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THE NEBULÆ

Address of the Retiring President of the American Association for the Advancement of Science.[1]

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IT is characteristic of most investigations in pure science that the quest is for the origin and history of things, and for the understanding of what now is, rather than for what is going to occur. One does not wisely venture to predict the future until he has explained the past and accounted for the present. Paleontologists are fruitfully studying the extinct animal life of our planet; several departments of science are busy with the life of to-day; and little effort has yet been made to forecast the animal life of the future. Anthropologists and ethnologists have been concerned with the men and the races of men who have already lived; they are just beginning to think scientifically of the men and the races that are to come. Conditions are moderately different in the one science, astronomy, whose chief domain lies far outside the earth and far beyond our sun. Some of the planets in our solar system may be passing through stages of existence that the earth experienced long ago, and others of our planets may be approximate examples of what is in store for the earth. When we undertake the study of the sun we have the great advantage that millions of suns within our view are representing the stages of stellar life through which our sun is thought to have passed, and millions of others the stages through which our sun will pass in the future. If we seek to know the history of our sun we can not avail ourselves of progressive changes in the sun itself. Such changes are too slow; we think the sun has remained substantially unchanged for hundreds of thousands of years. The student of stellar evolution proceeds by arranging the stars in general in the supposed order of their effective ages, and he endeavors to place our star and our planet at the logical points in the series. In this way astronomers, not unanimously, but in the great majority, have arrived at the conclusion that our own sun is in effect one of the middle-aged stars, and that our earth is in effect a middle-aged planet; and they attempt seriously to predict the future histories of the two bodies.

It is not my purpose to conduct you over the long road of stellar evolution. I shall invite your attention chiefly to the parts which the nebulæ seem to play in the development of the stellar universe; and this will lead me to touch lightly upon the birth and infancy of the stars, and to neglect the periods of their youth, middle life and old age.

[1] Delivered in the American Museum of Natural History, New York City, December 26, 1916. **Illustrated by lantern slides.**

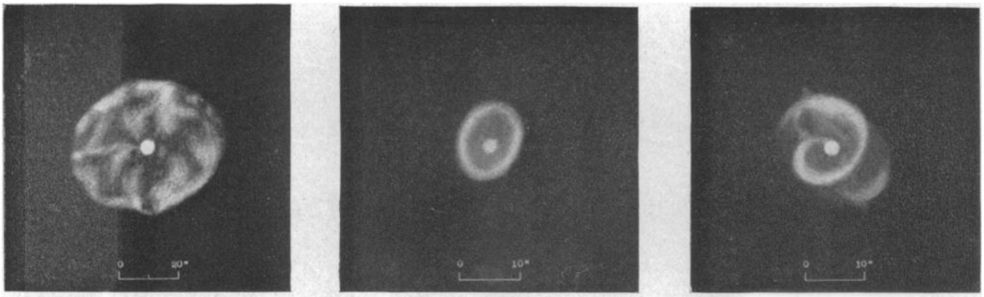


Fig. 1. (*a*) N.G.C. 1501. (*b*) N.G.C. 418. (*c*) N.G.C. 6543.
Planetary Nebulæ. Composite drawings by Curtis from his photographs with the Crossley Reflector of the Lick Observatory.

The classes of objects with which astronomers have to deal are very few. In our solar system we have the sun, the planets and their moons, the comets, the zodiacal light, and the meteors. To the best of our knowledge that exhausts the list. When we look beyond the solar system and out into the great stellar system we see only two classes of objects: the stars and the nebulæ; but there is an extremely great variety of each class, tens of millions of stars and tens of thousands of nebulæ, probably no two of either class exactly alike.

The serious study of the nebulæ began with Sir William Herschel in the 1780's. In less than two decades his famous sweepings of the sky had rewarded him with the finding of 2,500 nebulæ and star clusters. He did not separate them into a list of nebulæ and a list of clusters, as he was not clear about their relations to each other. When he observed certain of them with small telescopes and low magnifying power they looked like continuous structures, as if they were little clouds of luminous gases; but when some of the same objects were subjected to greater magnification they were resolved into star clusters. Here was the serious beginning of the hypothesis that all the nebulæ would be resolved into stars if only our telescopes were sufficiently powerful. Herschel was not satisfied with this view, and in 1791 he proposed the hypothesis that nebulæ evolve into stars. He thought that nebulæ of great size would condense very gradually, or break up, into smaller nebulæ; that the smaller ones would condense into nebulæ ever more and more regular in outline; and that these would eventually pass into the small, nearly symmetrical objects which he called planetary nebulæ, because in telescopes of low power they presented discs resembling the discs of our planets. He said the planetaries were the immediate forerunners of the stars, and that they would evolve into stars. Herschel actually classified a considerable number of the known nebulæ in accordance with this hypothesis. Speaking of a star surrounded by nebulosity, which is the condition existing in most planetary nebulæ (see Fig. 1), he said that the nebulous matter seemed "more fit to produce a star by its condensation than to depend upon the star for its existence."

Herschel's mind was profoundly philosophic, and his ideas about nebulæ attracted wide attention. They may easily have suggested Laplace's celebrated nebular hypothesis of the origin of our solar system, announced a few years later. Herschel thought of the birth of many stars from the nebulæ; Laplace's hypothesis ventured to describe in detail the process of the development of one nebula into our sun, its planets and their moons.

It is necessary for the satisfactory presentation of our subject that we grasp the principal features of our stellar system, and we shall devote a few sentences to its description.

The universe of stars—our stellar system—is believed by astronomers to occupy a limited volume of space that is somewhat the shape of a very flat pocket watch; more strictly, a much flattened ellipsoid or spheroid. It is not intended to convey the impression that the boundaries of the stellar system are sharply defined, nor that the stars are uniformly distributed throughout the ellipsoid (see Figs. 2, 18 and others), but only that the stars are more or less irregularly distributed throughout a volume of space roughly ellipsoidal in form. The thinning out of stars near the confines of the system may be both gradual and irregular. The equatorial plane of the ellipsoid is coincident with the central plane of

FIG. 2. Milky Way around the star Gamma Cygni, photographed by Barnard with the 10-inch Bruce telescope of the Yerkes Observatory.

the Milky Way. We see the Milky Way, or Galaxy, as a bright band encircling the sky because, looking toward the Galaxy, we are looking out through the greatest depth of stars. There remains considerable uncertainty as to the dimensions of the system, chiefly for two reasons: first, the stars near the surface of the ellipsoid are everywhere too far away to let us measure their distances; and, secondly, the system may be considerably larger than it seems because of possible obstruction of starlight in its passage through space. Newcomb has suggested that the shorter radius of the system, at right angles to the plane of the Galaxy, may be taken as of the order of three thousand light-years. The long radii, those in the plane of the Milky Way, may be at least ten times as great; that is, thirty thousand light-years, or more.

Our solar system is believed to be somewhere near the center of the stellar system: the counts of stars in all parts of the sky do not indicate that any one section of the Milky Way structure is appreciably closer to us, so to speak, than the other sections of it. It should be said that Easton's studies of the Galaxy place its probable center in the rich region of the constellation Cygnus.

These conceptions of the stellar universe and of the Milky Way agree in all important particulars with the ideas of Immanuel Kant published in the year 1755. However, it was the star counts by the two Herschels, father and son, which put this conception of the stellar system upon the basis of confidence. Sir William Herschel, using an eighteen-inch reflecting telescope in the northern hemisphere, and Sir John Herschel, using the same telescope in the southern hemisphere, counted the stars visible in the same eye-piece in 7,300 regions distributed rather uniformly over the entire sky. They found that the number of stars decreased rapidly as they passed from the central plane of the Galaxy toward the north and south poles of the Galaxy. Here is a table deduced by Struve from the Herschels' counts:

Galactic Latitude[2] Zones	Average Number of Stars Per Field 15′ in Diameter
+ 90° – + 75°	4.32
+ 75 – + 60	5.42
+ 60 – + 45	8.21
+ 45 – + 30	13.61
+ 30 – + 15	24.09
+ 15 – 0	53.43
0 – — 15	59.06
— 15 – — 30	26.29
— 30 – — 45	13.49
— 45 – — 60	9.08
— 60 – — 75	6.62
— 75 – — 90	6.05

The average number of stars in the Milky Way zone 30° wide, that is, between galactic latitudes + 15° and — 15°, visible in the eyepiece of the telescope, was fifty-six,[3] whereas in the regions surrounding the north and south galactic poles (latitudes between 75° and 90°) the average visible in the same eyepiece was but five.[3] The great condensation in the Milky Way is not fully evident from the table. The stars are much more numerous near the central line of the Milky Way than they are near its borders. The average number along the central line found by Sir William Herschel was 122. There is no reason to doubt that the pre-

[2] The galactic latitude of a star is its angular distance from the nearest point of the central line of the Galaxy, in the same way that the terrestrial latitude of a city is the city's angular distance from the nearest point of the earth's equator.

[3] A recent study of Mr. Franklin Adams's photographs of the sky, by Chapman and Melotte, shows a considerably smaller ratio than the 56:5 found by the Herschels. Seares has recently determined from Mount Wilson photographs that the number of stars per square degree along the central line of the Milky Way is more than twenty times as great as the number per square degree near the galactic poles; a result in remarkably close confirmation of the Herschels' counts. The source of the discordance between Chapman and Melotte's results and Seares's results remains unexplained.

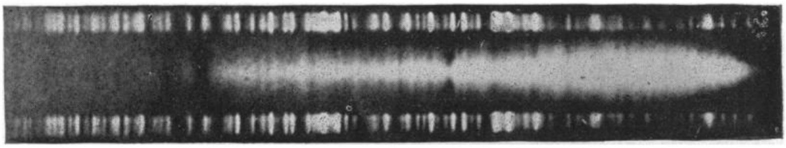


FIG. 3. The Spectrum of the Great Spiral Nebula in Andromeda, photographed by Slipher at the Lowell Observatory.
[The series of bright lines along the upper and lower margins are the reference spectrum. The nebular spectrum runs horizontally through the central area.]

ponderance of stars visible in the Milky Way is due to the greater extension of the stellar system in that direction than in the direction of the galactic poles.

Sir John Herschel, the son, extended the father's search for nebulæ to the southern sky, by observing at the Cape of Good Hope in the 1830's. He later charted all of the known nebulæ, both north and south, upon a sphere representing the entire sky, and found the surprising condition that the nebulæ in general avoid the Milky Way. Several decades earlier William Herschel had noticed within the Galaxy that the nebulæ are the more plentiful where the stars are scarce. When the stars in the eyepiece of his telescope would suddenly change from numerous to few he was accustomed to say to his recording assistant, "Get ready, nebulæ are coming." These general facts of stellar and nebular distribution, where stars are scarce nebulæ abound, and where stars abound nebulæ are scarce, led Herbert Spencer, among others, to emphasize the view that the evidence for a relationship of stars and nebulæ is overwhelmingly strong. This he called "the relationship of avoidance."

In the year 1864 occurred a great astronomical event. William Huggins pointed his spectroscope to a well-known planetary nebula in Draco (Fig. 1, *c*) and found that its visible spectrum consisted of three isolated bright lines (see Fig 32, N. G. C. 6543, the three lines at the right end of spectrum). This observation gave a death blow to the hypothesis then prevailing that all the nebulæ would prove to be clusters of stars if only our telescopes were powerful enough, or if the nebulæ were brought near enough to us. The spectroscope said very definitely and with finality: the Draco nebula is unresolvable; it is a mass of glowing gases. A cluster of stars can not give that type of spectrum. Other nebulæ were tested by Huggins's spectroscope. Some of these objects gave bright-line spectra, but the great majority had continuous spectra. Whether the latter were actually continuous or, as in the case of the sun and other middle-aged stars, the apparently continuous spectra of the nebulæ were really interrupted by hundreds and thousands of absorption lines, could not be decided because the nebular spectra were exceedingly faint. The eye could not have seen the absorption lines even if they were present. It is only in the last two decades, through the use of rapid photographic plates and of exposures a great many hours in length, that the existence of absorption lines in the continuous spectra of the nebulæ (see Fig. 3) has been proved for all of the nebulæ submitted to adequate test.

Lord Rosse's famous six-foot reflecting telescope marked an epoch in nebular research, in the year 1845, by showing that certain well-known nebulæ are of spiral structure—pretty certain evidence that they are in rapid rotation. Roberts's photography of nebulæ in the '90's added to our knowledge of them, but the number of spirals known to exist was still not more than two or three dozen out of the approximately 10,000 objects listed in Dreyer's General Catalogues of nebulæ and clusters.

FIG. 4. Spiral Nebula Messier 81, photographed by Keeler with the Crossley Reflector of the Lick Observatory.

A great impetus was given to the study of the nebulæ when Keeler began to photograph them, in 1898, with the Crossley reflecting telescope of the Lick Observatory. His photographs, covering small areas in many different parts of the sky, recorded hundreds of nebulæ hitherto unseen. Using these small photographs as sample tests of nebular distribution, he estimated conservatively that his telescope could discover at least 120,000 nebulæ in the entire sky whenever he cared to undertake the work. Keeler's photographs were revolutionary in another sense: they led him to the capital discovery that the great majority of the nebulæ are spirals. Keeler's results have been abundantly confirmed by later observers: Perrine, Wolf, Fath, Curtis and others. Using the sixty-inch reflector of the Mount Wilson Solar Observatory, Fath photographed 139 small areas uniformly distributed over the northern three fifths of the sky, and he estimated from the number of the nebulæ recorded on his small plates that similar photographs completely covering the sky, 22,000 photographs, would

FIG. 5. Spiral Nebula Messier 51, photographed by Curtis with the Crossley Reflector of the Lick Observatory.

record about 162,000 nebulæ. Perrine, using the Crossley reflector, estimated the number discoverable as still greater. All the observers have found the faint nebulæ to present a variety of elliptic forms, such as we should expect if they are spirals whose principal planes are distributed in direction at random. Many of them are approximately circles, as if they are spirals seen flatwise (Fig. 5); others appear as

FIG. 6. Spiral Nebula, edgewise, N.G.C. 4244, photographed by Keeler with the Crossley Reflector of the Lick Observatory.

spindles, or as spirals seen edgewise (Fig. 6); and the great majority have intermediate elliptic forms (Fig. 7). The plain inference is that the very faint nebulæ are for the most part, and perhaps almost entirely, spirals.

We have mentioned Sir John Herschel's charting of the nebulæ with reference to their distribution over the sky. Proctor charted all the nebulæ and star clusters known up to 1869, as in the illustration (Fig. 8). The positions of the nebulæ are indicated on the charts by the small dots. Their peculiar relationship to the Galaxy is apparent. The star clusters are plotted on the charts as crosses. It is clear that the clusters are found prevailingly in the galactic regions and in the two Magellanic Clouds (see Figs. 22 and 23), the Greater and the Lesser, which are about 20° from the south pole of the sky and are far to one side of the Galaxy. We should perhaps explain that the two Magellanic Clouds are great clusters of stars and nebulæ, covering many square degrees each, which have the same general appearance as many of the cloud forms of the Galaxy itself. We shall later find reason for believing that these Clouds are isolated stellar systems, separate from and independent of our stellar system.

It is the small star clusters, the clusters of rather widely separated stars, and the clusters of irregular form which show the strongest preference for the galactic regions; and there is no reason to doubt that all of such clusters belong to our system. The globular clusters, rich in stars and symmetrical in form, of which only 83 are known in the whole sky, likewise show a strong preference for the Milky Way, and it is probable that most of them, in fact nearly all of them, are within our stellar system; but the greatest of these clusters,

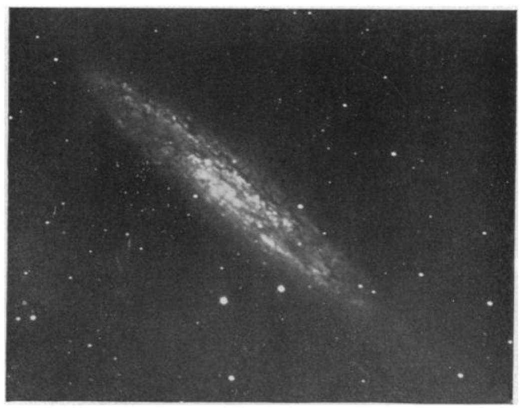
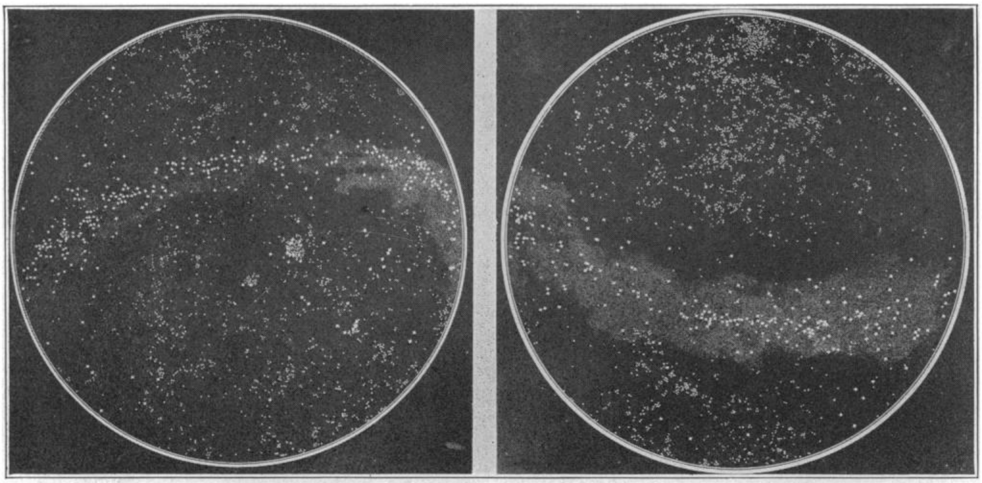


FIG. 7. Spiral Nebula N.G.C. 253, photographed by Keeler with the Crossley Reflector of the Lick Observatory.

such as the cluster in Hercules and two clusters even more prominent in the southern sky, are seen at considerable angular distances from the Milky Way structure.



Southern Hemisphere. Northern Hemisphere.

Fig. 8. Distribution of Nebulæ and Star Clusters according to Proctor. Nebulæ are marked by dots; clusters by crosses.

Fath's photographs, covering very small areas in the centers of 139 regions, recorded nebulæ hitherto undiscovered in the numbers set down in his chart, reproduced in Fig. 9. The curve drawn across the chart represents the central line of the Galaxy. The north pole of the Galaxy is at N, and the south pole is near S at the lower edge of the diagram. The distribution of the nebulæ is seen to be irregular and patchy, but the fact is indisputable that the faint nebulæ discovered with the most powerful photographic telescopes in the world, like the brighter nebulæ discovered visually by the Herschels and others, abhor the Milky Way. In the northern hemisphere, as

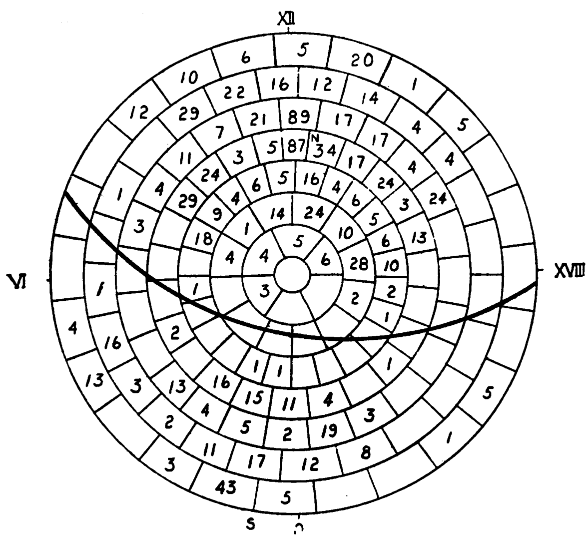


Fig. 9. Distribution of Faint Nebulæ discovered by Fath at Mount Wilson.

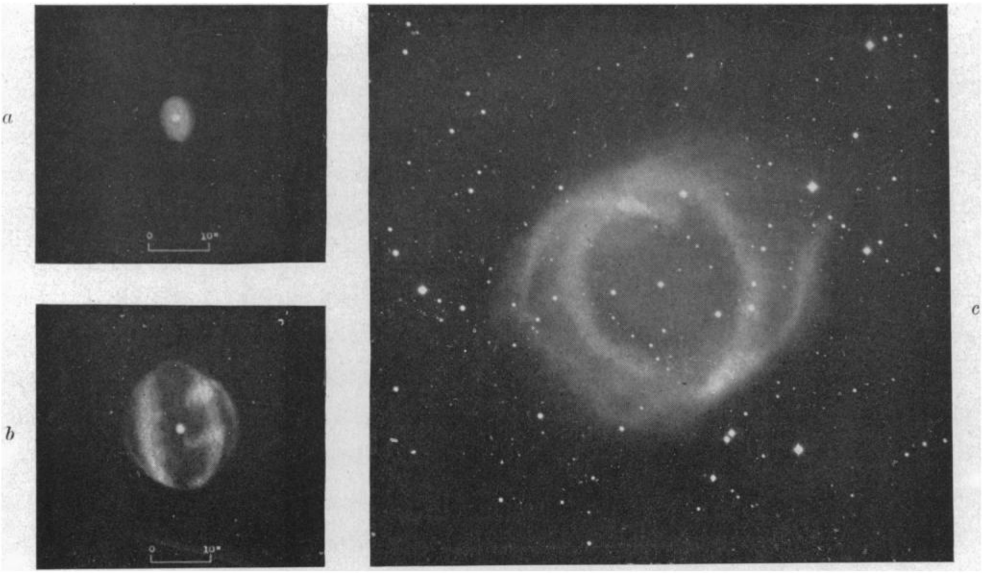


FIG. 10. Planetary Nebulæ. (*a*) and (*b*) are composite drawings from photographs, and (*c*) is a direct copy of a photograph, made by Curtis with the Crossley Reflector of the Lick Observatory.
(*a*) N.G.C.$_1$ 351. (*b*) N.G.C. 6818. (*c*) N.G.C. 7293.
1 inch = 8′.5.

Herschel and Proctor had established, they cluster more densely in the neighborhood of the pole of the Galaxy. In the southern hemisphere they show the same tendency, but not so strongly marked.[4] Two or three hundred of the brighter nebulæ have long been known to exist in and near the Milky Way, but faint nebulæ, such as those scores of thousands which Keeler showed are still awaiting discovery, are practically non-existent in the galactic region.

Let us examine more carefully the distribution of the nebulæ with reference to the Galaxy, and with reference to the physical conditions which seem to exist within them.

Out of approximately fifteen thousand nebulæ thus far discovered, fewer than 150 are planetaries. They exist in a variety of sizes, from a few that are only two or three seconds of arc up to others a quarter of a degree in diameter. The difference in size is due, at least in large part, as Curtis has recently made clear, to a difference in the distances of the bodies from us. A considerable number of them appear to be more and more condensed as we approach their centers, but the ring-form planetaries are the prevailing type (see Fig. 10). These rings of nebulosity are apparently not true rings, existing chiefly in two dimensions, but ellipsoidal shells of matter seen as rings in projection on the background of the sky. If they were true rings, we should see some of them as extremely elongated ellipses, and others ought to be long and slender as a result of seeing them edgewise. Those forms are wholly unknown. Now all of the planetaries give spectra consisting chiefly of isolated bright lines (see Fig. 32); that is, they are gaseous in constitution, and are

[4] It is not intended to convey the impression that the nebular distribution is merely a function of the galactic latitude; the observed nebulæ are more numerous in certain galactic longitudes than in others.

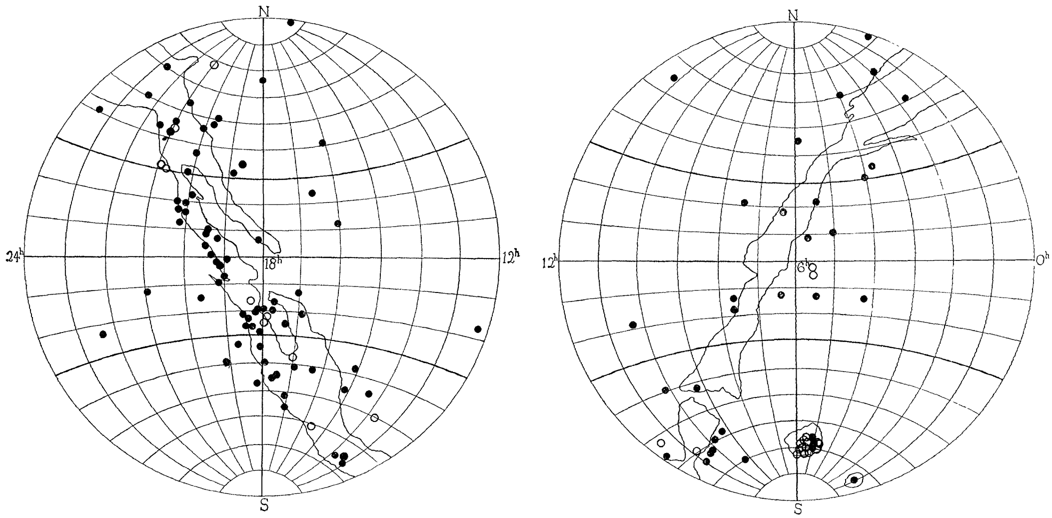


FIG. 11. Distribution of Planetary and Irregular Bright-line Nebulæ.
Right Ascen. 12^h to 24^h. Right Ascen. 0^h to 12^h.
● = Planetary nebulæ. ○ = Irregular bright-line nebulæ.
The irregular lines enclose the brighter galactic structure.
The positions of the Greater and Lesser Magellanic Clouds are shown above and to the right of the south pole of the right-hand chart.

shining by their own light. A very large proportion of them are in or adjacent to the structure of the Milky Way, or in the Magellanic Clouds (see Fig. 11). There are a few exceptions, but the exceptions almost certainly find their explanation in the relative nearness of these few to us, so that, being a little to one side of the central plane of the stellar system, they are seen in projection at some distance to one side or the other of the galactic structure.

The large irregular nebulæ whose spectra are known to consist of bright lines are charted as open circles. Such nebulæ at a considerable distance from the Galaxy are very scarce indeed.

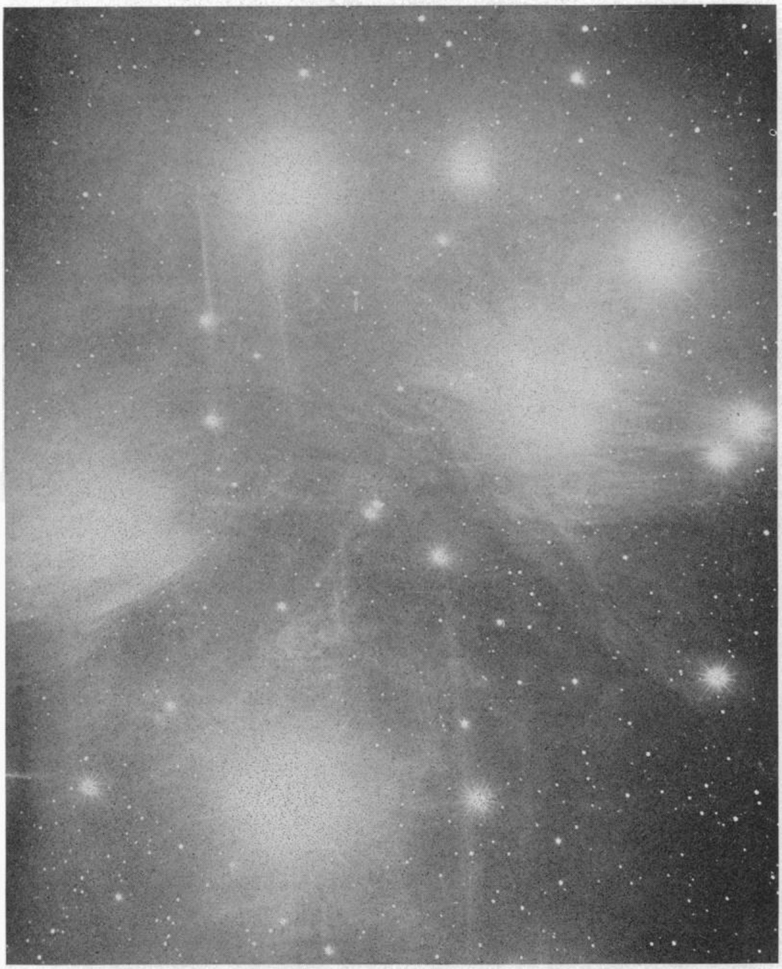
The motions of approach and recession of the bright-line nebulæ have been observed with spectrographs at the Lick and D. O. Mills observatories. The large and formless bright-line nebulæ, such as the Trifid and Orion nebulæ, are almost at rest amongst the stars; their individual velocities are small, and the mean velocity of the group, with reference to our stellar system, is zero. These nebulæ, considered as a system, are not moving through the stellar system. They are in it and a part of it. Many of the planetary nebulæ (see Figs. 1 and 10) have high velocities, as individuals, but when we consider them collectively their motion with reference to the stellar system is in effect zero. They too are of our system.

There are in or not very far from the Milky Way many irregular nebulæ, of a great variety of sizes, whose types of spectra are for the most part unknown. They are intrinsically faint, and their investigation is a most promising problem of the immediate future. Two of these nebulæ, according to Slipher, have spectra identical with the brilliant stars which seem to be immersed in them; that is, continuous spectra, except as the absorption lines of helium and hydrogen are present in both the nebular and the stellar spectra. These facts have led Slipher to favor the view that the two nebulæ are not shining by their own light, but by the reflected light of the brilliant stars in their midst. One of these is the nebula in which the Pleiades cluster is immersed (Fig. 13), and the other is around the bright star Rho Ophiuchi (Fig. 14). There are in the Milky Way many scores of nebulæ such as these, though for the most part fainter; but whether their spectra are of the bright-line type or reflected-light type, we do not know.

Our photographic telescopes are confirming William Herschel's observation that these large and formless nebulæ are in or are bordered by regions of sky showing fewer stars than abound in the surround-

FIG. 12. The Trifid Nebula, in Sagittarius, photographed by Keeler with the Crossley Reflector of the Lick Observatory.

W



S N

E

FIG. 13 The (inner) Pleiades Nebula, photographed by Keeler with the Crossley Reflector of the Lick Observatory. (By engraver's error the plate is reversed in one direction, as indicated by the letters W, N, E, S.)

ing regions. The bright stars in the Pleiades, those really belonging to the cluster, are numerous, but within the cluster as we see it, and in a considerable area of the adjacent sky, the faint stars are markedly scarcer than in the areas farther away. Barnard has found that the sky in the region around the Pleiades group is possessed of much nebulosity. It is a natural question, are the faint stars scarce because the nebulosity there existing has not yet condensed into stellar forms? This may be true in part, but we shall find much more probable the view that the faint stars are deficient in numbers because the nebular materials, at a certain distance away from us, are obstructing the light of the faint stars that are farther away from us than

FIG. 14. The Milky Way around Rho Ophiuchi, photographed by Barnard with the 10-inch Bruce Telescope of the Yerkes Observatory.

the nebula is. A similar deficiency of faint stars exists within the great nebula of Orion, and likewise in the adjacent areas, where Mr. William H. Pickering has found a very large part of the constellation of Orion to be covered with faint nebulosity. We shall give illustrations of several regions (see Figs. 14, 15, 16) where this condition—the presence of nebulosity and the scarcity of faint stars—is so marked as to be at once apparent. There are so many regions in and near the Galaxy where these relationships exist that we can not doubt their significance. The faint stars are relatively scarce chiefly because the nebular materials cut off the light of the more distant stars. This explanation is reached by several lines of evidence, but we take time to present only one.

It is established by modern astronomy that the individual stars are in rapid motion. The speeds of the naked-eye stars average about sixteen miles per second. The distant fainter stars, so far as they have been observed, are also traveling rapidly. There is a tendency to favor certain directions of motion, and the stars in certain small groups are keeping company through space; but a large share of stellar motion is at random. There are stars traveling in all directions. We have not the direct evidence as to the motions of the faint stars in the far distant outposts of the Galaxy, but we have no reason to suspect that their characteristic motions are unique. We can see no escape from the condition that all the stars are in motion. Under these circumstances we are unable to explain how within a great volume of space that is rich in stars there can be a smaller, but still enormous volume of space, nearly free of stars. Their random motions should distribute them more uniformly than we observe to be the case. Let us illustrate by the celebrated black holes, the so-called "coal sacks," in the constellation of Sagittarius (Fig. 17). In a region where the stars are especially plentiful are two small areas all but empty of visible

FIG. 15. Irregular Nebula N.G.C.$_2$ 5146, photographed by Curtis with the Crossley Reflector of the Lick Observatory.

(The circular halos around the brighter stars are unavoidable defects and are not real.)

stars. An enlargement of a photograph by Barnard, the preeminent student of this subject, shows the effect still better. How can such great "holes" through the stellar system be surrounded by a plenitude of stars moving more or less at random so as to give a high density of star distribution right up to the sharply defined edges of the holes, and yet leave the holes empty of stars? With the help of all astronomical experience we can not explain the phenomena by the absence of stars. I think we must assume, with Barnard and others, that the stars are actually there, and that they are invisible because invisible materials between us and the stars are absorbing or occulting the light which the stars are trying to send us. Much of the interesting structure in the Milky Way is probably due in a like manner to obstruction by materials lying between us and the great clouds of stars (see Fig. 18). It is characteristic of the galactic structure that where luminous nebulæ seem to reduce the numbers of faint stars visible, the reduction in numbers of stars extends also far out beyond the limits of visible nebulosity (see Figs. 14, 15 and 16), and we can scarcely resist the conclusion that invisible extensions of the luminous nebular fabric exist as obstructing agents.

There are many other lines of evidence in support of the hypothesis that invisible matter exists in abundance within the stellar system:

1. Newcomb and Kelvin, working independently and on the assumption that the motions of the stars are generated by gravitational attractions originating within the stellar system, were unable to account for the high observed velocities of stars, except on the hypothesis that the visible stars contain only a small fraction of the matter existing in the system; the greater part of the attracting material in the stellar sys-

Fig. 16. The North America Nebula, photographed by Barnard with the 10-inch Bruce Telescope of the Yerkes Observatory.

tem being non-luminous, or at least invisible.

2. There must be an enormous amount of comet material distributed throughout space. The astronomers discover only a negligibly small proportion of the comets which pass near the center of our solar system. May not comet materials exist also in abundance in the systems of the other stars?

3. Students of meteors have established that the separate little bodies which collide with the earth's atmosphere and are responsible for the so-called shooting stars are stupendous in numbers. It has been estimated that as many as twenty or thirty millions of such bodies collide with the earth every twenty-four hours. How incomparably and inconceivably greater must be the total number in our solar system. The power of these countless particles to obstruct the passage of light is not negligible. There may be as many such particles on the average around the other stars in our stellar system.

4. The so-called new stars, otherwise known as temporary stars, afford interesting evidence on this point. These are stars which suddenly flash out at points where previously no stars were known to exist; or, in a few cases, where a faint existing star has in a few days become immensely brighter. Twenty-nine such stars have been observed in the past three centuries, nineteen of them since 1886 when the photographic dry plate was applied systematically to the mapping of the heavens, and fifteen of the nineteen are to the credit of the Harvard observers. This is an average of one new star in less than two years in the last three decades; and, as some of the fainter new stars undoubtedly come and go unseen, it is evident that they are by no means rare objects. Now all of the temporary stars except five appeared in the Milky Way, and four of the five exceptions are worthy of note. Two of the five appeared in well-known nebulæ; another was located close to the edge of a spiral nebula, and quite probably in a faint outlying part of it; a fourth was observed to have a nebulous halo about it; and the fifth was but meagerly and imperfectly observed. Keeping the story as short as possible, a temporary star is seemingly best explained on the theory that a dark or relatively dark star traveling rapidly through space has met with resistance, such as a great nebula or cloud of particles would afford. While passing through the cloud the star is in effect bombarded at high velocity by the resisting materials. The surface strata become heated, and the luminosity of the star increases rapidly. The new star of February, 1901, in Perseus afforded interesting testimony. Wolf at Heidelberg photographed in August an irregular nebulous object near the star. Ritchey's photograph of September showed extensive areas of nebulosity in all directions from the star. In October Perrine and Ritchey discovered that the nebular structure had apparently moved outward from the star (see Fig. 19). Going back to a March photograph, taken for a different purpose, Perrine found recorded upon it an irregular ring of nebulosity closely surrounding the star which was not visible on later photographs. The region seemed to be full of nebulosity not visible to us under normal conditions. The rushing of the dark star into and through this resisting medium made the star the brightest one in the northern sky for several days. The great wave of light going out from the star when at this maximum brightness traveled far enough in five weeks to fall upon non-luminous materials and made a ring of nebulosity visible by reflection. Continuing its progress, with a speed of 186,000 miles per second, the wave of light illuminated the material which Wolf photographed far away from the star in August, the material which Ritchey photographed still farther away in September, and the still more distant materials which Perrine and Ritchey photographed in October, November and in later months. We

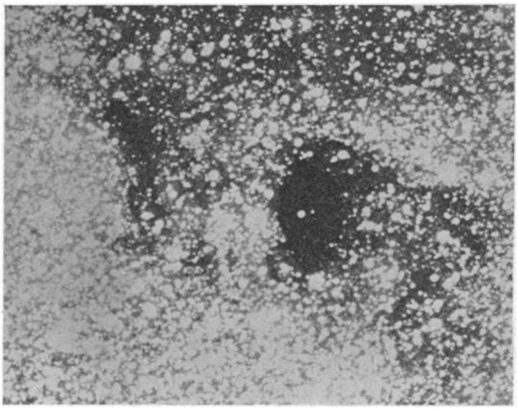


Fig. 17. The Dark Holes, or "Coal Sacks," in Sagittarius, photographed by Barnard with the 10-inch Bruce Telescope of the Yerkes Observatory.

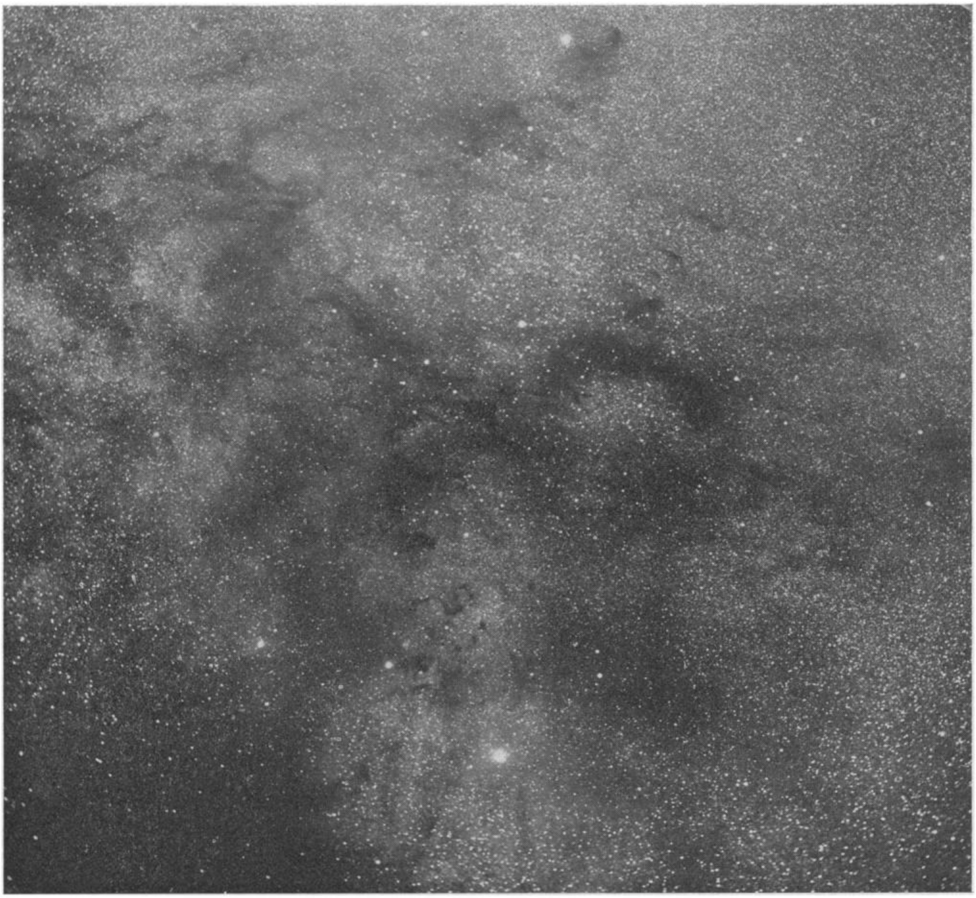


FIG. 18. The Milky Way in Ophiuchus showing apparent absorption or obstruction effects; photographed by Barnard with the 10-inch Bruce telescope of the Yerkes Observatory.

were able to see this material only as the very strong wave of light which left the star at maximum brightness made the material luminous in passing.

We can scarcely doubt, in view of all these facts, that there is a stupendous amount of obstructing material scattered throughout our stellar system. This may eventually be condensed into stars; but the point I wish to emphasize is that the material is there, and is evidently obstructing the passage of light. The efficiency of the obstructing material is no doubt the greater in the long dimensions of the system; in the direction of the Milky Way.

Let us now consider the nebulæ which are not in or near the Galaxy. The overwhelming majority of the stars are in the galactic zone of the sky. If we call this zone 30° wide, which makes it a shade over one fourth the entire sky, we may say that this fourth-area contains certainly three fourths of all the stars known to exist in our stellar system. The remaining three fourths of the sky do not show more than one fourth of all the stars. Of about 15,000 nebulæ recorded probably not over 300,[5] certainly

[5] It is not practicable to state the number more definitely. To illustrate the difficulty, we mention the fact that several small adjoining nebulæ re-

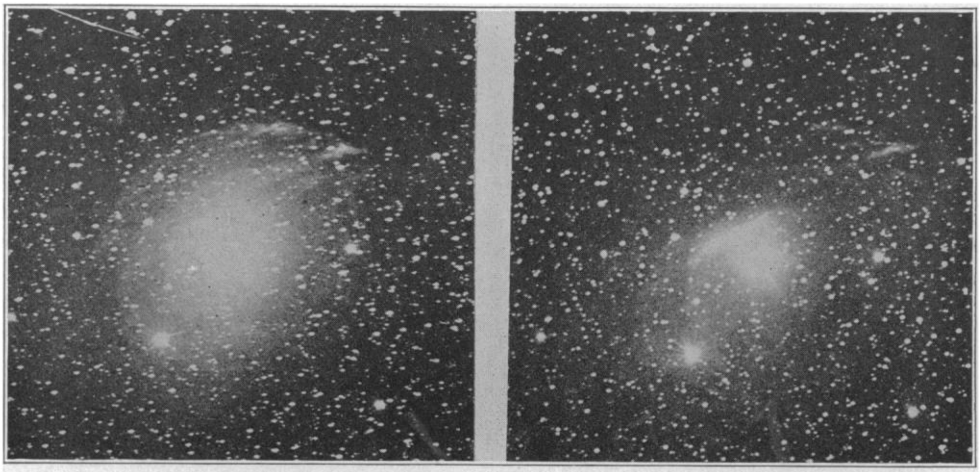


FIG. 19. Apparent movement of nebulous matter about Nova Persei. Photographed by Perrine with the Crossley Reflector of the Lick Observatory.

[The motion is best shown by the bright mass above and to the right of the center, in comparison with the surrounding stars.]

not over 400,[5] are found in the galactic zone. That is, not more than one fortieth or one fiftieth of the known nebulæ are in that one fourth of the sky which contains the Milky Way; and these possible 400 galactic nebulæ include nearly all of the planetary nebulæ, nearly all of the large gaseous nebulæ, nearly all of the regions where large absorbing or obstructing nebulæ are seen to be effective; in other words, as I have endeavored to make clear, nearly all of the nebulæ that are really within our stellar system. The other three quarters of the sky contain, on the contrary, nearly 15,000 recorded nebulæ. The nebulæ to the south of the galaxy have not been so well observed as those to the north, and we shall here consider the northern galactic hemisphere alone. The one quarter of the northern hemisphere immediately around the pole of the Galaxy contains three fourths of all the recorded nebulæ in the whole hemisphere, and the quarter of the hemisphere adjoining the central line of the Galaxy contains about one fiftieth of all the recorded nebulæ in the hemisphere. The density of nebular distribution in the Galaxy is only one fortieth that in the quarter-area farthest away from the Galaxy. A still more interesting fact concerning nebular distribution is this: *thousands of spiral nebulæ are known to exist, but not a single spiral nebula has been found within the galactic structure.* Some spirals have been found in regions adjoining the Galaxy, but they are relatively few. The spirals in particular abhor the Milky Way. As we said above, the very avoidance of the Milky Way seems at first sight to show that they are arranged with reference to it; that they hold some relation to it. Is this relationship real, or only apparent? Are the spiral nebulæ in or attached to our system, or are they outside of our system, at tremendous distances from us? This question is a live one in the astronomy of to-day. The old hypothesis that the unresolved nebulæ are

corded with a short exposure may be seen to be but parts of one great nebula when the exposure is longer.

other great universes of stars very far distant from our own universe of stars is receiving favorable consideration, as far as the spiral nebulæ are concerned. In fact, the related hypothesis that our own stellar system, if viewed from a stupendous distance, would be seen as a spiral nebula, has been seriously proposed and is receiving favorable consideration. There is much merit in the hypothesis that if an observer went very far away from our system, in the direction of one of the poles of the Galaxy, and looked back to our stellar system, he would see it fairly circular in outline, and that the cloud forms which we see in the galactic structure would to the distant observer resemble the ill-defined condensations so characteristic of the outer structure of spiral nebulæ (see Fig. 5). If the observer were at a very great distance outside of our system in the plane of Milky Way extended, we certainly think he would see our system as a greatly elongated ellipse resembling the many well-known spindle nebulæ which are interpreted as spirals seen edgewise (see Fig. 6).

Whether we regard the spirals as very large bodies at enormous distances, far outside and independent of our system, or as within our system and therefore comparatively small bodies close to us, we encounter apparent difficulties of interpretation. These proceed chiefly from their avoidance of the direction of the Milky Way. We are not content to think of this relationship of avoidance as a coincidence or accident of nature. If the spirals are far outside our system, we should expect to see a great many of them in the direction of the Milky Way, but beyond its structure.

We have seen reasons for believing, or at least strongly suspecting, that there is an immense amount of obstructing material in our system, and that this would be the most extensive and the most effective in the long dimensions of our system, and the least effective in the direction of the short axis of the system. If such obstructions are operating effectively upon the light of extremely faint and extremely distant nebulæ, they should produce something like the distribution which we actually observe to exist amongst the spirals.

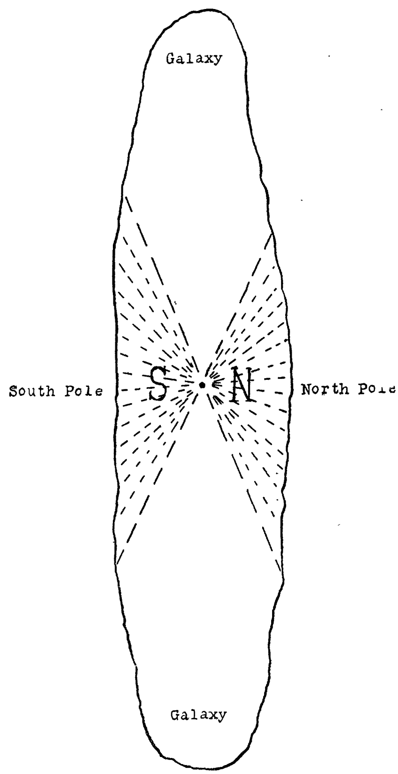


FIG. 20. Hypothetical Cross section of our Stellar System, showing spaces N and S occupied by the spiral nebulæ if they are within the stellar system.

Let us suppose, on the other hand, that the spirals are in our system. Why do we not find them in the Milky Way structure? Why do they absolutely avoid that structure? Why do they congregate around the shorter axis of our stellar system? If they are within our system they must be distributed as to distance and direction somewhat as sketched in the conical volumes N and S in Fig. 20, which represents a cross-section of the stellar system, with the solar system somewhere near its center. This is an assumed distribution which leads straight into difficulties and to some degree of absurdity. We should have to say that the spirals live close to the right of us and close to the left of us, but that they avoid getting between us and the Milky Way structure.

Slipher has measured the motions of approach and recession of more than a score of prominent spirals, and he finds they are moving with speeds surprisingly high, running up to 600 or 700 miles per second, with an average of roughly 250 miles per second. Now, if they are moving at random, which is the probable approximate truth, their average speed at right angles to the line of sight must be still higher, and their average speed in space would be of the order of 500 miles per second. There is no class of objects known to exist within our stellar system which have velocities at all approaching that scale.

Curtis has conducted an extensive investigation to determine whether and how much the principal spiral nebulæ have moved on the surface of the sky in the last fifteen years, on the basis of photographs taken at the beginning and at the end of that period. Lampland and van Maanen have similarly sought for evidences of change of position of three or four spirals. The indications of motion in all these cases are so slight as to leave us uncertain whether the motions of the brighter and larger spirals across the face of the sky in fifteen years have been sufficient for detection. Harmonizing this fact of their vanishingly small angular motions with Slipher's high speeds in miles per second, we conclude that they must be enormously distant, and therefore enormously large bodies.

With the spectrograph, Slipher has been able to measure the rotational speeds of two or three spirals, including the great spiral in Andromeda, and Pease has repeated and extended the experiment on one of them. The rotational speeds are also extremely rapid, as indeed one should expect from the tremendous inequalities in what we venture to call their equatorial and polar diameters. Assuming that Newton's law of gravitation controls their rotations, the probable masses are stupendous. Some of them seem to contain enough material to make tens of thousands, probably hundreds of thousands, and possibly millions, of stars comparable in mass with our own sun.

The spectra of only a few of the brighter spirals have thus far been investigated in any degree of adequacy, but they have the characteristics which we should expect to find if the spirals consist chiefly of multitudes of stars. I say chiefly, because in the spectra of some of them we find the bright-line spectrum of gaseous nebulæ superposed upon what we may call the stellar type of spectrum.

If we carried our spectrograph so far out into space that, looking back, our stellar system would be reduced down to the apparent size of the well-known spiral nebulæ, and we turned the instrument upon our condensed system, we should expect to see a spectrum very like the continuous and absorption-line spectra yielded by the spirals; and certain structures in our system, such as the region containing the Orion nebula, might well yield the bright nebular lines found in some parts of certain spirals. Curtis has recently examined the spectra of fifty of the brighter small nebulæ lying within 25° of the Galaxy which had not been subjected earlier to spectroscopic test. None of them showed bright lines; all appeared to be of the stellar or cluster type of spectrum. An extension of the survey to the pole of the Galaxy would probably have had similar results.

We are not able to resolve the spirals into stars, except as we seem to be ap-

FIG. 21. The Spiral Nebula, Messier 33, photographed by Keeler with the Crossley Reflector of the Lick Observatory.

proaching resolution in certain parts of one great spiral, Messier 33, in the constellation of Triangulum (Fig. 21). That one is probably relatively near us, but of that we are not sure. Some astronomers who have photographed the Magellanic clouds (see Figs. 22 and 23), in the far southern sky, say that these remarkable objects are spiral in structure. If so, they are spirals easily resolved into stars. Nevertheless, these clouds are enormously distant. Hertzsprung has estimated, from certain considerations, that the distance of the Lesser Cloud is of the order of 30,000 light-years. Wilson has measured the spectroscopic velocities of approach and recession of twelve nebulæ in the Greater Cloud, and has found that they are receding with speeds lying between 150 and 200 miles per second. The velocities of the twelve objects differ from each other as many miles per second as we should expect to find for twelve bright-line nebulæ selected at random in our galactic system, but the average for the twelve in the Cloud shows an abnormally high rate of recession. All of the known bright-line nebulæ in that great region of the sky are in the two Clouds. None is known to exist outside of the Clouds until we have gone far from them in the direction of the Milky Way (see Fig. 11). There are still other reasons for the unquestioned conviction that these nebulæ are actually a part of the structure of the Clouds. It is difficult to avoid the conclusion that the observed speed of recession of the twelve nebulæ within the

Fig. 22. The Greater Magellanic Cloud, photographed by Bailey, at the Arequipa, Peru, station of the Harvard College Observatory.

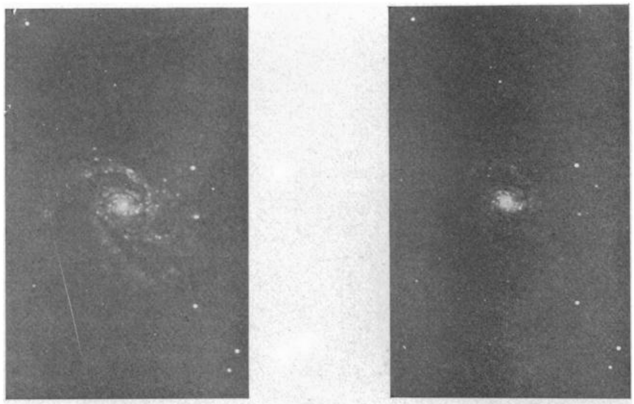
Greater Cloud, averaging 175 miles per second, is the approximate speed of recession of the Greater Cloud. Motions of this magnitude have not been observed for any objects known to be within our stellar system, except in the case of three or four individual small stars. We can not seriously doubt that the Magellanic Clouds are distinct from and independent of our great stellar system; and, if they are of spiral structure, they are spirals relatively near to us, as the distances of spirals go.

Seares has recently discovered an interesting peculiarity of spiral nebula, at least of the four or five thus far studied, by means of photographs of spirals, with exposures first on ordinary plates sensitive to the blue-violet rays, and secondly on isochromatic plates and through screens which transmit only the yellow-green rays. The results, illustrated in Fig. 24, show that the light from the outer arms of the spirals is richer in the blue and violet rays than is the light from the central nuclei. The significance of these facts is not yet clear.

We can not say that the problem of interpreting the spiral nebulæ has been solved. In fact, it is a fair statement that our positive knowledge as to the conditions existing within them is regretfully meager. *We are not certain how far away they are; we are not certain what they are.* However, the hypothesis that they are enormously distant bodies, that they are independent systems in different degrees of development, is the one which seems to be in best harmony with known facts. It should be said that this hypothesis is a very old one. Swedenborg speculated upon the idea that our stellar system is but one of a great number of systems. The serious consideration of the hypothesis, upon the basis of observed facts, may be said to date from the two Herschels. Following Keeler's epoch-making observations of nebulæ in 1898–1900, many astronomers have studied the subject.

We naturally ask why it is that certain globular star clusters are visible not far to one side or the other of the Milky Way, whereas the spirals there are faint and

Fig. 23. The Lesser Magellanic Cloud, photographed by Bailey, at the Arequipa, Peru, station of the Harvard College Observatory.



Seed 27, 20 min. Iso, 2 hours.

Fig. 24. The Spiral Nebula, Messier 99, photographed without and with absorbing color screen, by Seares with the 60-inch reflecting telescope of the Mount Wilson Solar Observatory.

scarce. No one has given a satisfactory answer to this unless it be correct to say that these great globular clusters of stars, though extremely distant, are yet near at hand in comparison with the distances of the spirals. Ritchey's photograph of the great cluster in Hercules (Fig. 25) records fully 30,000 stars, and these are undoubtedly only the more brilliant members of the cluster. Still longer exposures might record 100,000 stars and yet leave unrecorded the fainter members of the cluster in vastly greater numbers. Shapley estimates the distance of this cluster, from several lines of investigation, as of the order of 100,000 light-years. Other great clusters have not been so thoroughly studied, but the available evidence concerning them is in harmony with the hypothesis of their great distances. Our own universe may be enormously more extensive than we see it because the outer stretches of it may be hidden by obstructing materials. If the obstructing materials consist chiefly of discrete particles whose diameters are large in comparison with the wave-lengths of light, we should expect the obstruction to be such as to reduce the brightness of distant objects without changing seriously the quality of their light.

The most elaborate structure yet proposed to explain the origin and development of the solar system is the planetesimal hypothesis by Chamberlin and Moulton. They postulate that the materials now composing the sun, planets and satellites, at one time existed as a spiral nebula, or as a great spiral swarm of discrete particles, each particle in elliptic motion about a central nucleus. The authors go further back and endeavor to account for the origin of spiral nebulæ, but it should be said that this phase of the subject is not vital to their hypothesis. It will happen once in a while, they say, that two massive stars will approach and pass each other closely. These stars will raise great tidal waves upon each other by their mutual attractions, and there will be outbursts of matter from each body, not only on that side of each which faces the other body, but on the opposite side of each, for somewhat the same reason that tidal waves in our oceans are raised on the side opposite the moon as well as on the side toward the moon. They assume that a great star traveling in what is now the principal plane of our solar system passed close to our sun when it was in an earlier stage of its existence; that a resulting disruption of our sun led to the drawing out of solar materials in two opposing spiral branches; and that these materials in part, or for the most part, remained outside of the sun and in revolution about it, the whole composing a spiral nebula. The materials in the two branches of the spiral, the authors say, eventually combined into certain central

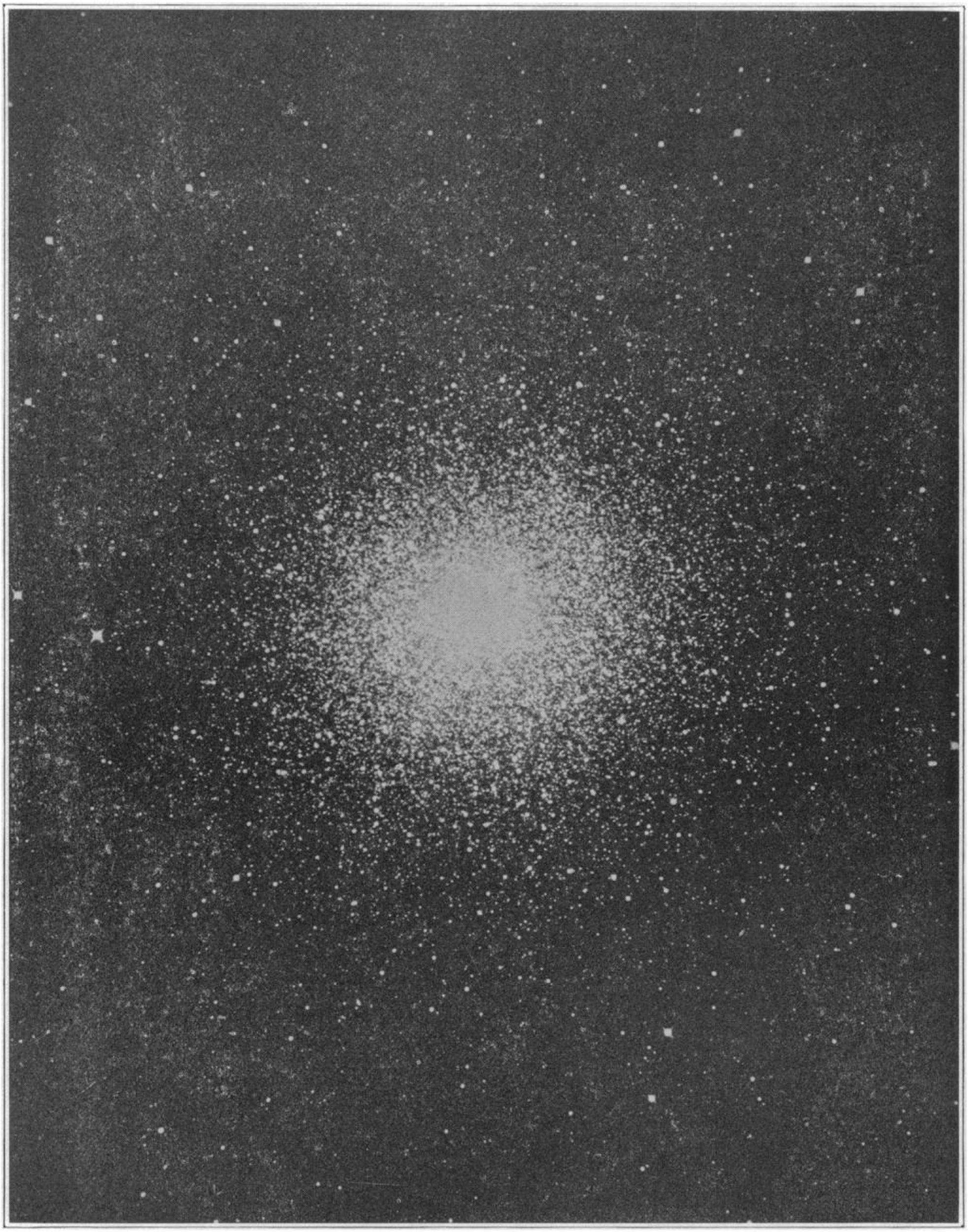


Fig. 25. The Great Star Cluster in Hercules, photographed by Ritchey with the 60-inch reflecting telescope of the Mount Wilson Solar Observatory.

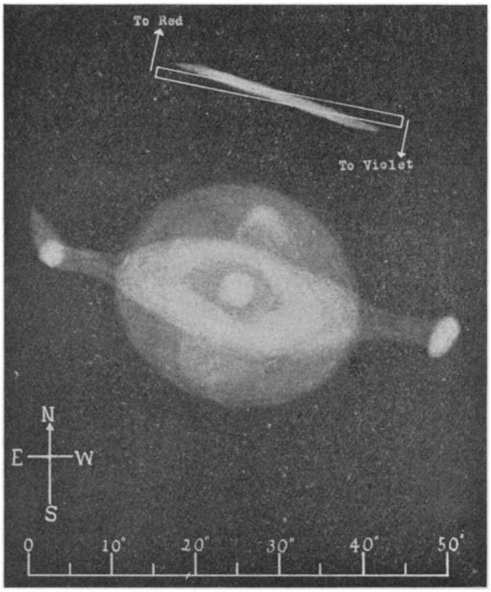


FIG. 26a. Planetary Nebula N.G.C. 7009. Composite drawing by Curtis from photographs made with the Crossley Reflector of the Lick Observatory. With the slit of a 3-prism spectrograph placed on the longer axis, the bright nebular lines were found to be inclined to the direction of the slit, owing to the rotation of the nebula, as shown (exaggerated) in the upper part of this figure, and as reproduced from the spectrogram in Fig. 26b.

masses, in accordance with the simple laws of physics, and the planets and their satellites of our system, as they exist to-day, are the result.

I see no reason to question that a spiral nebula could originate in this manner: the close passage of two massive stars could, in my opinion, produce an effect resembling a spiral nebula, quite in accordance with Moulton's test calculations on the subject. Some of the spirals have possibly been formed in this way; but that the tens of thousands of spirals have actually been produced in this manner is another question, and one which, in my opinion, is open to grave doubt. The distribution of the spirals seems to me to negative the idea. If the close approaches of pairs of stars are producing the spirals we should expect the spirals to occur and to exist preeminently in and near the Milky Way structure, for that is where the stars are; and that is precisely where we do not find the spirals.

I think it is more probable that our stellar system as a whole is a spiral nebula, or has analogies to a spiral nebula, and that our solar system has been formed from an insignificant detail of spiral structure, than that our sun and its system of planets and moons should be the evolved product of an entire spiral nebula. Of course we have not

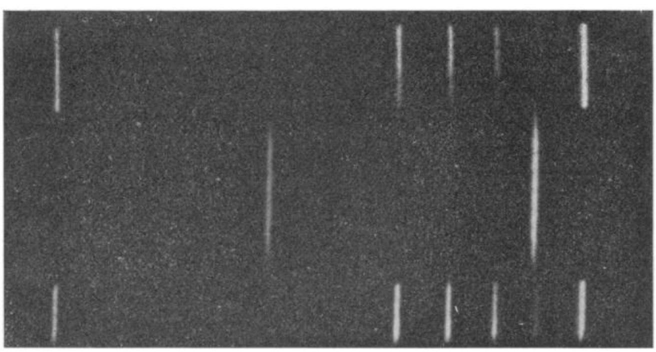


FIG. 26b. The First (right) and Second (left) Green Lines of Nebulium in the Spectrum of N.G.C. 7009.

[Enlargement approximately 20-fold. The six lines at the upper and lower edges of the figure are the reference spectrum of titanium.]

the proof of this; but the chances would appear to be strong that the ancestor of our solar system was a mass, nebulous or otherwise, comparatively diminutive in size.

There seems to be no reason to doubt the value of Herschel's opinion that a planetary nebula will develop into a star. Laplace's hypothesis that our solar system has

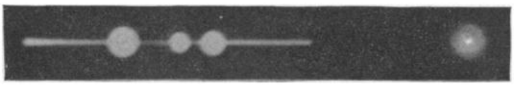


FIG. 27. Visual Image (right end) and Part of Visual Spectrum (left end) of the Planetary Nebula N.G.C.$_2$ 418.

[The horizontal line in the left half of the figure is a part of the continuous spectrum of the stellar nucleus of the nebula at the right end. Of the three white circles in the spectrum the left one is the hydrogen Beta image of the nebula 14 sec. of arc in diameter, the middle circle is the "second nebulium" green image of the nebula 9 sec. of arc in diameter; and the right one is the "first nebulium" green image of the nebula, 11 sec. of arc in diameter.]

developed from a small rotating nebula is still exceedingly valuable, but it has been so buffeted by the winds and waves of criticism that many of the details have had to be thrown overboard. I think we should give ourselves some assurance that certain of the planetary nebulæ may develop into systems bearing many resemblances to our solar system. Campbell and Moore have been able in the past year and a half to prove, by means of the spectrograph (see Figs. 26*a* and 26*b*), that these bodies are in rotation—just as we should expect them to be from their more or less symmetrical forms—around axes passing through their centers; these axes, in general, at right angles to their longest dimensions. The rotation of our sun and the revolution of our planets about the sun, all in one and the same direction and very nearly in the principal plane of the system, afford a close analogy.

The rotational velocities of the gases composing the principal rings in the planetary nebulæ are comparable with the orbital speeds of our great planets, Jupiter, Saturn, Uranus and Neptune; and the rotational speeds of the gases are slower and slower as we go out from the principal rings, which is true of the orbital speeds of the planets of our system.

It appears that there is very little material between the stellar nuclei and the principal rings of the planetaries. The material which we should normally expect to find there has apparently been drawn into the central stars. Very little material is left in that space to condense into planets, just as in our solar system the four inner planets, Mercury, Venus, earth and Mars, and the many asteroids, are of almost negligible mass. Jupiter and the other three outer planets contain 225 times as much matter as the earth and the other three inner planets and the more than 800 asteroids.

If we assume that the rotational speeds of the particles composing the rings and other outer structure of the planetary nebulæ are controlled by Newton's law of gravitation, we have means of estimating the masses of their central nuclei, or stars. The indications are extremely strong that the planetary nebulæ are in general at least as massive as our solar system: many times as massive in some cases, possibly less massive in others. In them we seem to have enough materials to develop into systems comparable in mass with our solar system.

More than twenty years ago I observed that the different gases composing several of the nebulæ are not uniformly distributed throughout the nebular structure. The hydrogen in some of the nebulæ that were

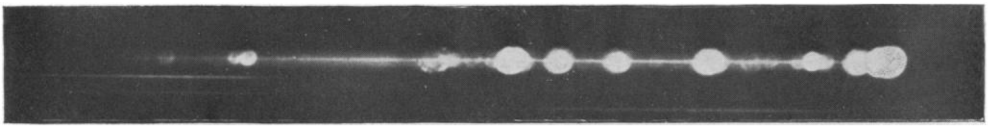


FIG. 28. The Spectrum of the Planetary Nebula N.G.C. 7662, photographed by Wright with the Draper slitless quartz spectrograph and the Crossley reflecting telescope of the Lick Observatory.

[The images of the nebula given by the radiations of different elements and different wave-lengths show a great variety of diameters and structural details. The two ellipses at the extreme right, strongly overlapping, are the two green nebulium images of the nebula. The adjoining smaller ellipse, slightly overlapping, is the hydrogen Beta image. The small images at the left end of the figure are far out in the ultra-violet region of the spectrum.]

critically examined was found to extend out farther than do the other chemical elements. Such was the case in the great Orion nebula, in the Trifid nebula, and in one of the small planetaries, N. G. $C._2$ 418. Viewed in the telescope, the latter was observed to be a disc of greenish-blue light, about fourteen seconds of arc in diameter, with a well-defined star near the center of the disc. Viewed in the spectroscope, the spectrum of the central star was a continuous line of light, and the composite disc was resolved into three separate discs (see Fig. 27); the largest one of hydrogen, fourteen seconds of arc in diameter; a smaller one, corresponding to the first green line of the element nebulium, eleven seconds of arc in diameter; and a still smaller one, corresponding to the second line of nebulium, nine seconds of arc in diameter. The nebulium did not extend out so far from the central star as the hydrogen. Wolf and Burns applied photographic methods to a similar study of the Ring Nebula in Lyra, in 1908 and 1910, respectively, and found differences both in the sizes and in the detailed structure of the spectral rings. Wright has in the past two years carried the development of the subject much further, by photographic methods applied to the principal planetary nebulæ (see Fig. 28). He finds, for example, that the distribution of the helium in the structure of the planetary nebulæ always favors the central nucleus or star more than the hydrogen and nebulium distribution do. In some of the planetaries, the helium has apparently been drawn entirely into the central nucleus. In one of the planetaries the hydrogen globes seem to persist brilliantly after the nebulium images have become reduced in size, or have become exceedingly faint. We can scarcely doubt that in these phenomena we are witnessing certain stages of progress in the gradual evolution of the planetary nebulæ into the stars which we see at their centers, or, possibly, into systems of stars and planets. The materials, for the most part, seem to have been drawn —possibly are still moving—into the central stars, into suns that are forming; and a very little of the materials shown by observation to be revolving around the central suns may ultimately be left to form planets of the systems. Let us recall that in our own solar system 99 6/7 per cent. of the materials are in the sun, and that only one seventh of one per cent. of the materials exists outside of the sun, in the eight major planets and their moons.

The different sizes of the elliptic images of different chemical elements in the spectrum of a planetary nebula give some basis for the speculative thought that the chemical composition of the large outer planets of our solar system may be quite different from that of the small inner planets.

While a strong case can be made out for

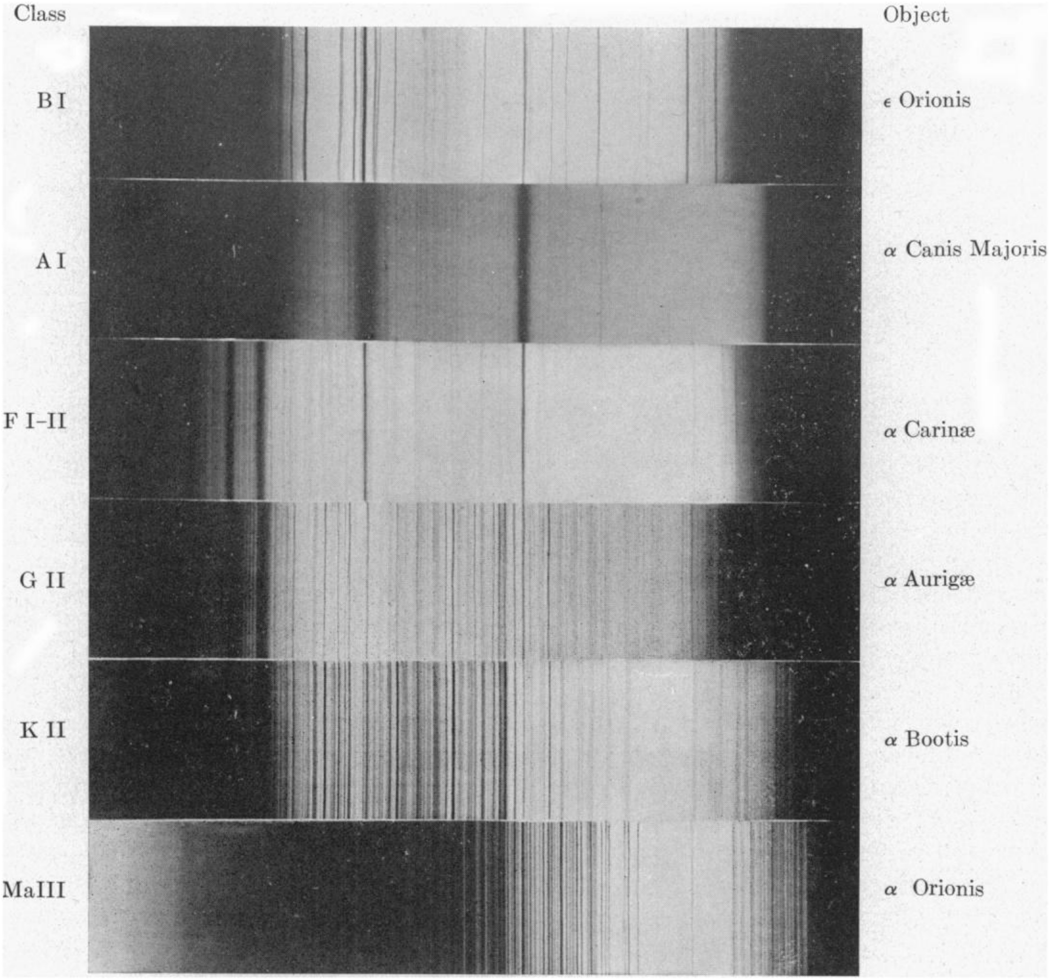


Fig. 29. Types of Stellar Spectra, Henry Draper Memorial, Harvard College Observatory.

the evolution of planetary nebulæ into stars at their centers, with possible planets revolving around them, we must not conclude that all stars have been formed from planetary nebulæ. There are reasons for rejecting that view.

1. Amongst the many millions of stars whose images have been examined in the telescopes or on photographic plates, fewer than 150 planetary nebulæ have been found. Unless the planetary-nebula stage of existence is lived very rapidly, the numbers are too few to play a controlling part in the development of stars in general at any point in stellar evolution.

2. The average speeds of the planetary nebulæ and of the different classes of stars are now fairly well defined. The average speed of the planetary nebulæ is about seven times that of the extremely blue stars, which are the only ones, we shall see later, that we need consider as the immediate descendants of the nebulæ. There are indeed individual stars which are traveling as rapidly as the individual planetary nebulæ, but on the average the discrepancy

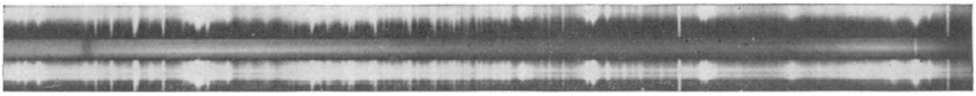


FIG. 30. The Spectrum of Alcyone, photographed by Wright with the Mills Spectrograph of the Lick Observatory.

[The star spectrum occupies the central horizontal section. The bright hydrogen Alpha line is one fourth inch from the right end, and the dark hydrogen Beta line is one half inch from the left end.]

seems entirely too great to let us conclude that the blue stars in general could have been formed from planetary nebulæ such as the 150 planetaries now known to us.

For the hypothesis that the stars in general have evolved from irregular nebulæ a vastly stronger case can be made.

In a priceless possession of astronomy, the Draper catalogue of stellar spectra, Harvard College Observatory has classified the spectra of a great many thousands of the brighter stars. They have been arranged in a sequence, running from the so-called extremely blue stars through the yellow stars to the red stars, which can be readily described. The main divisions are illustrated in Fig. 29. Each main class has ten subdivisions, but we need not dwell upon details. The dark lines in these spectra indicate the presence of certain vapors and gases of the chemical elements in the outer strata of the stars. In the Class *B* stars the helium lines rise to their maximum strength near the middle of the *B* subgroups and sink to insignificance in the later *B* or earlier *A* subdivisions, and the helium lines are not found at all in Class *F* and the later types. The hydrogen lines are fairly prominent in the Class *B* stars, but they increase to maximum intensity in Class *A*, and then decrease continuously throughout the remaining groups. The hydrogen lines are very inconspicuous in Class *M*, or red stars. The magnesium lines go up to a maximum in Class *A* and down to disappearance in the *F*'s and *G*'s. Some of the metallic lines, such as titanium and iron, usually begin to show in the later subdivisions of Class *A*, other metallic lines first enter upon the scene in Class *F*, and they increase in numbers and prominence up to a maximum in the red stars. The calcium lines are weak or entirely wanting in the Class *B*'s, and they increase in intensity as we pass down through the series, until they become the most prominent features in the spectra. We can not change the arrangement of these spectral classes without throwing the sequence of development of the spectral lines into hopeless disorder. This sequence is thought to represent the order of stellar evolution. A Class *B* star, according to that hypothesis, is a comparatively young star. It should develop, in the course of long ages, into an *F*, a *G*, a *K*, an *M*, and so on, to its final destination of darkness and invisibility.

Some of the Class *B* stars contain bright lines of hydrogen. Alcyone (Fig. 30) and Pleione, in the Pleiades, contain both bright

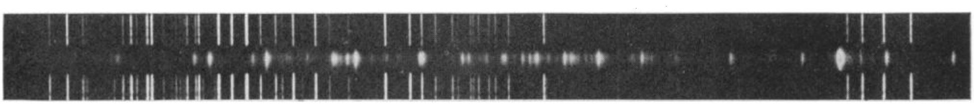


FIG. 31. The Spectrum of Eta Carinæ, photographed by Moore at the D. O. Mills Observatory Santiago, Chile.

[The series of bright lines above and below the star spectrum are the reference spectrum of iron.]

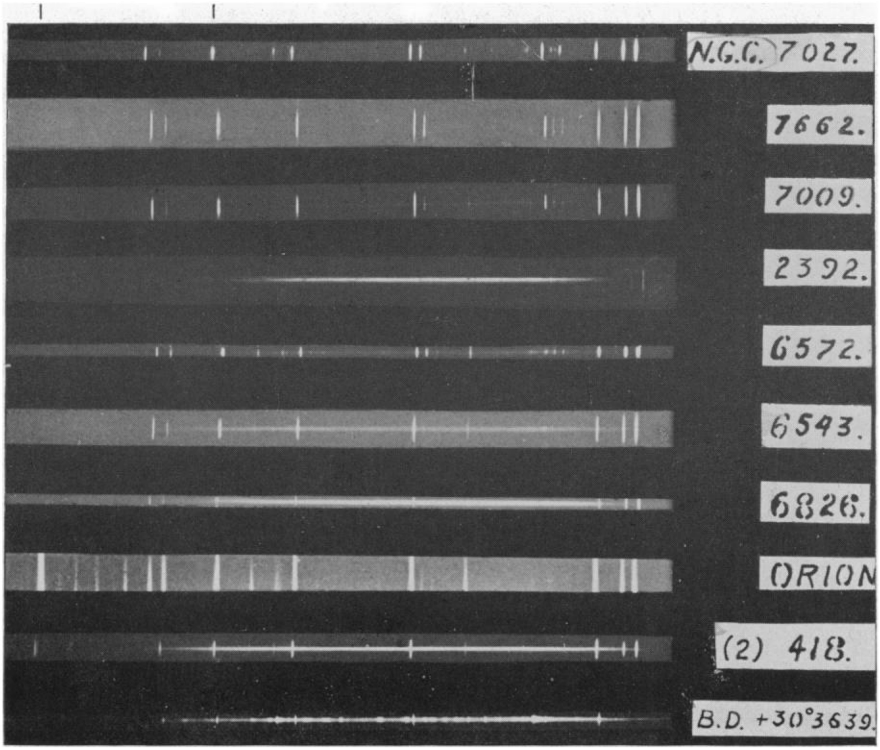


Fig. 32. Representative Spectra of Bright-line Nebulæ, photographed by Wright with the Mills spectrograph and 36-inch refracting telescope of the Lick Observatory.

and dark lines of hydrogen. There are hundreds of stars whose spectra contain a wide variety of bright lines and dark lines. Now and then a star's spectrum consists almost wholly of bright lines, as in the case of Eta Carinæ (Fig. 31). The bright lines in stellar spectra tell us that their stars contain extremely extensive atmospheres of the gases and vapors hydrogen, helium, and so on. A close relationship exists between the Class *B* stars, with and without bright lines, and a class of stars found extensively in the Milky Way structure whose spectra, containing many bright lines, are known as Wolf-Rayet spectra, after the discoverers of the first few stars in the class. Now, as Wright has shown, the central stars in the planetary nebulæ are of the Wolf-Rayet type (see Fig. 32, B.D + 30° 3639) in nearly all cases, and in other cases their spectra are closely related to Class *B* spectra (see Fig. 32, N.G.C. 2932). It has been shown, also chiefly by Wright, that the spectra of the nebulous parts of the planetary nebulæ have many points of connection with the spectra of their central stars. The spectra of the planetary nebulæ and the spectra of those large extended nebulæ (see Fig. 32, Orion, etc.) which give bright lines are essentially alike in character. The nebulium lines of the nebulæ have never been found to exist in any true star, no matter what its class, and we leave them out of account in this discussion; they do not influence our present question one way or the other. Aside from nebulium, the hydrogen and helium lines are the most prominent ones in the bright-line nebulæ. They are the most prominent ones in the nuclei of the planetary nebulæ. They are prominent in the isolated Wolf-Rayet stars, in the Class *B* stars containing bright lines, and in the

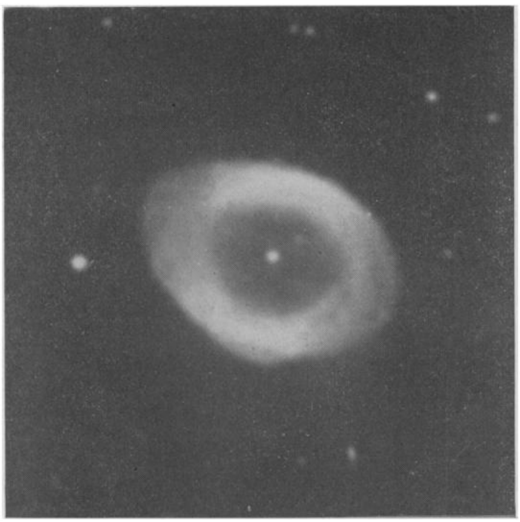


FIG. 33. The Ring Nebula in Lyra, photographed by Curtis with the Crossley Reflector of the Lick Observatory.

Class *B* stars containing only dark lines. Helium has never been found in any yellow or red stars, except feebly in a certain stratum of our sun's atmosphere, and that is due to our ability to observe our sun somewhat in detail; and the hydrogen is relatively feeble in the later classes of the Harvard sequence.

The continuous spectra of stars as arranged in the Harvard sequence decrease continuously in the relative strength of the blue, violet and ultra-violet regions as we pass from the central stars of the planetary nebulæ, which are wonderfully strong in ultra-violet light, down through the blue stars with both bright and dark lines, through the blue stars[6] containing dark lines only, and on through the yellow stars to the red stars. The central star in the ring nebula in Lyra (Fig. 33) is invisible to many inexperienced observers, even in the great Lick telescope. Yet it is so rich in violet light, and especially in ultra-violet light, that it can be photographed in the great reflecting telescopes with an exposure of only two or three seconds. Wright has recently made the interesting discovery that the continuous spectra of many planetary nebulæ are remarkably strong in a long stretch of the ultra-violet region. The sequence of decreasing richness in blue and violet light extends unbroken from the nebulæ and nebular nuclei down to the red stars.

The spectra of the stars are indicative of conditions existing in their surface strata. We do not know definitely just what conditions produce or accompany certain types of spectra, but surface temperature seems to be a prime influence, and there are some reasons for thinking that electrical conditions may also be extremely important. Now all determinations of the surface temperatures of the stars make the extreme blue-violet stars the hottest of all, with the effective temperatures decreasing continuously as we pass from the nuclear stars of the planetary nebulæ down through the Harvard sequence to the red stars. Fabry and his associates in Marseilles have recently arrived at the result, by physical methods, that the temperature of the Orion nebula is very high, vastly higher than the temperatures of the red and yellow stars,

[6] Huggins has called attention to a reduction in the brightness of the ultra-violet spectrum of the first-magnitude star Vega (Class *A*) by virtue of what seems to be an absorption band many hundred Angstrom units in width. It is not yet known to what extent the ultra-violet spectra of blue stars in general may be affected by such an absorption band.

and comparable with the temperatures of the blue stars. There again is a sequence with the nebulæ and the blue stars at one end and the red stars at the other.

Fowler has called attention to the remarkable facts that certain lines of helium, etc., requiring the most powerful electric discharges at command to produce them in the laboratory—super-spark lines, he calls them—are found in the greatest relative strength in the gaseous nebulæ; next in order of strength in the bright-line or Wolf-Rayet stars, which class includes the central stars of the planetary nebulæ; and in lesser strength in the first subdivision of the Class *B* stars, that is, in the bluest of the blue stars containing dark lines only; secondly, that the lines in the spectra of the later Class *B* stars, of the Class *A* and Class *F* stars are prevailingly those produced under the less intense conditions of the ordinary electric spark; and, thirdly, that the lines in the yellow-red stars are prevailingly the arc lines which indicate relatively weak electrical conditions. That is another sequence of conditions running from the nebulæ down to the red stars.

There are still other sequences running harmoniously through the Harvard classification. For example, the velocities of the stars in their travels within the stellar system increase as we pass by spectral classes from the large bright-line nebulæ and the very blue stars down through the yellow stars to the red stars. The distances apart of the two components of double stars, and consequently their periods of revolution

FIG. 34. The Irregular Nebulæ near Gamma Cassiopeiæ, photographed by Curtis with the Crossley Reflector of the Lick Observatory.

[The immensely over-exposed image of the brilliant star Gamma Cassiopeiæ is at the lower left-hand corner. The lines radiating from the center of the star image are diffraction effects produced within the telescope. The upper right half of the figure contains much nebulosity, the brighter angles of two nebular structures pointing approximately toward the star Gamma.]

around each other, increase consecutively as we pass from the blue stars to the red.

It might be said that, so far as all these stellar sequences are concerned, the course of evolution could begin with either the red stars or the blue stars and proceed to the other end of the sequence. Not to mention several very weighty objections to the assumption that the red stars are effectively young and the blue stars effectively old, we submit the case on the evidence of the nebulæ. The planetary nebulæ, the irregular nebulæ, the Wolf-Rayet stars, the Class *B* stars with bright lines, and the Class *B*

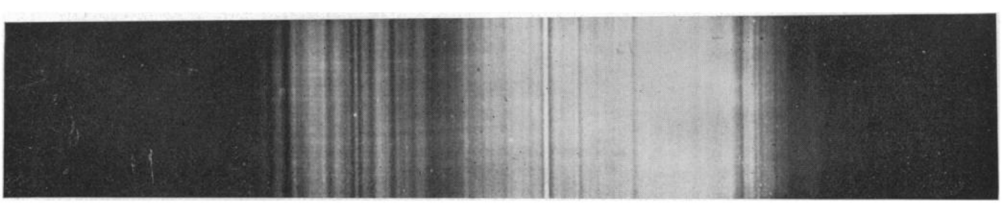


FIG. 35. The Spectrum of Gamma Cassiopeiæ, Henry Draper Memorial, Harvard College Observatory.

stars with dark lines are found prevailingly in and near the Galaxy. Pickering's study of the distribution of 6,106 of the brightest stars is summarized in the accompanying table.

GALACTIC LATITUDES OF STARS BRIGHTER THAN 6.25

Average Latitude	*B*	*A*	*F*	*G*	*K*	*M*	All
+ 62°.3.....	8	189	79	61	176	56	569
+ 41°.3.....	28	184	58	69	174	49	562
+ 21°.0.....	69	263	83	70	212	57	754
+ 9°.2.....	206	323	96	99	266	77	1,067
− 7°.0.....	161	382	116	84	239	45	1,027
− 22°.2.....	158	276	117	100	247	69	967
− 38°.2.....	57	161	94	59	203	59	633
− 62°.3. ...	29	107	77	67	202	45	527
Sums........	717	1,885	720	609	1,719	457	6,106
Means......	90	236	90	76	215	57	763

The sky is divided into eight zones of equal areas, with the boundaries of the zones parallel to the galactic plane. The first line of figures contains the numbers of stars of the different spectral classes in the one eighth of the sky around the north pole of the Galaxy; the fourth and fifth lines the numbers in the zones containing the Galaxy, one zone adjoining the Milky Way on the north and the other on the south; and the last line the numbers of stars of the different classes in the eighth of the sky around the south pole of the Galaxy. If the stars of the different classes were uniformly distributed over the sky, the eight numbers in each vertical column would be equal. It is seen that the Class *B* stars are prevailingly in the Milky Way, and that the red stars of Class *M* are about uniformly distributed over the sky, though they are all in our stellar system.

The Class *B* stars and the stars containing bright lines are where the planetary and irregular nebulæ exist. Going further into detail: wherever there is a great nebulous region either in, or near, or outside of the Milky Way you will find the Class *B* and earlier types of stars abnormally plentiful; and the chances are fairly strong that some of the stellar spectra will contain bright lines. This is true of great regions in the Milky Way, it is true of the Orion and Pleiades regions, which we see at some distance outside of the Milky Way structure, though they are doubtless within our system. If you see a wisp of nebulosity near a bright star, look up the star's spectrum and you will probably find it an early Class *B*, as in the case of Gamma Cassiopeiæ, a second magnitude star, with nebulous structure near it (Fig. 34), whose spectrum contains both bright and dark lines of hydrogen and helium (Fig. 35). If you see an isolated bright star apparently enmeshed in an isolated patch of nebulosity, such as the one shown in Fig. 37, and the books say the star (*BD*–10°-4713) is yellow, or of Class *G*, communicate your suspicions that the books are mistaken about that star's spectrum to Professor Pickering, and he will probably reply that the star is in reality a very blue one, of early Class *B*. That is what happened a fortnight ago about this particular nebula and the star near its apparent center. If you find a red or yellow star of normal type, do not look for a nebula in apparent contact with it. Nebulæ and red stars do not coexist. You will find about the same number of red stars in the Milky Way that are visible in similar areas far from the Milky Way. You will find an occasional red star in the region of the Orion nebula and of other large nebulæ, but red stars will not appear there in greater numbers than their approximately uniform distribution over the sky requires.

The connection between the nebulæ and the bright-line stars, and between the nebulæ and the early Class *B* stars is close, both as to their types of spectra and as to their geometric distribution.

Do the nebulæ form stars or do the stars form nebulæ, or both? There is abundant evidence that the catastrophes which produce new or temporary stars produce temporary nebulæ, for at a certain stage of their existence the temporary stars have nebular spectra; but in all cases thus far observed—as Adams has shown—the nebular spectrum quickly transforms itself into the Wolf-Rayet stellar spectrum. It is not impossible that the planetary nebulæ have in some cases resulted from the more violent catastrophes of distant space and time; that bodies originally stars may have been expanded under the heat of collision or other catastrophe to nebular conditions; but that an ultimate condensation will transform such nebulæ again into the stellar state, we can not doubt. That such nebulæ as those in the Pleiades (Fig. 13) or as the great Net-Work nebula in Cygnus (Fig. 36) were formed from stars can not be regarded with favor for a moment; but that the many Class *B* stars existing in those regions should have been formed from nebulous matter, and that others may be forming, implies an evolutionary process that is both natural and easy of comprehension. Transformation from star to nebula is abnormal, is *rev*olution, under the influence of catastrophe. Transformation from nebula to star is normal, is *ev*olution, under the continuous and regular operation of the simple laws of physics.

Fig. 36. The Net-work Nebula in Cygnus, photographed by Keeler with the Crossley Reflector of the Lick Observatory.

FIG. 37. The Milky Way, photographed by Barnard with the Bruce 10-inch telescope of the Yerkes Observatory.

[Of special interest is a small isolated nebula with a fifth magnitude star, BD — 10° 4713, near its center; nebula and star in the region poor in stars near the center of the photograph.]

Those who would suggest that the red stars[7] may be the young stars must start with stars uniformly distributed over the sky, and unassociated with nebulosity; and, transforming them through and past the red and yellow stages, must carry them prevailingly into the galactic regions, where, as Class *B*, or extremely blue stars, they

[7] This does not include the extremely red (Harvard Class *N*) stars. We refer to the 457 naked-eye red stars of Class *M* in Pickering's table, page 507, which are prevailingly the more massive members of their spectral class.

preferentially collect in the great nebulous areas, or, in many cases, become enmeshed in details of nebulous structure. We should pause long and consider well before embarking upon a voyage in that direction.

Long centuries of ignorance as to our surroundings gave way, finally, to the enlightening influence of the discovery of the place of the continents upon the earth, and of the place of our planet with respect to the sun. Working at peace and under extreme encouragement, the astronomers of to-day are learning the place of our star and its planets amongst the other stars. If the Magellanic Clouds, the greater globular star clusters, and the spiral nebulæ prove to be separate and independent systems, we shall bequeath to our successors the mighty problem of finding the place of our great stellar system amongst the host of stellar systems which stretch out through endless space.

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