, as compared with the eleventh, is 100 x 100 or 10,000 times as intense; if we extend the scale downward another ten magnitudes, which brings us to the practicable working limit of large modern telescopes, the intensity ratio takes on another factor of 10,000, and we have for the interval of 20 magnitudes a ratio of 100,000,000 to 1. The light of a first-magnitude star is thus 100 million times as intense as that of a star of the twenty-first magnitude. The numbers involved are to each other about as the distance separating California from New York is to a length of two inches.

The construction of the magnitude scale therefore requires the ultimate comparison of sources of light differing by an enormous ratio; in part, the undertaking is analogous to finding how many times a length of two inches is contained in a distance of about 3000 miles, without having even a foot rule or an engineer's chain to start the measurement. Actually the photometric problem is far the more troublesome, for the unavoidable error in measuring the intensity of a light is much greater, proportionally, than that involved in measuring a length. Indeed it is so much the more difficult that, although the concept and definition of the magnitude scale have been clear enough for many years, it is only recently that some approach to practical realization has been made in the attempt to fix standard limits of brightness within which the stars may be counted.

Before turning to the results of counting, the impossibility of counting all the stars must be noted. The whole sky over, about 6000 stars may be seen without a telescope; but among the fainter stars the numbers run into millions and hundreds of millions. For these even the simplest enumeration would be impossible, whereas much more than simple enumeration is required. In order to specify the group with which any star is to be counted, the scale of magnitudes must be applied to the star to measure its brightness, much as a yardstick might be applied to a man to determine his height. Only when this has been done can it be said that the star belongs with those whose magnitudes are between, say, 10.0 and 10.5. But measurements of brightness take time. At Potsdam Müller and Kempf spent 19 years in deriving the magnitudes of 14,000 stars. At Mount Wilson we have measured some 70,000 stars; but even with modern photographic methods, the labor involved represents the continuous occupation of several people for a number of years.

To avoid a task that could never be ended, we follow the plan first used for the star gauges of the Herschels and count only stars in representative regions of the sky. We deal with samples of stars, just as the census-taker, if pressed for time, might count the inhabitants of only every other block, or perhaps of every fifth block, of a great city like New York, and still arrive at useful conclusions about the population of the city as a whole. In any such restriction of the counting the samples must really represent the whole, a condition satisfied in practice by counting regions uniformly distributed over the sky, and, by using areas that are not too small. In general, much smaller areas may be used in counting faint stars than for stars of moderate brightness. Thus, for the very faint stars counted at Mount Wilson the sample regions are so small that their total area is less than a thousandth part of the sky. Notwithstanding the general sufficiency of small sample regions, it must not be supposed that the resulting counts are free from statistical irregularities. They are not; but those present are chiefly of a local character, and may be smoothed out by averaging the counts in several neighboring regions.

II

THE GENERAL FORM OF THE STELLAR SYSTEM

From these general considerations, we turn to some of the results of counting, noting at once an important conclusion which follows, not from the actual numbers of stars counted, but from the size of the sample regions which is sufficient for the counting. If counts covering a total area of only a thousandth of the whole sky give useful information, then the stellar system must possess much structural unity and regularity. Otherwise, small sample regions chosen at random could not reveal as they do the underlying structural features of the system.

The first peculiarity to be noted is the extraordinary rapidity with which the numbers of stars increase as we pass to fainter and fainter limits of brightness. Four photographs of the same region (Plate 24), exposed just long enough to show stars brighter than the twelfth, fifteenth, eighteenth, and twentieth magnitudes, respectively, are perhaps as impressive as the numbers themselves.

Another peculiarity is that the stars are most numerous in the Milky Way and decrease in numbers as we count in regions more and more distant, in either direction, from this cloud-like band which encircles the sky. This also is well shown by photographs (Plate 25) which record stars to the same limit of brightness in the two regions, one in the Milky Way itself, the other far distant therefrom. The phenomenon is so striking, and the changes in the numbers on the two sides of the Milky Way are so similar, that it suggests, as it did to Sir William Herschel, a symmetrical arrangement of the stars about the plane passing through the Milky Way clouds. The regularity of the system already inferred from the sufficiency of small sample regions as an indication of stellar distribution thus becomes the regularity of a symmetrical arrangement in

TABLE I. MEAN DISTRIBUTION OF STARS

Number of stars per square degree brighter than photographic magnitude *m* at different distances from the Milky Way.

m	Galactic Latitude				Galactic Concentration
	0°	30°	60°	90°	
4.0	0.0156	0.00741	0.00514	0.00452	3.5
5.0	0.0449	0.0214	0.0148	0.0130	3.4
6.0	0.128	0.0614	0.0421	0.0372	3.4
7.0	0.361	0.173	0.118	0.103	3.6
8.0	1.01	0.482	0.325	0.278	3.6
9.0	2.81	1.31	0.871	0.723	3.9
10.0	7.71	3.49	2.23	1.81	4.3
11.0	20.8	9.06	5.47	4.33	4.8
12.0	55.6	22.7	12.8	9.89	5.6
13.0	146	54.4	28.6	21.4	6.8
14.0	371	125	61.0	44.3	8.4
15.0	910	272	123	87.1	10.4
16.0	2140	561	236	163	13.2
17.0	4780	1090	428	288	16.6
18.0	10200	1990	733	482	21
19.0	20800	3440	1190	769	27
20.0	40100	5620	1820	1160	34
21.0	73600	8690	2650	1670	44

which the Milky Way stands out as the framework of the system.

To study these phenomena more closely it is customary to average for each limit of brightness all the counts in the Milky Way and tabulate the results; then, similarly, to average and tabulate the counts along circles parallel to the Milky Way, on either side and separated from it by intervals[2] of 5° or 10°. The result is a "mean distribution table" (Table I). The numbers in the first column are the magnitude limits to which the stars are counted; those in the second, the average numbers of stars per square degree in the Milky Way brighter than the successive limits, while the following columns give sim-

[2]Angular distances measured on the sky perpendicular to the great circle through the Milky Way clouds (the galactic circle) are called galactic latitudes. Angular distances measured along the galactic circle from a certain starting-point are galactic longitudes. These coordinates are analogous to terrestrial latitudes and longitudes used to define the position of points on the Earth.

ilar averages for circles parallel to the Milky Way in latitudes 30°, 60°, and 90°.[3]

Table I recognizes the symmetrical arrangement of stars on the two sides of the Milky Way in that it applies to either side, and, in fact, is the average of the counts in the two halves of the sky. It shows the rapid increase in the numbers of stars with increasing magnitude, the general crowding of the stars toward the Milky Way, and now, a third peculiarity, namely, that the crowding is much greater for faint stars than for bright ones and increases regularly with the limiting brightness. This is shown by the numbers in the last column, which are the ratios of the average counts for latitudes 0° and 90°. Thus the first line of the table shows 3.5 times as many stars in the Milky Way as at latitude 90°; but for the much fainter limit in the last line, the ratio is more than 40 to 1.

The general crowding of stars toward the Milky Way has been known since the time of the Herschels, but the relatively great concentration shown by the faint stars, although long suspected, was first definitely established only a dozen years ago by counts made at Mount Wilson. That so conspicuous a feature of the distribution could remain long in doubt illustrates the uncertainty attached to the magnitude scale then available. This, it was feared, might be affected by an error depending on distance from the Milky Way, which would modify the relative numbers of stars counted in the Milky Way and elsewhere, and hence render any estimate of the concentration uncertain.

Let us now try to picture what these peculiarities in the counts of stars mean. Table I shows that each extension of the counts over an additional magnitude increases the total number of stars visible in any direction from two to three times. The exact increase is important and is therefore shown in detail for different parts of the sky in Table II. The quan-

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[3]For convenience the logarithms of the numbers, rather than numbers themselves, are often tabulated. One square degree is equivalent to about five times the area of the sky covered by the Sun or the full Moon. For brevity Table I gives results for only four values of the galactic latitude. A more extended table may be found in *Mt. Wilson Contr.* No. 301 (Table XVII) or in *Contr.* No. 346 (Table XIV).

TABLE II. STAR RATIOS

Factors by which total numbers of stars counted to limiting magnitude *m* are multiplied when the counts are extended one magnitude.

m	Galactic Latitude			
	0°	30°	60°	90°
4.0	2.88	2.89	2.87	2.88
5.0	2.85	2.86	2.85	2.85
6.0	2.82	2.82	2.81	2.77
7.0	2.80	2.78	2.75	2.70
8.0	2.77	2.72	2.68	2.60
9.0	2.75	2.67	2.56	2.50
10.0	2.70	2.59	2.45	2.39
11.0	2.67	2.50	2.34	2.29
12.0	2.62	2.40	2.23	2.17
13.0	2.55	2.29	2.13	2.07
14.0	2.46	2.18	2.02	1.97
15.0	2.35	2.06	1.91	1.87
16.0	2.23	1.94	1.81	1.77
17.0	2.13	1.83	1.71	1.68
18.0	2.04	1.73	1.62	1.60
19.0	1.93	1.64	1.54	1.51
20.0	1.84	1.55	1.45	1.43
21.0				

tities in this table are nothing but the ratios of the numbers standing above each other in Table I. Thus from the second column of Table I, 0.0449/0.0156=2.88; 0.128/0.0449=2.85, etc. The several quotients 2.88, 2.85, etc., appear in succession in the second column of Table II, while similar ratios for other parts of the sky are in the remaining columns. These ratios vary smoothly over the sky, and range from about 3 for bright stars near the Milky Way to 1.4 for faint stars at 90° distance from the galactic circle.

The rapid increase in the numbers of stars with increasing magnitude recalls the old problem of the cost of shoeing the horse, with a penny for the first nail, two for the second, four for the third, and so on. Doubling the cost for each successive nail runs the total into an incredible sum; but with the stars, as shown by Table II, the numbers, on the whole, are rather more than doubled, each time an additional magnitude is counted. No wonder the total is great.

To illustrate further the meaning of Table II, imagine a small stellar system in which the individual stars are candles, all alike and equally spaced, we ourselves being at the center of the system. With the eye alone we should be unable to see candles beyond a certain distance, because the light reaching the eye would be too faint to produce a visual sensation. A telescope, however, would bring some of them into view; and for the purpose let us choose an instrument just powerful enough to reveal candles exactly one magnitude fainter than the faintest seen without the telescope. The relation between intensity and brightness which defines the unit of magnitude tells us that such a telescope would penetrate about 1.6 times farther into space than the unaided eye. Now let us count all the candles visible from our central station, both with and without the telescope. The numbers will be those contained in the two spheres whose radii are to each other as 1 to 1.6, and, since the candles are everywhere equally spaced, their ratio will be equal to that of the volumes of the two spheres, or very nearly 4 to 1. Under the conditions supposed, we must therefore expect that extending the counts of candles by one magnitude would multiply the number visible by 4.

Now, since the star ratios of Table II nowhere equal this theoretical value and, for the most part, are far below it, there must be some essential difference between the real stellar system and the miniature system of candles. Candles, to be sure, are not stars; but for the moment that is not an essential difference. Stars, on the other hand, may not all be of the same candle power, as the candles are. In fact, they are not; but it can be shown that this also is not the explanation. Again, some of the distant stars may be hidden by haze and dust scattered throughout space. This certainly would reduce the ratios of the numbers counted and actually may have some effect on their values; but the presence of absorbing material seems at most to be a local phenomenon, and cannot be the complete explanation. The only other significant factor is a possible lack of uniformity in the spacing of the stars, and this indeed is where the difference lies. Uniform spacing means a factor of 4; but if the stars should thin out with increasing distance from our station in space, the numbers of faint stars would be less than we should otherwise find, and the ratios from magnitude to magnitude would necessarily be less than 4. The converse is equally true, and since in the stellar system the increase is less than four fold when the counts are extended by a magnitude, the stars must thin out with increasing distance from the point of observation; further, the more the factor drops below 4, the faster does the thinning out take place.

Consider now more in detail the ratios in Table II, and first, those in the second column, corresponding to directions toward the Milky Way. From what has been said it follows that the brightest of these stars thin out with increasing distance, while the faint stars, which, as a whole, are at much greater distances, thin out even more rapidly. Consider now the last column, referring to the direction perpendicular to the plane of the Milky Way. Here the ratios are generally smaller than those standing opposite them in the second column, which leads to the important conclusion that the stars in this direction not only thin out, but thin out very much faster than they do toward the Milky Way.

The statement that the stars thin out with increasing distance often rouses the feeling of an implied contradiction wi h the rapidly increasing numbers of Table I. Discrimination as to what is meant sets the matter straight, however. The conclusion that the stars thin out means only that the number of stars per unit volume decreases with increasing distance; the total number of stars counted depends on the density, but also on how many units of volume are included. Thus in the case of the candles, the extension of the counts by one magnitude gives a total which includes all the candles in a volume four times that which the eye alone can survey. The additional volume made accessible by the extension is therefore three times that already known to the unaided eye; the density of candles in the added volume might therefore drop to one-third that near the center of the collection and the total number visible would still be doubled by extending the counts.

In brief, therefore, Table II indicates that the stars of our system are not equally scattered in space, but thin out in all directions with increasing distance from the point at which we make our observations, least rapidly in directions toward the Milky Way and fastest in a direction perpendicular to its plane.

The table also suggests another inference with respect to the stellar system in that the ratios steadily decrease as the magnitude limit is extended downward. If this decrease continues for stars beyond the reach of existing telescopes, the ratios themselves must eventually become zero. Hence for some low limit of brightness no more stars will be added when we attempt to extend the counts to a still lower limit; the total number of stars in the system is therefore limited.

The evidence afforded by star counts alone does not fully establish this inference as a fact, for the counts do not indicate with certainty the relations among fainter and still undiscovered stars; the extrapolation is too great. The conclusion itself, however, is well founded, but the proof comes from evidence other than star counts. This being the case, we may accept the conclusion and thus arrive at the certain result that the factors of Table II do eventually become zero.

If the limiting magnitude for which this occurs were accurately known, we should be able to estimate with fair approximation the total number of stars in the system. As it is, we know that such a limit exists, but the only guide to its value is the rate of decrease in the ratios of Table II. This is slow, and as the ratios for the faintest stars known are still rather large, the magnitudes for which they become zero, in different directions in the sky, are very uncertain.

Any attempt to learn the total number of stars in the system by extrapolating Table II can therefore lead only to the roughest sort of an estimate. About a thousand million stars are within reach of the 100-inch reflector. If the invisible stars behave as those accessible to observation would lead us to expect, the total number in the system must be some 30 times greater, or of the order of 30,000 million. The uncertainty of this result is illustrated by the fact that the estimated total in the direction of the Milky Way is about 70 times the number of stars actually counted.

The stellar system thus appears to be a limited collection including many thousand million stars; as a first approximation it may be thought of as having the form of a much-flattened swarm of bees, with the densest part of the swarm at the center. The rate at which the stars thin out in different directions shows that the greatest extent of the system is in the direction of the Milky Way and equal to some six or seven times its thickness. The actual linear dimensions are very uncertain. Indeed they lie outside the conclusions that may be derived from star counts alone; but for completeness it may be added that two or three lines of evidence suggest values of two to three hundred thousand light years for the diameter in the plane of the Milky Way, although even larger values are by no means excluded. The gradual thinning out of the stars probably means that no sharply marked boundary exists, just as none exists for the upper limit of the Earth's atmosphere. Star counts, supplemented by other information, do tell us, however, something about the distance at which the number of stars per unit of volume drops to a given value, say to 1 per cent of what it is in our own neighborhood. Thus we should probably have to travel out in the direction of the Milky Way at least 30,000 light years, on the average, before we reached the point at which the stars had thinned out to this extent. In the direction perpendicular to the Milky Way the distance would be much less—perhaps 4000 or 5000 light years.

III

ECCENTRIC LOCATION OF THE SUN—DIRECTION OF THE CENTER

The symmetry found in the distribution of stars on opposite sides of the Milky Way shows that the Sun and its planets must be close to the plane passing through the Milky Way and the center of the system; but it does not follow that they are close to the central point of the system. The mean distribution table (Table I) was prepared chiefly as a means of studying how the stars crowd together toward the Milky Way. In order to smooth out local irregularities in distribution as much as possible, counts all around the sky in the Milky Way, and in circles parallel to the Milky Way, were combined into single averages, one for each latitude; further, the results for the two halves of the sky were also averaged. This procedure was well suited to the purpose then in mind, and led to the conclusions described. But now we must see if the averaging process has concealed anything of importance. This inquiry has point because it is known that the stars are not equally numerous in all parts of the Milky Way.

The irregularity meant is not the rapid fluctuation in numbers shown by the cloud-like grouping of stars, but a more fundamental difference revealed by the exceptional size and richness of the star clouds in the general direction of *Sagittarius* as compared with those in the opposite part of the sky. Because of this difference, it has often been suggested that the solar system may indeed be at some distance from the central point of the system. If so, slow progressive changes should appear in the counts along the Milky Way, and, in fact, along any parallel circle, up to a high galactic latitude. We therefore turn again to the original counts in order to see whether they show any such change when these circles are followed around the sky.

In studying the crowding of stars toward the Milky Way, we concentrated attention on this one feature of the distribution by dealing with the average of the counts in all longitudes. This eliminated any influence arising from the possible progressive change with longitude in which we are now interested. And now we avoid any disturbance which might arise from the crowding toward the Milky Way by comparing only counts of stars in the same latitude, and, of course, to the same limit of brightness. A simple procedure is to compare the actual number of stars counted in each region with the average number for the whole circuit of the sky in a given latitude, and then examine the differences in order to see whether they show any progressive variation. Finally, to test the reliability

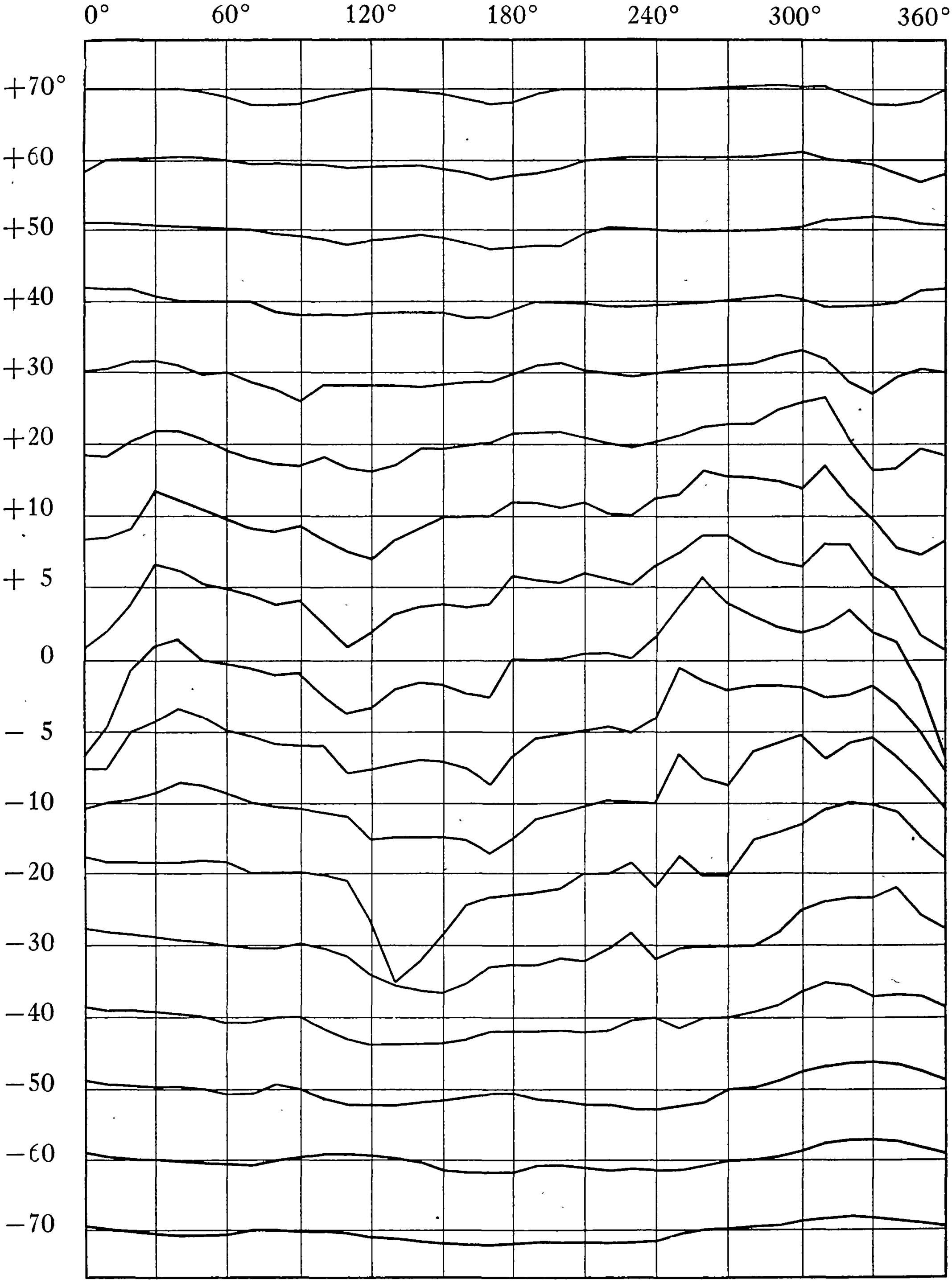

Figure 1

Deviations of the observed numbers of stars in different parts of the sky from the average numbers shown in Table I. The stars here considered are brighter than magnitude 16.0; the general similarity in the curves for all galactic latitudes (figures on the left), with low points around longitudes 120° to 160° (figures at top), and high points around 300° to 350°, indicates that the center of the system of these stars is in longitude −19°.

of the results we may make independent comparisons for each of several different latitudes and for a number of limits of brightness.

Figure 1 illustrates the results for the stars brighter than the sixteenth magnitude, in general for every 10°, up to latitude 70° on either side of the Milky Way. Similar diagrams, showing very similar results, were also prepared for limiting magnitudes 9.0, 11.0, 13.5, and 18.0. Positions along the Milky Way or one of the parallel circles, which may be identified by the galactic latitudes on the left of the diagram, are indicated by longitudes at the top, measured from a standard meridian just as in the case of longitudes on the Earth. Portions of curves which lie above the horizontal axes mean that the observed numbers of stars in the corresponding regions of the sky are greater than the average number for the whole circuit; points below the axes represent observed numbers which are less than the average.

In spite of numerous irregularities, most of the curves show a general similarity in that in longitudes 240° through 360°, and on to 60°, they lie above their respective axes, while in longitudes 60° to 240° they drop below. This general statement disregards a conspicuous drop near longitude 360° in the curves for low latitudes. This drop must be disregarded, for it represents the great rift between the two branches of the Milky Way, where the number of stars counted is not representative of those probably present. There, we have reason to believe, great numbers of stars are blotted out by obscuring clouds of dust and nebulous material.

With proper allowance for this anomaly, a systematic departure from the average numbers of stars is clearly revealed in the counts, which can be traced to a great distance from the Milky Way. Figure 1 shows that in all latitudes we have counted the largest number of stars in the same general longitude, the smallest in the opposite longitude. The longitudes of the richest regions found by a numerical discussion of the data run as in Table III.

Table III

Latitude	0°	5°	10°	20°	30°	40°	50°	60°	70°	
Longitude	303	301	298	301	307	334	336	299	277	North of M.W.
		317	328	328	332	331	345	354	340	South of M.W.

These numbers are by no means equal; indeed they range over a good many degrees, especially in high latitudes. But it must be remembered that the stars are not distributed with exact uniformity and that local and purely random irregularities tend to obscure any structural feature, however important, when we attempt to trace that feature in limited portions of the data. In the present instance the individual longitudes cluster around a mean value of 319°, with an average departure of 15°. The deviations from uniformity in the distribution fully account for the scatter in the individual values, whence we conclude that we have brought to light something fundamental in the arrangement of stars in space. The magnitude of the phenomenon becomes clear only when we translate the deviations in longitude into numbers; then we find that nearly five times as many stars are visible in the direction of the center as in the opposite direction.

The accordance of the results in Table III, the progressive change in the curves of Figure 1 with longitude, and the fact that they flatten out with increasing distance from the Milky Way all agree with what would be found were we really at some distance from the center of the flattened system of stars. Indeed the accordance is so close that we do not hesitate to accept this as a valid explanation of the phenomena. The direction of the center itself must of course agree with that in which the stars are most numerous, and is therefore to be looked for in the neighborhood of longitude 319°, in *Sagittarius,* where, as already noted, the richest star clouds are to be found.

It is natural to ask next as to how far we are from the center; but this turns out to be a very difficult question, not yet fully settled. The attempt to answer it has brought to light new features of stellar distribution, however, to which we now turn our attention.

IV

DEPENDENCE OF CENTER AND SECONDARY GALAXY ON LIMITING MAGNITUDE OF COUNTS

Since the curves for the other magnitude limits have the general appearance of those for the sixteenth magnitude shown in Figure 1, they support the conclusion that the Sun and planets are not at the center of the stellar system. The results for the direction of the center, however, are remarkable in that the mean longitude as found from the different series of curves is not constant, but shows a large progressive change with limiting magnitude. Thus for stars brighter than the ninth magnitude, the center seems to be in longitude 270° ; as we extend the counts to fainter limits, the direction changes slowly but regularly along the Milky Way some 50° toward the east, until for the eighteenth magnitude we find it about where, a moment ago, we thought it actually to be located.

It is probable that the true center is indeed very nearly in this direction, and that its apparent dependence on magnitude arises from some peculiarity in the distribution of the brighter stars. When we consider counts which include only bright stars, this peculiarity asserts itself and spoils our calculation; when we add the faint stars, however, which are vastly more numerous than the bright ones, the peculiarity, whatever it may be, has little influence on the general distribution, and we find very nearly the true direction.

This conclusion is strengthened by considering another feature of the curves of Figure 1—one not to be traced with the eye alone. It appears clearly and consistently, however, when we deal with the numbers themselves. It consists in a small difference between curves for the same latitude on opposite sides of the Milky Way, of the kind to be expected were the stars symmetrically distributed, not with respect to the Milky Way, but about a plane slightly inclined thereto. Thus far we have thought of the stars as all tending to crowd together toward the Milky Way; but now apparently we must admit that some of them cluster about another circle, a little tilted with respect to the Milky Way. Since we sometimes speak of the Milky Way itself as the galaxy, we call this new circle the secondary galaxy.

The small differences existing between curves for equal and opposite latitudes may be used to compute the amount and the direction of the tilt of the secondary galaxy; and since several pairs of curves are available for each limiting magnitude, a number of independent solutions can be made, the accordance of which will test the reality of the results. Since the existence of a secondary galaxy modifies slightly the longitudes already found for the center of the system, these must be redetermined when the position of the secondary galaxy is calculated. The complete results for limiting magnitude 16 are shown in Table IV.

TABLE IV

Latitude	0°	5°	10°	20°	30°	40°	50°	60°	70°	Av. Dev.
Long. of Center	303	310	317	318	324	332	341	334	322	± 9°
Tilt	..	3.8	5.6	3.9	4.9	4.6	1.6	3.1	5.6	± 1
Long. of Tilt	..	362	357	358	352	329	368	392	367	±12

Here again, the agreement in values derived from different latitudes is all that can be expected. The mean for the tilt is 4°, in longitude 357°, with a scatter in the individual values so small as to leave no doubt as to the general result.

When we extend the calculation to other limiting magnitudes, however, we find that the secondary galaxy is no more a fixed thing than is the direction of the center of the system, and, like the direction of the center, depends on the limit of brightness to which the stars have been counted. From counts to the eighteenth magnitude we find a secondary galaxy which deviates but little from the Milky Way; and had we counts to the twenty-first or twenty-second magnitude, we should probably find practical coincidence. Counts to other limits show, however, a very appreciable departure and a progressive change in the position of the secondary galaxy, which attains its greatest inclination to the Milky Way when only bright stars are included in the calculation. The diagram in Figure 2

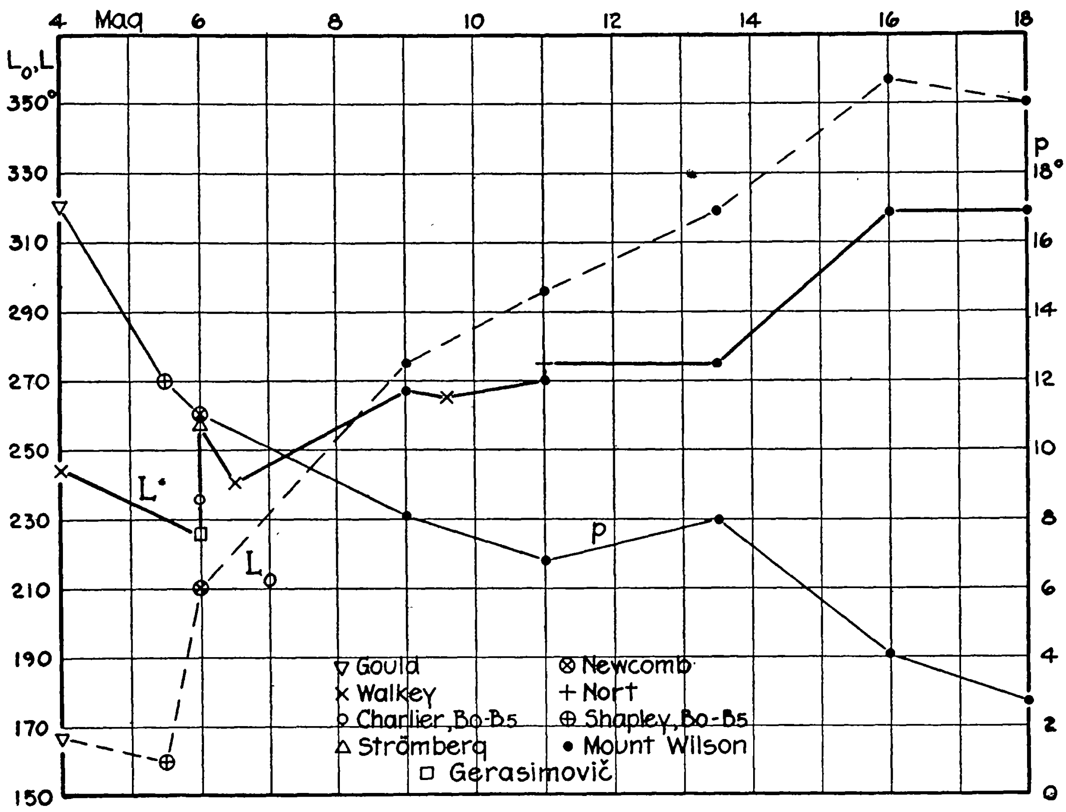

Figure 2

L is the longitude of the center of the stellar system as derived from stars brighter than various limits of magnitude; p and L_0 are the tilt with respect to the Milky Way, and the direction of the tilt, of the circles (secondary galaxy) about which the stars are symmetrically situated and toward which they tend to crowd.

illustrates the various results found from the Mount Wilson counts, and some by other observers from other data, plotted in such a way as to show the changes in the direction of the center (L) and in the position of the secondary galaxy (p, tilt of plane; L_0, direction of tilt).

These calculations afford opportunity for a closer comparison of the numbers of stars on opposite sides of the Milky Way. The results, expressed as a ratio of the numbers on the north side to the numbers on the south, run as follows:

Limiting Magnitude.......	9.0	11.0	13.5	16.0	18.0
Ratio, North to South......	0.67	0.75	0.77	0.98	1.01

Here again we find a change with limiting brightness. Counting only to the ninth magnitude, we find fifty per cent more stars in the southern half of the sky than in the northern. The excess decreases as fainter stars are added and disappears near the sixteenth magnitude. From there on the numbers in the two halves of the sky are sensibly equal. Moreover, the ratio for individual zones in equal latitudes, north and south, shows a similar sequence of values; hence, although the distribution of bright stars in latitude is notably asymmetrical, that of faint stars is very symmetrical.

V

THE LOCAL SYSTEM

To find a probable explanation of these changes with magnitude it is only necessary to follow the curves of Figure 2 back to about the sixth magnitude, for there we come to figures with which we are familiar in another connection. Immediately surrounding us in space is a large collection of very hot, massive stars, mostly brighter than the sixth magnitude, with the lines of helium very conspicuous in their spectra. These bright helium stars lie close to the Milky Way and constitute a local cluster, very much flattened—so much so, in fact, that the cluster is little more than a thin sheet of stars, extending out a thousand light years or so in the general direction of the Milky Way. The Sun and planets lie a little outside the thin layer of stars, and at a distance of about 300 light years from the center of the collection. The direction of the center is in longitude 236°; the tilt of the plane about which the helium stars cluster is 12°, in longitude 160°. These figures are nearly those shown by Figure 2 for the center and for the secondary galaxy derived from counts of all kinds of stars to the sixth magnitude. The agreement is too close to be simply coincidence, and we conclude that most, if not all, of the stars brighter than the sixth magnitude bear some close relation to the local cluster of helium stars. That the bright helium stars do form a localized cluster is easily recognized from their physical characteristics and their distribution, which cause them to stand out from their neighbors as a unit. Since the stars brighter than the sixth magnitude, as a whole, are symmetrically distributed about the same plane as the helium stars, the inference is that most of them also belong to that cluster, and that together they constitute a local system of which the helium stars are only the nucleus.

Apparently, therefore, we must amplify our picture of the stellar system by supposing that a secondary aggregation of stars—the local system—exists within the larger system. The local system lies near the plane of symmetry of the larger system, but at a great distance from the central point. Like the larger system, it is flattened, with its plane of symmetry tilted 12° to that of the larger system. We ourselves are within the local system, 300 light years from its center, situated in longitude 236°; the far more distant center of the larger system seems to be in longitude 325°, a little to the east of that indicated by the stars brighter than the eighteenth magnitude.

When we look out on the sky we see the intermingled stars of both systems. If we count the stars to the sixth magnitude only, we deal chiefly with those of the local system, and hence find them crowding toward the secondary galaxy marked by the thin stratum of bright helium stars; the center appears to be in longitude 236°, because that is the direction of the center of the local system. When we extend the counts to a fainter limit, we add many stars belonging to the larger system, and thus introduce the characteristics of that system. The resulting distribution is not that of either system alone, but something in between; the secondary galaxy is less inclined to the Milky Way, while the direction of the center has shifted a little eastward along the Milky Way toward that of the larger system. But when we count to a very faint limit, we include such enormous numbers of stars belonging to the larger system that the local system has no appreciable influence on the observed distribution; the stars crowd toward the great fundamental plane of the Milky Way, and the center appears in its true direction toward *Sagittarius,* in longitude 325°.

Finally, if we suppose the local system to be a little to the south of the plane through the Milky Way clouds, and the Sun almost exactly in this plane, we account for the relative numbers of stars on opposite sides of the Milky Way—an excess of bright stars to the south, and an equal division of faint stars between the two halves of the sky.

Our star counts even tell us something about the size of the local system, for both Figure 2 and the relative numbers of stars north and south of the Milky Way show that the influence of this system can be traced down to the sixteenth magnitude at least. From this circumstance alone it seems likely that we should still find stars belonging to the local system at a distance of 10,000 light years from the Sun. Other features of Figure 2, supplemented by other information, indicate that the members of the local system are to be counted by many millions, and that they comprise something like three-fourths of all the stars in our immediate neighborhood in space; the larger system would thus contribute only a fourth of the total stellar population near the Sun.

The dominating influence of the local system may be shown very simply by examining star counts in another way. In studying the numbers of stars added by extending the counts downward, magnitude after magnitude, the results in different longitudes, as already explained, were averaged. To gain a general idea of the way in which stars are scattered throughout space, we ignored the fact that we might not be at the center of the system, and were led by the ratios in Table II to conclusions which likened the stellar system to a much-flattened swarm of bees, thinning out in numbers from the center toward the edge. Now, however, we know that we are not at the center of the swarm; and it seems likely that, should we proceed in the direction of that point, we might find the stars crowding together, while, should we travel in the opposite direction, we would find them thinning out even more rapidly than the averaged counts would indicate. This at least would be the expectation were it not for the presence of the local system.

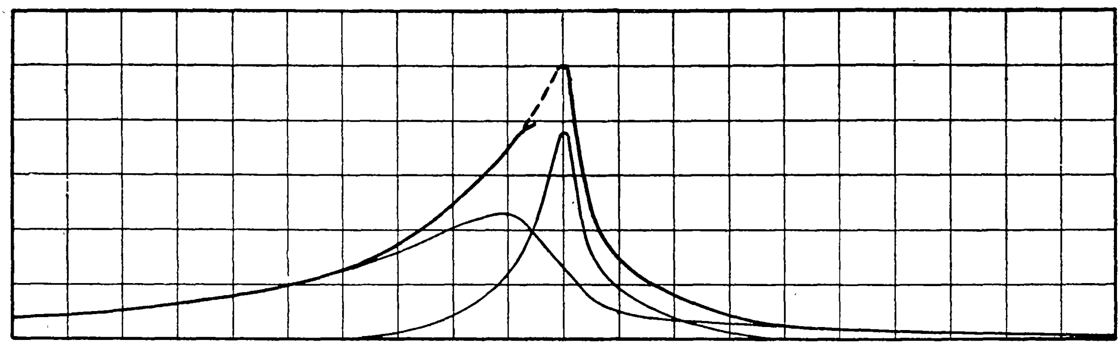

Figure 3

Variation in the number of stars per unit volume at different distances from the Sun (figures at bottom) in the direction of the center of the stellar system (toward the left) and in the opposite direction. The upper curve includes all stars together. This can be resolved into two other curves, one, nearly symmetrical, representing the local system, and another representing the larger system. Distances in Parsecs may be expressed in light years by multiplying by 3.26.

When we turn again to the original counts to see how those in different directions along the Milky Way increase in numbers as we add fainter and fainter stars, we find that they build up much faster in the direction of the center than toward the opposite point in the sky, but not nearly fast enough to indicate any crowding together of stars as the center is approached. On the contrary, the ratios are such that, as we leave our neighborhood in space, the stars must begin to thin out almost at once, whatever the direction in which we proceed outward; they thin out least rapidly when we move toward the center, faster when we reverse our steps and travel in the opposite direction, and fastest of all when we proceed in the direction of the poles of the Milky Way. The significant detail is the behavior in the direction of the center of the larger system, which turns out to be just the opposite of that to be expected were the local system not present. We thus conclude, not only that a local system exists, but that it dominates the situation to such an extent that the characteristic distribution within the larger system which we expected to find is totally obscured. How completely this is the case is illustrated by the uppermost curve of Figure 3, which shows the numbers of stars per unit volume at different distances from the Sun in two different directions, one (left) toward the center of the larger system, the other (right) in the direction diametrically opposite. Distances of points on the curve above the bottom of the diagram represent numbers of stars. Even toward the center, the stars thin out so rapidly that at 2000 parsecs (6500 light years) the density is only one-half that near the Sun, while at 5000 parsecs (16,250 light years) it is only one-fifth. The great concentration of density near the Sun represents the influence of the local system.

However we approach the matter, therefore, the larger system, in our own vicinity at least, seems to sink into a position of relative unimportance, and, when we attempt to learn more about it, we meet with great difficulties.

VI

SEPARATION OF THE LOCAL AND LARGER SYSTEMS

To proceed, we must try to get rid of the local system by removing its members from our counts. This is a hazardous undertaking, because, in general, we cannot specify the system to which any given star belongs; and we are thus obliged to make an assumption, namely, that the local system is symmetrical about a central point, or at least that it is not highly asymmetrical. Stated in another way, though rather crudely, we suppose that the point within the local system where the stars are thickest is not far from its geometrical center. Such an assumption is not without inherent probability, for most aggregations of stars seen in the sky possess a rough symmetry of this kind; and within the local cluster itself, in the nucleus of helium stars, we find evidence of its presence.

The operations involved in separating the local and larger systems are illustrated by Figure 3, where, as already explained, the uppermost curve represents the varia ion in the number of stars per unit volume in the direction of the center and of the point diametrically opposite. From the densities corresponding to this curve we must subtract those contributed by the local system. By the assumption just made, these will be represented by a curve, nearly symmetrical, having a maximum coinciding closely with the Sun. The size and shape of the curve are not otherwise specified, and the choice of a definite form is beset with uncertainty. Nevertheless, certain guiding principles may be laid down: Thus, the central density of the local system, represented by the height of the maximum of the symmetrical curve, must be greater than some minimum value; otherwise, after the local system has been removed, the region of maximum density in the larger system will remain near the Sun, which is at variance with all our ideas as to the structure of the system. On the other hand, the central density of the local system cannot exceed a certain amount without leaving in the larger system, close to the Sun, a region of abnormally low density. Finally, the relation between density and size in the local system must be such that the change in density in the larger system revealed by removing the adopted local system is everywhere smooth.

The result of the analysis is shown by the two component curves in Figure 3. Under the circumstances described we should scarcely expect more than a qualitative indication of relations; nevertheless, the central density and the diameter thus found for the local system are in general numerical agreement with the results derived from Figure 2, namely, a density of three-fourths the total near the Sun and a diameter of six or eight thousand parsecs. Further, the curve for the larger system shows an increase in the density in the direction of the center, as we should expect, but, surprisingly enough, the stars seem to reach their highest concentration at a distance of only 3000 to 6000 light years, according to the degree of asymmetry admitted in the local system.

The position of this maximum must be far short of the geometrical center of the system; and even where thickest, the concentration of stars is only about one-half that at the center of the local system. Regarded as the dominant portion of so vast a collection as the larger system, the region of maximum stellar concentration is not an impressive feature; and our instinct for symmetrical arrangements in the heavens makes us reluctant to accept this off-sided aggregation as the nucleus of the larger system, or the very unsymmetrical curve of Figure 3 as an indication of how the stars in this system are distributed.

VII

THE ANALOGY WITH SPIRAL NEBULÆ

At first sight it seems difficult to reconcile the improbabilities thus brought to light with the symmetry for which we instinctively look. Nevertheless, we are not without helpful suggestions. The trend of cosmological thought in recent years has been in the direction of analogies between the stellar system and the great spiral nebulæ like Messier 33 or Messier 101 (Plate 26). In form, there is close resemblance. The outline in the principal plane is roughly circular in both cases; and, seen edge-on (Plate 27, a, b, c), the spirals show the flattened contour found in our own system. Further, photographs made at Mount Wilson by Hubble with the 100-inch reflector (Plate 27b) show that at least some of these nebulæ are gigantic systems of stars, composed of different classes of objects—diffuse nebulosity, novæ, Cepheid variables, and ordinary giant stars of different spectral types, which, class for class, correspond to those of the system about us; and, finally, that the nebulæ, if not actually as large as the stellar system, are nevertheless of the same general order of dimensions.

Seen broadside (Plate 26), the curving arms of the spirals, with their irregular knots and condensations of stars, lack the smoothness of distribution that counts in our own system seem to suggest; but it requires little imagination to realize that were we situated in the central plane of a spiral like Messier 33, we should find the scattered aggregations of stars blending into an encircling band of Milky Way clouds, with irregularities perhaps no greater than those in the star clouds of our own galaxy. Again, the conspicuously bright central condensation which is characteristic of the spirals makes us wonder if the cosmological analogy is complete, for thus far we have looked in vain for anything in our own system resembling a dominant central nucleus. But even this seemingly well-marked exception falls into line when the position of the observer is properly credited with its influence on appearances.

With the examples of edge-on spirals (Plate 27) before us, imagine ourselves again within one of these objects, at some distance from the center, with our eyes turned toward the nucleus. Does it seem likely that we should then see the central condensation? Apparently not, at least not the brightest portion at the very center. Even the most casual inspection of Plate IVa, b, c will not fail to reveal the dark broken band extending the length of the images, which is a conspicuous feature of almost every edge-on spiral that we know. This band consists of obscuring clouds of nebulous material, dark ordinarily, unless illuminated or stimulated to shine by some external source, and invisible, unless outlined by projection on a background of stars or luminous cloud. Photographs of spirals inclined to the line of sight suggest that these dark clouds extend well in toward the central condensation, and would blot out, in part at least, the bright central region from our imagined point of observation. The chances are, too, that above and below the dark clouds, in the general direction of the center, we might see outlying aggregations of stars, strewn nearly parallel to the plane of the nebula. The Milky Way of the nebula would then appear split for part of its length into two branches by a great rift, like that which in our own system extends from *Cygnus* in the north to *Circinus* far down in the southern heavens. We know that much obscuring material is scattered over the galactic plane among our own stars, and that the dark, almost starless region between the two branches of the Milky Way is probably a thick pall of cloud. The direction of the center of the system cuts into this cloud, and it may well be that but for the cloud we should see something comparable with the central condensation of the spirals. The off-sided concentration of stars which, as a central nucleus, seemed so out of harmony with the vastness and grandeur of the system, would then represent the thickening-up of the stars naturally to be expected toward the center, modified and ultimately suppressed by the obscuring clouds, long before the center is reached.

The asymmetry of distribution is further accentuated by the fact that the curve for the larger system shown in Figure 3 has been derived from counts made, not in the exact direction of the center, but in the branches of the Milky Way immediately above and below the central point. For a system perfectly symmetrical about its center the distribution of density along lines thus inclined to the principal plane would necessarily be unsymmetrical; the maximum density would be less than at the center, and less distant than the central point. Finally, the position of the maximum may also be influenced by one of the local aggregations of stars which the Milky Way structure, as well as the appearance of the spirals, suggests as lying scattered over the galactic plane.

When invoked to explain the peculiarities of stellar distribution, the well-known analogies between spirals and our own system answer very well; but, unfortunately, they leave us still in doubt as to our exact location within the larger system. The presence of obscuring material means that star counts probably can never remove that doubt. For the present we can only accept Shapley's estimate based on the distribution of the globular clusters, which places the center of the system at a distance of 50,000 to 60,000 light years in the direction of longitude 325°. The close agreement of the longitude with that found from star counts supports the belief that the clusters also correctly indicate the distance to the center. If the diameter of the system may be regarded as of the order of two or three hundred thousand light years, as suggested above, we should then find ourselves something like half-way out toward the edge of the system.

But where does the local system, which so dominates the situation about us, fit into the picture? It is, perhaps, only an exceptionally large aggregation of stars similar to those scattered along the arms of the spiral nebulæ; or it may be a more or less independent organization of stars entangled within the larger system—instances of the close juxtaposition of two spirals, for example, are not unknown; but perhaps the only safe conclusion at present is that a local system of unexpected richness and size exists. The members of this system are numerous enough to impress something of their own characteristics on the distribution of the stars as a whole down to a low limit of brightness, and are therefore certainly to be counted by millions. In so large a collection it is natural to expect stellar luminosities and spectral types similar to those in the larger systems. This being the case, the surprisingly large dimensions found for the local system follow as a matter of course.

In closing, a word of caution may perhaps be added: The picture drawn of the stellar system is only a sketch in broad outlines. Conclusions based solely on star counts may be regarded as reliable, for it is probable that the counts rest on a sound photometric system; structural features derived from analogies with spiral nebulæ are less certain, but still probable; estimates of dimensions and distances are uncertain, and, in some instances, possibly not even of the right order of magnitude. Above all, it must not be forgotten that practically all the conclusions formulated depend on a study of but two characteristics of the stars—the numbers seen in different directions in the sky and the totals down to different limits of brightness. This restriction accounts in part for the lack of detail in the picture; at the same time, it may mean that results which now seem well established will require modification and readjustment when other stellar characteristics have been intensively studied.

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