THE ADOLFO STAHL LECTURES IN ASTRONOMY

CORRECTIONS TO THE ADOLFO STAHL LECTURES IN ASTRONOMY.

In order to avoid a possible misunderstanding regarding the nature of the tests made upon the 100-inch mirror during the process of figuring, the following modification of the wording of the description contained in the third paragraph on page 250 of the *Adolfo Stahl Lectures in Astronomy,* is suggested:

". . . .Visual optical tests were made each morning after a day's figuring; frequently repeated tests on different days were necessary before figuring could be resumed. These tests were made both at the center of curvature and at the focus of the paraboloid; the former method is better for determining the figure of the mirror as a whole, while the latter test is invaluable for detecting and correcting zonal errors in the general curvature. At intervals during the figuring the Hartmann method of testing was also used, the measurements of the photographic plates by Mr. Adams furnishing explicit data regarding the figure of the mirror. . . ."

In referring to the black notch in the nebula extending south from *Zeta Orionis*, the statement is made, on page 167, that "This particular marking has not, so far as I am aware, been photographed before." Professor Barnard, in a kindly letter, has given me references to several earlier photographs showing this feature, including one by Dr. Isaac Roberts taken January 25, 1900, and reproduced in the *Astrophysical Journal,* Vol. 17, Plate IV, p. 76; and one by himself, reproduced in the negative form in Vol. 38, Plate XX, p. 496, of the same journal. The earliest photograph on which it can be detected appears to be one taken at Harvard on February 6, 1888, by Professor W. H. Pickering (Harvard Annals, Vol. 32, Plate III, Fig. 3.).

The caption for Figure 9, p. 128, should read "Eratosthenes' Method of Determining the Size of the Earth."

In Figure 14, p. 183, the letter *V* and the words *Line of Equinoxes* should be stricken out. The horizontal line may be assumed to be the intersection of the plane of the ellipses with the plane of the Earth's orbit, or the line of nodes.

R. G. Aitken.

THE ADOLFO STAHL LECTURES IN ASTRONOMY

THE SOLAR CORONA, JUNE 8, 1918.

From a photograph with the 40-foot camera of the Crocker Eclipse Expedition of the Lick Observatory to Goldendale, Washington. Exposure, 0^m 21^s to 25^s of totality. South is at the left, west at the top. See page 67, footnote.

THE ADOLFO STAHL LECTURES IN ASTRONOMY

DELIVERED IN SAN FRANCISCO, CALIFORNIA, IN 1916-17 AND 1917-18, UNDER THE AUSPICES OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC

SAN FRANCISCO
1919

PRINTED FOR THE SOCIETY
BY THE STANFORD UNIVERSITY PRESS

DEDICATION

TO MY ILLUSTRIOUS FRIEND, MANUEL ESTRADA CABRERA, THESE LECTURES ARE DEDICATED. AS PRESIDENT OF THE REPUBLIC OF GUATEMALA HIS LOFTY AIM HAS BEEN TO RAISE THE STANDARD OF EDUCATION AND LITERARY ACHIEVEMENTS. HIS ENERGY HAS BEEN DEVOTED WHOLEHEARTEDLY TO ESTABLISHING SCHOOLS OF EVERY DESCRIPTION EVEN IN THE REMOTEST PARTS OF HIS COUNTRY; LEARNING OF ANY TYPE WHATSOEVER HAS AT ALL TIMES HAD HIS UNLIMITED SUPPORT. TO WHAT MORE DESERVING PERSON, THEREFORE, COULD ANY LECTURES WHICH HAVE AS THEIR OBJECT THE DIFFUSION OF KNOWLEDGE, BE PRESENTED?

Adolfo Stahl

PREFACE

From the time of its organization in 1889, the chief object of the Astronomical Society of the Pacific has been to stimulate interest in astronomy among the people of the Pacific region by giving to discoveries and advances made in that science the widest publicity through the medium of its *Publications* and, more directly, by means of public lectures. In harmony with this policy, plans were made early in the autumn of 1916 for a course of lectures to be given in San Francisco by members of the staff of the Lick Observatory, in the season of 1916-1917.

When the question of securing financial support for this undertaking arose, a public-spirited citizen of San Francisco, Mr. Adolfo Stahl, came forward and offered the Astronomical Society a sum of money amply sufficient to cover all the necessary expenses of the proposed course. Mr. Stahl imposed no conditions upon his gift except that the lectures should be given in San Francisco, that they should be adapted to the understanding of all intelligent people, and that they should later be printed in the Society's *Publications* or elsewhere.

Mr. Stahl's offer was gratefully accepted by the Society and it was voted that the course of lectures be known as THE ADOLFO STAHL LECTURES IN ASTRONOMY. It was further voted that, in recognition of this gift, Mr. Stahl be elected a patron and a life member of the Society.

The lectures were given, as originally planned, by Director W. W. Campbell and Astronomers R. G. Aitken and H. D. Curtis of the Lick Observatory, in Native Sons' Hall, San Francisco, in November and December, 1916, and January, February, March, and April, 1917.

Since it was clearly Mr. Stahl's desire that the lectures should be an educational influence in San Francisco, special efforts were made to direct the attention of the teachers and pupils in the schools of the city to the opportunity he had provided for securing information concerning the worlds of outer space. That the opportunity was appreciated was evident from the large attendance at all six of the lectures.

The directors of the Astronomical Society were gratified by the interest thus shown by the public and were delighted when Mr. Stahl most generously offered to repeat his gift, to provide for a second series of lectures, to be delivered in the season 1917-1918 under the same conditions as the first course.

The committee on the ADOLFO STAHL LECTURES IN ASTRONOMY invited members of the staff of the Solar Observatory, Mount Wilson, and of the staff of the Students' Observatory, Berkeley, to give the six lectures of the second course. The astronomers of these two institutions cordially accepted the invitations and the first two lectures of the course were given in Native Sons' Hall, San Francisco, in November and December, 1916, by Professor R. T. Crawford, of the Students' Observatory, and Astronomer C. E. St. John, of the Solar Observatory. The sudden and serious illness of one of the other lecturers required a change in the rest of the program, and, to meet the emergency, Astronomer R. G. Aitken, of the Lick Observatory, gave the lecture in January, 1918. The lectures in February, March, and April, 1918, were delivered by Professor A. O. Leuschner, Director of the Students' Observatory, and Astronomers F. H. Seares and G. W. Ritchey, of the Solar Observatory.

The interest shown by the public in the preceding year continued, notwithstanding the general unrest created by the entry of our country into the world war; and this interest was manifest not only at the times when the lectures were delivered, but also in the numerous requests received by the Society that the lectures be collected and published in book form.

These requests were carefully considered by the directors of the Society, and the chairman of the Publication Committee was instructed to prepare an estimate of the cost of publishing such a volume. The estimate was placed before Mr. Stahl in July, 1918, and he was pleased to stand sponsor for the Society in the matter.

The editorial responsibility for the volume has devolved upon me, but, with one exception, the lectures have been revised by their authors, thus lightening the burden. It is a pleasure to acknowledge here the indebtedness of the editor and of the Society to the University of Chicago Press, the Yale University Press, the Macmillan Company, Mrs. Isaac Roberts, and the directors and astronomers of the Lick, Lowell, Mount Wilson, and Yerkes observatories for their courtesy in supplying many of the photographs or half-tone blocks used in the illustrations for the volume.

It is the editor's privilege to express in this place the high appreciation in which Mr. Adolfo Stahl's generous gifts are held, not only by the directors and members of the Astronomical Society of the Pacific, but also by all those who found pleasure in the lectures his generosity provided. We recognize that in making these gifts Mr. Stahl has been influenced primarily by the desire to contribute to the advancement of the intellectual life of his chosen city; but we trust that in their present form the STAHL LECTURES may also appeal to lovers of astronomy everywhere.

R. G. AITKEN

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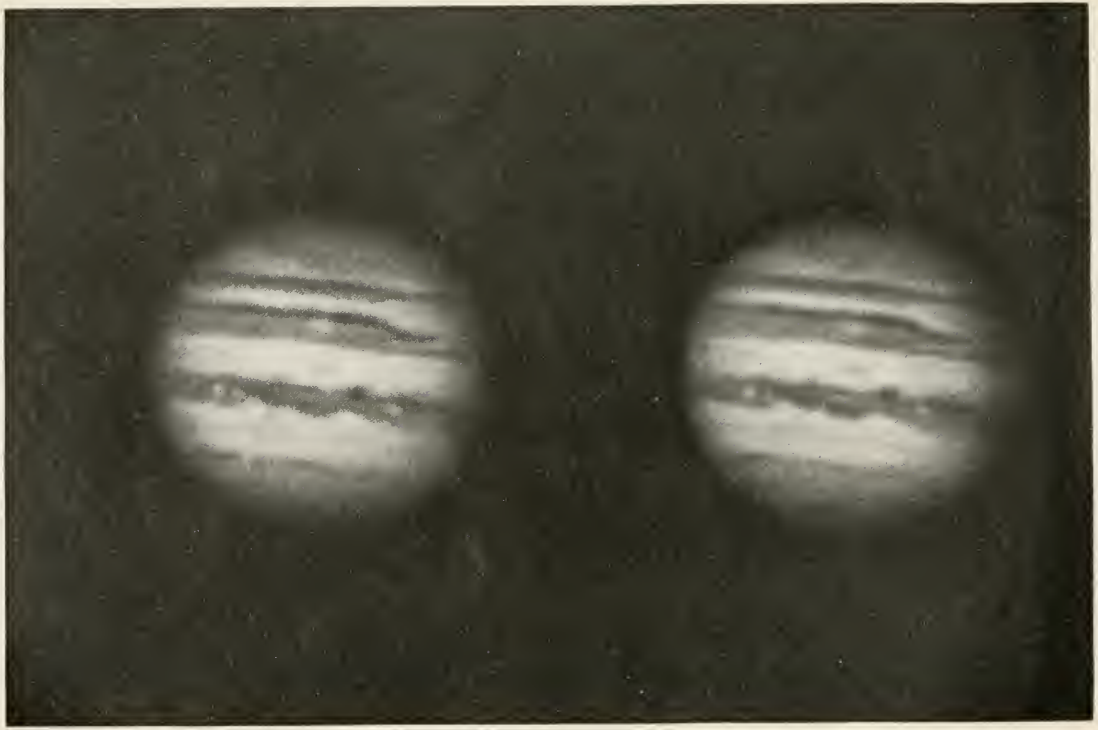


PLATE I. JUPITER.

Region of "the great red spot" is seen near the right edge of the planet.

Photographed by E. C. Slipher, Oct. 19, 1915, Lowell Observatory.

THE SOLAR SYSTEM[1]

By W. W. Campbell

The study of astronomy begins naturally with the solar system. The solar system is our abode. It is the observing station from which we look out in all directions to the great stellar system. The solar system is only a minute detail in the structure of the universe. He who would explore the universe should begin by knowing his immediate surroundings. Our visual telescopes could show us sixty or seventy millions of stars, distributed over the whole sky, and our great reflecting telescopes could photograph possibly two or three times as many. With only one exception all of these stars are so far away that they are seen as mere points of light in our most powerful telescope, even when the magnification is nearly 3,000 diameters. The one exceptional star is our Sun. It alone of all the stars can be seen to have a "diameter." It alone of all the stars can be studied in any geometric detail by means now available. This is because our Sun is relatively near to us. The next nearest star known, *Alpha Centauri,* is 275,000 times as far away from us as our star is. If we would know what the stars in general are we should begin by learning about our own star. That is the chief reason why there are solar observatories in many countries of the world. Those institutions are occupied wholly or chiefly in the study of the Sun. Our Sun is an exceedingly interesting body in itself, especially for beings who live in the solar system, but its main interest to astronomers lies in the fact that knowledge of conditions existing in our Sun enables us to draw many conclusions concerning conditions existing in millions of other suns.

It is not our purpose to describe the solar system in detail, nor shall we burden the lecture by quoting the enormous distances which separate the heavenly bodies: astronomers do not comprehend them any better than the laymen do. One or

[1] Delivered November 10, 1916.

two distances, one or two masses, will be sufficient to serve as scale values for the entire system. We shall make it our chief concern to emphasize the characteristic features of the solar system so that we may comprehend the relation of its different members to each other, and the relation of the solar system as a whole to the great stellar system. We shall try to visualize the solar system as it exists in space, highly isolated from all other members of the stellar system.

The solar system consists of the great central Sun, the eight[2] major planets and their twenty-six satellites, the more than eight hundred minor planets or asteroids, the zodiacal-light materials, the comets and the meteors. Only one other class of bodies is known to astronomers: the nebulæ. Now many of the nebulæ are far out in the stellar system, and a great many others are probably outside of our stellar system. Certainly none of the nebulæ existing today have a direct connection with our solar system.

We have said that the Sun is one of the ordinary stars. Compared with the thousands of other stars visible to the unassisted eye on any clear night, our Sun is merely an average star. Nevertheless it is a very large body. Its diameter is 110 times the Earth's diameter. Its volume is therefore 1,300,000 times the Earth's volume. If the Sun were a hollow shell of its present diameter, we could pour more than a million Earths into it and still leave empty the space between the Earth-balls.

The average density of the Earth is five and a half times that of water. The average density of the Sun is only a quarter that of the Earth; that is, the Sun is forty per cent more dense than water. From the figures quoted it follows that the mass of the Sun, in other words, the quantity of material that the Sun contains, is 333,000 times that of the Earth. It is this immense mass which gives the Sun its tremendous gravitational power, a power sufficient to maintain the planets in their elliptic orbits around it.

At an average distance of ninety-three millions of miles from the Sun are the Earth and its Moon. The Earth-Moon system revolves once around the Sun in what we have agreed

[2] These are the numbers known to exist in the year 1916.

to call our year. To complete the circuit in the year requires the Earth to travel a little more than eighteen miles and a half per second. Between the Earth and the Sun are two known planets, *Mercury* and *Venus*. *Mercury* is a little planet, 3,000 miles in diameter, whose average distance from the Sun is about three-eighths the Earth's distance. It is so close to the Sun that it must travel very rapidly in its orbit, an average of twenty-eight miles per second, to keep from being drawn into the Sun. Relatively few people have seen *Mercury*. It does not get very far away from the Sun, but if observers know when it is going to be at its greatest distance east of the Sun shortly after sunset and west of the Sun shortly before sunrise, they will have no difficulty in seeing the planet as a first-magnitude star low in the sky, and small telescopes will show the planet's disk.

The planet *Venus*, whose orbit lies between those of *Mercury* and the Earth, is for those who live on the Earth the most brilliant of all the planets. It is just a shade smaller than the Earth in size. The Earth, as you know, is a little over 7,900 miles in diameter. The diameter of *Venus* is 7,700 miles. Its distance from the Sun is not quite two-thirds the Earth's distance. It requires seven and a half of our months to complete its journey around the Sun.

Going outward from the Earth we come to our interesting neighbor *Mars*. It is fifty per cent farther from the Sun than we are, and its year is a little under two of our years. Its diameter is slightly more than one-half the Earth's diameter—about 4,200 miles. It is therefore a little larger than *Mercury* and a good deal smaller than *Venus* and the Earth. It has two tiny moons. The smaller one is only eight or ten miles in diameter, and the larger one less than forty miles. The surface areas of these little satellites are smaller than some of the counties in California.

Next in order of distance from the Sun are the asteroids, or little planets. The first one was discovered on the first day of the last century, and up to the present time more than 800 have been found. It is not an uncommon thing for ten or fifteen of these bodies to be discovered in a single year, by means of photography. The first one discovered is, so far as we know, the largest: a little less than 500 miles in diameter. The smallest ones are certainly less than ten miles in diameter.

The largest of our planets is *Jupiter*, whose average distance from the Sun is a little over five times the Earth's distance. *Jupiter's* mean diameter is eleven times the Earth's. Its volume is therefore thirteen hundred times the Earth's volume, and if that planet were a hollow shell you could pour more than one thousand Earths into it. *Jupiter* requires nearly twelve years to complete its circuit, at an average speed of eight miles per second. This great planet is known to have nine satellites. The four bright moons, visible even with opera glasses, were the first celestial bodies discovered by Galileo and his telescope—in the year 1610. It is of special interest to Californians to note in passing that the fifth moon of *Jupiter* was discovered with the 36-inch refractor of the Lick Observatory in 1892; the sixth and seventh moons with the Crossley reflector of the Lick Observatory in 1904-5; and the ninth satellite with the Crossley reflector in 1914. The eighth was discovered at the Royal Observatory, Greenwich, in 1908.

Still farther from the Sun is *Saturn* with its wonderful ring system and nine known moons. Its mean diameter is nine times that of the Earth, and it goes once around the Sun in a little less than thirty years. Maxwell and Keeler proved that the rings are a great collection of little moons—probably millions of them.

The six major planets already named were well known to the ancients. References to them are frequent in the extant literature of the nations, past and present. The planet next in distance, *Uranus*, was discovered by Sir William Herschel in 1781 in one of his famous sweepings of the heavens. It is nineteen times as far from the Sun as the Earth, its diameter is four times the Earth's, and, traveling four miles per second, it requires eighty-four years to complete the circuit of the Sun. It has four known satellites.

The discovery of the next planet, *Neptune*, was, as you know, a great event in the history of astronomy. *Uranus* did not follow precisely the path marked out for it by astronomers, and Adams of Cambridge in 1845, and Leverrier of Paris independently a year later, proved that the discrepancies in its

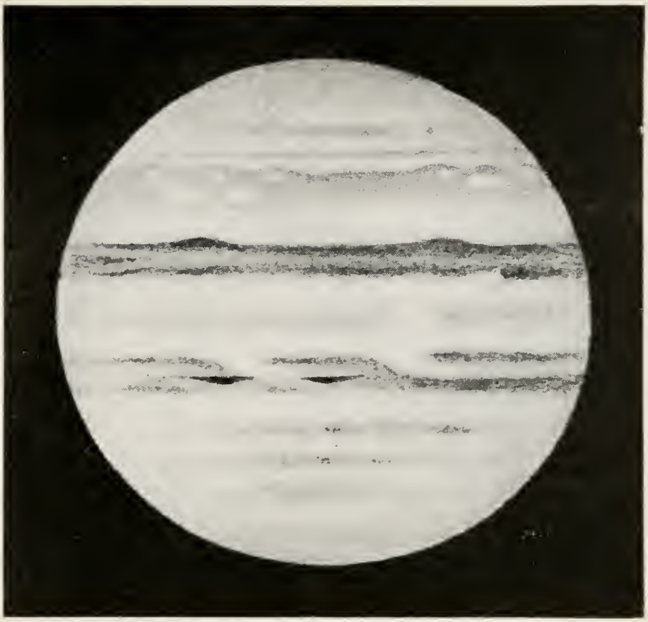


PLATE II. Drawings of Jupiter by James E. Keeler.

Upper: 1889, July 10d 10h 2m P. S. T.
Lower: 1890, Aug. 30d 11h 9m P. S. T.

motion could be caused by the attractions of an undiscovered planet farther from the Sun than itself. They computed the position of the undiscovered planet. Adams tried to enlist the services of the greatest telescopes in England to discover the body, but his advice and requests were neglected. It is especially appropriate in these days of war between the nations to note this illustration of the international character of astronomical research: Leverrier of Paris requested Astronomer Galle of Berlin to search for the new planet, with the largest telescope on the continent. Galle found the planet on the first night of the search, almost exactly where Leverrier said it would be. *Neptune* is a little over four times the Earth in diameter, and he requires 165 years to travel through his orbit. He has gone less than half-way around the Sun since his discovery. *Neptune* has one known moon.

It is not impossible that other planets more distant than *Neptune* are revolving around the Sun. Several astronomers have devoted much time to searching for them.

The Earth-Moon system is a unique combination, in that the two bodies are more nearly of the same size than are any other planet and its satellites. The Moon's diameter is considerably over a fourth of the Earth's diameter. It required the Washington 26-inch telescope to discover the two tiny moons of *Mars*, but an astronomer on *Mars* or on *Venus*, when those planets are in favorable positions, would not need any telescope at all to see the Earth and its Moon as a double planet—the only double planet, so to speak, in the solar system.

It is a most remarkable fact that all of the eight major planets and all of the more than 800 asteroids revolve around the Sun in the same direction, which astronomers have agreed to call from west to east. There is no exception to this rule.

It is an equally remarkable fact that the eight planets revolve in orbits lying nearly in the same plane, and that the average position of the orbital planes of the 800 asteroids coincides closely with the average for the eight planets. Let us refer the planes of the orbits of the planets and asteroids to what we may call the average plane of the planets' orbits. *Mercury's* orbit is inclined six degrees to the average plane, and *Venus's* orbit two degrees. The orbit planes of the other five planets are inclined, without exception, less than two degrees to the average plane of the system. The orbit planes of a few of the little asteroids are inclined as much as thirty or forty degrees to the plane of the system, but the great majority of the asteroids do not get far from that plane.

Other striking and related facts are these: The Sun rotates on his axis from west to east. We do not positively know the directions of rotation for *Mercury* and *Venus*, but there are reasons for thinking that their direction is also from west to east. Our Moon revolves around the Earth from west to east, and the Earth and Moon both rotate on their axes from west to east. *Mars* rotates from west to east, and his two moons revolve around the planet from west to east. *Jupiter* and *Saturn* rotate on their axes from west to east, but in the satellite systems of these planets and in the systems of *Uranus* and *Neptune* we come upon exceptions to the west-to-east rule. The seven inner satellites of *Jupiter* revolve from west to east, but the eighth and ninth satellites, which are farther out from the planet than the other seven, travel from east to west. The eight inner satellites of *Saturn* travel from west to east, but the far-out ninth reverses the direction. The four moons of *Uranus* revolve around that planet in a plane which is nearly at right angles to the average plane of the planets, and the plane of the satellites of *Uranus* is probably the approximate plane of the equator of that planet. The satellite of *Neptune* revolves around its planet from east to west in a plane inclined at an angle of thirty-five degrees with the plane of the planets. We should note that the exceptional cases refer to the outermost planets of the solar system, *Uranus* and *Neptune,* and to the outermost satellites in the systems of *Jupiter* and *Saturn.* Everywhere else in the solar system prevails the rule of motions of revolution and rotation from west to east.

The solar system, of great extent in the plane of the system, is an exceedingly "thin" system. Let us call the distance from the Sun to the Earth one; then the distance from the Sun to the outermost planet, *Neptune,* on the same scale is thirty, and the diameter of *Neptune's* orbit is sixty. Now our system of Sun, planets, satellites and asteroids lies so nearly in one plane that we could put it in a very flat bandbox, sixty units in diameter and one unit in thickness, so that the major planets and their satellites, and all the asteroids, with a very few exceptions, would perform their motions entirely within the box. The exceptional asteroids and the majority of the comets would dip out of the box on one side or the other because the planes of their orbits make considerable angles with the central plane of the solar system.

I want to call your attention as forcibly as possible to the extreme isolation of our system from other systems. If it is one unit of distance from the Sun to the Earth and thirty units from the Sun to the outermost of our planets, *Neptune*, it is, on the same scale, 275,000 units to the nearest star of which we have any knowledge, *Alpha Centauri*. It is about 400,000 units in an entirely different direction to our second nearest neighbor, and so on. Most of the comets and some of the meteors, as we shall learn in the next lecture, travel out much farther from the Sun than *Neptune* is; but, aside from some of the comets and meteors, we do not know that there is anything in space between *Neptune*, thirty units from the Sun, and the nearest star, several hundred thousand units from the Sun.

Let us illustrate our isolation in still another way. Light travels from the Sun to the Earth in eight and one-third minutes, and from the Sun to *Neptune* in four and a half hours; but it requires four and a half years to travel from our Sun to the next nearest star, *Alpha Centauri*. The distance of *Alpha Centauri* is described as four and a half light-years. The average distances between the stars are of the order of six or seven or eight light-years.

It must be clear that the stars and the planets occupy little space, and that they have a superabundance of room to move about. We have found that the average speed of the naked-eye stars in their motions through space is about sixteen miles per second, which means that if one star should start to travel precisely toward its nearest neighbor, assuming its nearest neighbor to be at the average distance, it would require some eighty thousand years to arrive at its destination. Now the diameter of our Sun, an average star, is not more than one fifty-millionth as great as the average distance between neighboring stars. Under such conditions it is not difficult to see that a collision of two stars must be an exceedingly rare event. The approach of two stars so close as to disturb each other violently must also be rare. However, when we consider the number of stars in the stellar system, we should perhaps expect a few close approaches to occur within a human lifetime.

The researches of the early astronomers were confined almost exclusively to the solar system. Their small and imperfect telescopes lacked the power, and their methods lacked the accuracy for attacking the problem of the distant stars. They made a specialty of the motions of the bodies which compose the solar system, of their forms and dimensions, and of their orbits. Their labors, supplemented by those of astronomers still living, have been so thorough and complete that we can predict the motions of the planets around the Sun and the motions of the satellites around the planets with very great accuracy. It would be possible to compute the point in the sky which the planet *Jupiter* will occupy one hundred years from this evening, and the telescope could this year be directed to that point so accurately that, on looking through the telescope one hundred years from tonight, when the clock said the precise second had arrived, the planet would be seen very close to the center of the telescopic field of view. The eclipses of the Sun are computed so accurately that the astronomer may, if he chooses, go years in advance to the proper point for observing a given eclipse and direct his telescope so precisely to the position which the eclipsed Sun will occupy as to witness the phenomenon when it arrives, without more than an exceedingly small change in the pointing of his instrument. The pointing of the instrument would probably not be exactly right, because the Moon deviates a little from the path laid down for it; astronomers do not know why. It has, in fact, been suggested that the Moon's motion may be affected slightly by some force or forces whose nature has not yet been determined. There is likewise an appreciable discrepancy in the motion of *Mercury*. Whether this discrepancy will ever be removed by virtue of a more complete application of Newton's law of gravitation to the problem is uncertain; some other force than gravitation may be acting, but it need be only a very minute force.

The zodiacal light, a faint illumination of the sky visible above the Sun when the Sun is a few degrees below the horizon, is an interesting phenomenon surrounding the Sun. There is no reason to doubt that the zodiacal light which we see comes originally from the Sun, and that this light falls upon and is scattered by finely-divided material—dust grains or very small bodies in great numbers which revolve around the Sun, each such particle in effect a little planet. This material is distributed through a great volume of space, somewhat in the shape of a double-convex lens whose center coincides with the Sun and whose edge extends out even farther than the Earth's orbit. Its shorter dimension extends so far to the north and to the south of the Sun that northern observers, well situated, may see the zodiacal light at midnight in May, June and July above the northern horizon.

Belonging to the solar system also are the comets, which pass around the Sun in orbits for the most part very elongated. We shall study the comets in the next lecture.

There are the meteors, many of which revolve around the Sun in orbits which mark them as members of the Sun's system. It is probable that some of the meteors are merely passing through the Sun's system and are not of it. Occasionally a meteorite gets down through our atmosphere to the Earth's surface, is found, and is installed in a museum; but many millions which collide with our atmosphere every twenty-four hours are consumed by the friction of the Earth's atmosphere and lose their identities.

The distribution of the material in the solar system is most remarkable. Nearly all of it is in the Sun. If we add together the masses of the major planets, their satellites, the hundreds of asteroids, make liberal allowance for the masses of the comets, meteors and zodiacal-light materials, and call the total one, then the mass of the Sun on the same scale is 744; that is, of 745 parts of matter composing our solar system 744 parts are in the Sun and only one part is in the bodies revolving around it. To state this in another way: ninety-nine and six-sevenths per cent ($99\frac{6}{7}\%$) of the material of the solar system is in the Sun, and only one-seventh of one per cent ($\frac{1}{7}\%$) is divided up to make the planets, satellites, asteroids, etc. The four outer planets, *Jupiter, Saturn, Uranus* and *Neptune*, contain 225 times as much material as the four inner planets, *Mercury, Venus,* Earth and *Mars*. The Earth is fully 3,000 times as massive as the more than 800 asteroids combined. It is not known how much material is responsible for the zodiacal light. The more finely divided that material is, the smaller is the total mass required to reflect and scatter the quantity of solar light observed in that phenomenon. Seeliger has thought that the scattered zodiacal-light materials, if condensed into one body, might have a mass fairly comparable to that of the little planet *Mercury*, and he has concluded that the attractions of the zodiacal-light materials upon the planet *Mercury* could explain the deviation of that planet from its computed orbit. This problem cannot yet be regarded as definitely settled. For several decades astronomers thought there might exist an undiscovered planet or planets of considerable size between the Sun and the orbit of *Mercury* whose attractions upon *Mercury* were responsible for the discrepancies in its motion. The work of the Crocker eclipse expeditions from the University of California is morally conclusive that there are no such planets massive enough to explain the observed discrepancies. We do not know the mass of any single comet, but we do know that cometary masses are exceedingly small in comparison with the masses of the smallest planets. The recent comets which have approached close to *Mars,* Earth, *Mercury,* or *Venus* have produced no appreciable disturbances in the motions of those planets.

We have described the known members of the solar system as to dimensions, masses, orbits and geometrical relations one to another. We have seen that they form the Sun's system—a system very completely isolated in space, and independent of other systems so far as its internal relations are concerned. Now the solar system as a whole is traveling through space with reference to the other members of the stellar system. Sir William Herschel suggested, a century and a third ago, that the apparent motions of the other stars were such as to indicate a motion of our star and its system toward the constellation *Hercules,* and this conclusion has been amply verified by Herschel's successors. The logic of the demonstration is

PLATE III. Saturn.

Drawing by J. E. Keeler, Jan. 7, 1888.

(This was the first night on which the 36-inch refractor was used.)

very simple. Let us use an illustration which every one has had or may have the opportunity to test. Suppose the observer is traveling rapidly by railway train across a level tract of country, say toward the west. He will notice that the trees, buildings, or other objects on his western horizon appear to separate gradually. Similar observations on the trees and other objects on the eastern horizon will show that they appear to approach each other. The trees and buildings on the horizon to the right and to the left of him will seem to be traveling toward the east. The explanation is apparent. The motion of the solar system through space is a much more complicated problem, in that we must deal with space of three dimensions, instead of the two dimensions of the terrestrial surface, and the stellar objects which the observer sees in all directions from him are themselves in motion. However, if the positions of a great number of stars have been accurately determined at some past epoch, as was indeed the case, and the recent determinations of positions of the same stars be compared with the early positions, it will be found that the stars have moved. They will have moved with a great variety of speeds in a great variety of directions: but if the stellar motions are studied with care, it will be found that the prevailing motion of any great group of stars in any large area of the sky will be away from the region of the constellation *Hercules* and toward the opposite point of the sky. Herschel reasoned truly that this prevailing drift of the stars away from the constellation *Hercules* was due to the motion of the solar system, year after year, decade after decade, toward that constellation. Modern solutions of the same problem have changed the estimated position of the Sun's goal very slightly toward the southeast, to a point near the boundary line between the constellations *Hercules* and *Lyra*.

Astronomers did not succeed in determining the speed of the solar motion from these apparent motions of the stars. The difficulty lay in the fact that we did not know the distances of the stars whose angular motions had been observed. The spectrograph has enabled the second part of the problem to reach a satisfactory solution. This wonderful instrument enables us to measure the motions of approach and recession of the stars, and this has been done for 2,000 or more of the stars, chiefly under the auspices of the University of California, by the Lick Observatory for the northern stars, and by the D. O. Mills Expedition to Santiago, Chile, for the southern stars. It has been found that the stars have a great variety of motions of approach and recession. If we examine the results for a hundred neighboring stars in some one large area of the sky, we shall find that a few will be approaching the solar system at high speed, a few will be receding from our system at high speed, and the others will be represented by a great variety of motions of approach and recession. This happens for great groups of stars in any part of the sky. If we consider the observed motions of 100 stars in and surrounding the constellations *Hercules* and *Lyra,* we shall find the same variety of speeds, but if we take the average speed of the group we shall find that the group as a whole seems to be approaching us at the rate of about twelve and a half miles per second. In a similar manner, if we consider the motions of 100 neighboring stars in precisely the opposite region of the sky, we shall find the same variety of approach and recession, but we shall obtain for the average speed of the 100 stars as a group an apparent recession of about twelve and a half miles per second. No one questions the explanation of these observed facts, that the solar system is traveling toward the *Hercules-Lyra* region with a speed of about twelve and a half miles per second with reference to the system of naked-eye stars.

Now this speed of motion is carrying the solar system through space at the rate of approximately 400,000,000 miles per year. There are the best of reasons for believing that our solar system is very old. Its age can scarcely be less than many tens of millions of years, and more probably hundreds and thousands of millions. It is clear that the youth of the solar system was spent in a very different part of the stellar system from where it now is, and that its old age will be lived in a still different region. We do not know whether the motion of the solar system follows a straight line, or a closed curve such as an ellipse, but the system is probably obeying the gravitational attraction of the rest of the material universe. It seems probable that the orbit is a great ellipse, whose circuit is so great that many hundreds of millions of years will be required to travel over it once, even though our system meet with no disturbing element in the meantime.

It will be profitable to consider briefly the conditions existing in the Sun and planets. Geologists have been able to study in a limited way the outcropping geologic strata of the Earth, but all of these strata combined are only a few miles in thickness. There are indirect ways of studying the interior of the Earth, and essentially every modern student of the subject has come to the conclusion that the interior of the Earth is solid throughout, with the possible exception of relatively small pockets of molten matter here and there. We know something about the oceans and the atmosphere of the Earth. Do any of the other planets resemble the Earth? *Mercury, Venus* and *Mars* certainly have some resemblances to our planet, but the giant planets *Jupiter, Saturn, Uranus* and *Neptune* are extremely unlike the Earth. The Earth appears to be the densest of all the planets, though considerable uncertainty exists as to the density of *Mercury*. *Venus* is about nine-tenths as dense as the Earth, and *Mars* is about seven-tenths. The four great planets average about one-fifth the density of the Earth. *Jupiter, Uranus* and *Neptune* are a little more dense than water, whereas *Saturn* is so light that if it could be thrown upon a great terrestrial ocean it would float like a piece of wood.

We can get no trace of an atmosphere on *Mercury*, and much remains to be done in the way of investigating the atmosphere of *Venus*. The latter planet certainly has an atmosphere, but whether it is comparable in quantity and chemical composition with the Earth's atmosphere we do not know. As *Venus* is only a shade smaller than the Earth, we should expect the atmospheres of the two planets to be not very unequal. We know that *Mars* has an atmosphere, but it is a very light one. The Martian atmosphere at the surface of that planet is probably not over one-half the density of the Earth's atmosphere at the summit of Mount Everest, our highest mountain peak. There is no reason to doubt that the composition of the Martian atmosphere is very much like our own. A great white area around the north pole of *Mars* waxes and wanes with the coming and going of winter in the northern hemisphere of *Mars*, and a similar white cap comes and goes at the south pole of the planet. These are just such phenomena as occur every year on the Earth. If we were transported a few thousand miles above the northern hemisphere of the Earth, we should see a great white cap growing in the fall and winter from the arctic regions southward across Europe and Asia to the latitudes of the Mediterranean Sea and the Himalaya Mountains, and across Canada and the United States well toward the Gulf of Mexico; and we should see the southern edge of this cap retreating northward with the advent of spring and summer. An observer over the southern hemisphere of the Earth would witness the annual waxing and waning of the white cap around the south pole of the Earth, save as the southern oceans interrupted its continuous progress.

The four giant planets have enormously extensive atmospheres. We appear to be able to see at all times clouded areas of tremendous extent. These clouds are more prominent in *Jupiter* than in *Saturn, Uranus* and *Neptune,* but that the surfaces of all four have a very high percentage of clouds we can scarcely doubt. The immense masses of material in these planets and their low average densities lead us unavoidably to conclude that they are not solid, as in the case of the Earth, but that they are largely, and perhaps entirely, in a gaseous state, except as the enormous interior pressures, due to the overlying strata, may liquefy or even solidify their central volumes. It is thought that the gaseous strata in each of the four planets extend to great depths and that there is nothing in the nature of a solid or permanent crust over the surface of any of them. Their low densities probably mean that their enormously deep atmospheres are still quite hot. Yet we have no evidence that any one of them is shining by its own light. When one of *Jupiter's* large satellites passes between the Sun and the planet, eclipsing a small area of the planet's surface, that area looks black, but this may be in part a contrast effect.

We should call attention to the flattened forms of *Jupiter* and *Saturn*. The rotation of the Earth once in about twenty-four hours has caused the equatorial regions to be thrown out by centrifugal force, in effect, and the polar regions to be correspondingly drawn in, until the difference between the equatorial and polar diameters is twenty-six miles. The great

Fig. 1—Photographs of Saturn, Nov. 19, 1911, 60-inch reflector (100-foot focus) of the Solar Observatory. Direct enlargement exposures by E. E. Barnard.

Fig. 2—Drawing of Mars, May 29, 1890, $11^h\ 45^m$ P. S. T. 36-inch refractor, Lick Observatory, by J. E. Keeler.

PLATE IV.

planet *Jupiter* rotates on its axis in a little less than ten hours, whereas the little Earth takes twenty-four hours. A point on *Jupiter's* surface is traveling by rotation some twenty-seven times as rapidly as a corresponding point on the Earth's surface. The centrifugal force is enormous, and the result is easily observable in the equatorial and polar diameters, for there is a difference of about 5,000 miles. The effect is even larger in the case of *Saturn,* where the difference of the diameters is nearly 7,000 miles. The throwing of the clouds in the atmospheres of these two planets into belts parallel to the equators is undoubtedly connected with the extremely rapid rotations of the planets, probably through the medium of trade winds blowing nearly parallel to their equators. If our Earth rotated more and more rapidly our trade winds would approach more and more to parallelism with the equator.

The rings of *Saturn* are unique in the solar system. Maxwell of England proved by mathematics, and Keeler of America proved with the spectrograph, that these rings are a great collection of minute and separate bodies. There are so many of these particles or separate masses that they seem to form a continuous and solid system, except as we see the dark lines dividing them into several component rings. If the rings were solid like a wagon wheel, to use a homely illustration, the outer edge would travel by rotation more rapidly than the inner edge. The spectrograph has shown that the reverse is the case. A moon at the inner edge of the ring system would have to travel very rapidly to save itself from falling upon the planet. A moon at the outer edge of the ring would travel much more slowly. Keeler proved that each point of the ring system is traveling with the speed which a moon at that distance from the center of the planet would have. Each point in the ring system is a separate moon revolving in an essentially circular orbit about the planet, and in harmony with the gravitational power of the planet.

Our Moon, as you know, is apparently without atmosphere and water, though it should be said that one astronomer thinks he has observed changes in the bottoms of the lunar craters, such as to suggest the presence of a trace of water in the form of frost crystals. These observations should be verified before they are interpreted on the basis of water vapor. The verification has not yet been provided.

Most interesting of all the bodies in the solar system is the Sun itself. It is an intensely hot sphere whose outer strata, certainly, are gaseous. The gaseous composition may indeed extend from surface to center; but it is much more probable that the great central volume is in the liquid or even solid state, owing to the tremendous pressures which exist there. We know that the surface temperature of the Sun is in effect as high as 10,000° Fahrenheit. The interior temperatures must be vastly higher. The chemical elements known to us could exist at such temperatures only in the form of incandescent gases or vapors, except as immense pressure condenses them to the liquid or solid state. We know that our atmosphere and hydrogen and the other gaseous elements of the Earth can be liquefied and solidified by means of such pressures as our laboratory methods are able to produce. The pressures in the depths of the Sun run up into the millions of pounds per square inch; and, while the temperatures there existing undoubtedly tend to preserve the gaseous state of the Sun's interior, the stupendous pressure probably conquers the expansive forces and reduces the central mass to the liquid or solid state. It is scarcely possible that a liquid or solid core extends from the center out to near the surface of the Sun, for the average density of the entire body is only 1.4 times the density of water.

About forty elements familiar to us on the Earth have been shown to exist in the outer strata of the Sun by means of the spectroscope. Rowland has said that if the Earth were heated up until its temperature was equal to that of the Sun, the Earth's spectrum would probably resemble closely the spectrum of the sun.

When we look at the Sun we see what we call the photosphere. The prevailing opinion of the photosphere is that it consists of clouds produced by the condensation of some of the vapors, formed in the atmosphere of the Sun when the conditions for condensation are right, very much as our own clouds form in our atmosphere when the conditions are right. The clouds of water vapor with which we are familiar form at a low temperature because we are dealing with water which has a freezing temperature of +32° Fahrenheit. Clouds would be expected to form from iron vapor at a very high temperature, for the freezing point of iron is about 1500° above zero Fahrenheit.

The atmosphere of the Sun is in rapid circulation. There are great storms in its atmosphere, vastly more violent than those in the Earth's atmosphere. In terrestrial storms there are great whirling disturbances in our atmosphere. The sun-spots are to us the outward and visible sign of somewhat similar storms, on a tremendous scale. The motions of gases and vapors in sun-spots have been measured by means of the spectroscope, and Hale has shown that sun-spots are the centers of local magnetic fields. The magnetic field is probably developed in each case by the rapid rotation of electrically charged particles within the volume of spot disturbance.

The sun-spots, as well as other details of the Sun's surface, reveal a curious law of solar rotation. The entire Sun is rotating rapidly from west to east, but the equatorial regions are rotating more rapidly than the regions of high latitude. Areas near the equator rotate once around in twenty-four days, but at forty-five degrees of north and south latitude the rotation period is twenty-eight days, and at seventy-five degrees of north and south latitude the period is thirty-three days. The forging ahead of the equatorial regions has never been satisfactorily explained.

The sun-spots vary in size most curiously, and for reasons unknown. The spottedness passes from minimum to maximum and back again to minimum in an average period of eleven and one-tenth years. During the years of minimum it is not unusual for the spots to be entirely absent for weeks at a time. The curve which represents the spottedness of the Sun as observed from the year 1740 up to 1870 shows that twelve maxima and twelve minima occurred in this interval. The maxima and minima do not come with perfect regularity. Sometimes a maximum is a year or two early, or a year or two late, and similarly for the minima. Many investigators have tried to find an explanation of the sun-spot period, but the results have not been satisfactory. The cause has been looked for in the action of the planets. It would seem that if any of the planets is responsible it should be the giant *Jupiter*. There is no apparent connection, however, for *Jupiter's* period about the Sun is 11.9 years, whereas the sun-spot period is 11.1 years. It has been suggested that the spots are formed when two or more of our planets are in the same straight line with the Sun, but the fact is there are just as many spots visible when the planets are equably distributed around the Sun, with no two of them in or near a straight line with the Sun. The cause of periodicity seems to lie within the Sun itself. It is perhaps not impossible that certain forces develop and accumulate within the Sun until they reach the breaking-out intensity, once in eleven years, somewhat after the fashion of the forces which are responsible for the geysers on the Earth. I do not mean to convey the impression that the motions within sun-spots and the motions of water expelled from geysers are the same, as they are not.

Experienced investigators have tried to find a relationship between sun-spots and terrestrial weather, but they have not succeeded in proving that such is the case. There have been and still are people who say that the sun-spots rule our weather, but they seem not to know what constitutes a scientific proof; at least, no proof has been published. They remind me of the small boy's first experience with an electric trolley car. The street-cars in his town had been drawn by horses, and he had no doubt as to the motive power. There came a morning when he and his father got on a successor to the horse-car, and he was interested to know what made the car go. His father tried to explain that it was electricity, but the boy was not convinced, and this is not surprising, for nobody even now knows what electricity is. Before he got to the end of his trolley ride he said, "Father, I have discovered what makes this car go. It is that bell up there above the driver's head, for I have noticed that every time that bell rings the car starts." Therefore, according to the same logic, as there are spots on the Sun and there are rain storms on the Earth, the sun-spots cause the rain. Unfortunately it happens, now and then, that we have an exceedingly dry winter month when the Sun is rich in spots, and a wet month has been prophesied; and that we have an exceedingly wet winter month, now and then, when no spots whatever are visible. It rains no more in the three or four years of sun-spot maximum than it does in the three or four years of sun-spot minimum. Likewise, the storms are no more numerous and no more severe when there are two or three planets almost exactly in line with the Sun than when the planets are equably distributed around the Sun.

In one respect we are sure that the sun-spots do have a terrestrial influence. Magnetic disturbances on the Earth are directly related, in some way, to the sun-spot activity. The curve of magnetic disturbances when correlated with the curve of solar spottedness, shows an agreement that is unmistakable.

Outside and beyond the spherical body of the Sun which we see every clear day are the prominences and the corona. The prominences are certainly connected with, or are the fruits of, the circulatory system of the Sun's atmosphere. They require special spectroscopic apparatus for their observation in ordinary times, but they can be seen directly at times of solar eclipses, when the main body of the Sun is hidden behind the Moon and the background of sky is relatively dark. They are of great variety as to forms and speeds of development. They sometimes shoot up to heights of two or three hundred thousand miles above the Sun's surface, with speeds as high as 250 miles per second.

The solar corona may also be a product of the rapid circulation within the Sun's structure. It is not impossible that the materials composing the corona are expelled from the Sun by something in the nature of volcanic force, or by the pressure of the intense solar rays upon the minute particles of the corona, or by other force or forces, and that these particles find their way back in descending streams to the Sun. The corona is a part of the Sun. A complete understanding of our Sun requires a study of the corona, and it is chiefly for investigations of this solar appendage that eclipse expeditions are dispatched to the out-of-the-way corners of the Earth. It has been found that the form of the corona depends upon the spottedness of the Sun. At times of spot maximum the corona is nearly circular in general outline, whereas at times of minimum the coronal streamers which extend out from regions of low latitude are extremely long, and the streamers which originate at high latitudes and in the vicinity of the poles of the Sun are very short.[3]

People in general know that the Sun is vital to life on the Earth, but they do not realize that all other sources of energy are negligible. The Sun's light and heat grow the farmers' crops. The solar radiation grows the forests of today. It grew, long ages ago, the luxuriant vegetation which, submerged and compressed, is the coal that today drives the railway trains of the land and the ships of the sea. It is the Sun's power which evaporates the water of the ocean and creates the winds which carry the evaporated water over the mountains where it is deposited as rain and snow. Our hydro-electric plants control the descent of this water from the mountains to the sea, and their water-wheels and dynamos generate electric current. The Sun's energy thus transformed illuminates our cities and drives the trolley cars. We do not depend at all upon the Earth's internal heat. The temperature of the Earth's surface is determined by the heat received from the Sun. To realize this fact, let us recall the frigid conditions perpetually existing at the poles of the Earth. During several weeks in the middle of the northern summer the north pole receives more solar heat than any other region of the Earth, and throughout the year some of the heat from the tropics and the north temperate zone is constantly transmitted by atmospheric circulation to the north polar region. Similarly, during several weeks in the middle of the southern summer the south pole of the Earth receives more heat than any other region of the Earth, and constantly throughout the year some of the heat of the tropics and of the south temperate zone is conveyed through the atmosphere to the region of the south pole. Yet how frigid and essentially useless in the vegetable and animal world are the polar regions! The interior heat of the Earth is not able to do anything appreciable for those regions. Now if the Sun's heat were cut off completely from the Earth for one short month, the equatorial regions would be at the end of the month so wintry that the north and south polar regions as they are today are rose gardens in comparison.

[3] The observed form of the corona on June 8, 1918, seems to call for some modification of this hypothesis.

To create due respect in our minds for the overwhelming power of the Sun, we may reflect upon the following statement: When the Sun is directly or approximately over any region of the Earth and our atmosphere above that region is in normally clear condition, each square yard of that region receives energy from the Sun's rays at the approximate rate of four-fifths of one horsepower. This is at the rate of 4,000 horsepower per acre. If you own 250 acres of desert in Arizona, or Mexico, or northern Africa, the Sun in the middle of each summer day is pouring down energy upon your little ranch at the rate of one million horsepower. Your neighbor's ranch of the same size is receiving solar energy at the same rate. And so on for the entire surface of the Earth, in proportion as the Sun's rays fall perpendicularly or slantingly upon each area. Yet this is far from the whole story. Nearly the half of the energy which the Sun tries to send to the Earth's surface is intercepted by our atmosphere and turned back into space. With the Sun directly overhead for the various regions of the Earth, only about sixty per cent of the Sun's energy gets down through the atmosphere to the land and water surface of the Earth, and the remainder is refused transmission. Now the Sun, to the best of our knowledge, is sending out energy in all directions at essentially the same rate. The little Earth covers so small an area of the sky, as one would see the sky if he were on the Sun, that the Earth intercepts only one two-billionth part of the Sun's radiation. If we could cover the Sun with a shell of ice forty feet thick, the heat energy radiated from the Sun, at its present rate, would be sufficient to melt that shell of ice in one minute of time. To produce this quantity of energy from the combustion of coal would require that a layer of the best anthracite twelve or fifteen feet deep over the entire solar surface be consumed every hour. Now, if the Sun were composed of anthracite the consumption of the whole mass would not furnish sufficient heat to supply the Sun's output, at the present rate, for as long as 10,000 years.

It was Kant in the eighteenth century, and Helmholtz independently a hundred years later, who showed that the contraction of the Sun under the influence of its own gravitational power is the most probable explanation of its source of heat;

perhaps not its sole source, but a source which would suffice to maintain the present rate of radiation for many millions of years. The Sun's own gravitational power is struggling constantly to draw every one of its particles to the center of the Sun; it is subjected to its own immense compressive force. Now we know that when we compress air, for the purposes of industry or to fill an automobile tire, a great quantity of heat in the air compressed is liberated and radiated into surrounding space. In the same way the constant and stupendous process of compression which the Sun suffers from its own internal gravitation liberates the heat that is latent within its mass. The immense quantity of energy represented by the actual motion of the Sun's materials inward toward the center is also converted into heat. These are such fruitful sources of heat that the Sun need contract no more than 300 feet per year at the present time to supply the radiation which goes out in all directions and of which a very little reaches us upon the Earth. This is so slow a rate of solar contraction that we could not hope to observe any diminution in the Sun's diameter, even with our most refined measuring apparatus, until after the passing of some 5,000 years. There can be no doubt that this solar compression will liberate sufficient heat to maintain the present rate of flow for five or ten millions of years, and it can be shown by the application of the same principles that the Sun may well have been radiating heat at an approximately equal rate for five or ten millions of years in the past. It is essentially certain that the radium within the Earth is a powerful factor in developing the Earth's internal heat. We have no evidence as to the existence of radium in the Sun, but it or some of its radio-active relations may be there to assist in giving long life to the Sun and to the planets which draw their sustenance from the Sun.

What can be said as to the existence of life on the other bodies of the solar system? We may dismiss the Sun as too hot to support any form of life with which we are acquainted. Our Moon cannot support life, at least of the terrestrial kinds, because of the total lack of air and water. The probabilities are strong that *Mercury* is lifeless, for the same reason, but this is not a certainty. I think we may dismiss *Jupiter, Saturn,*

Fig. 1.

Fig. 2.

Figs. 1 and 2. By Percival Lowell, in *Mars and Its Canals*, pp. 126, 229.

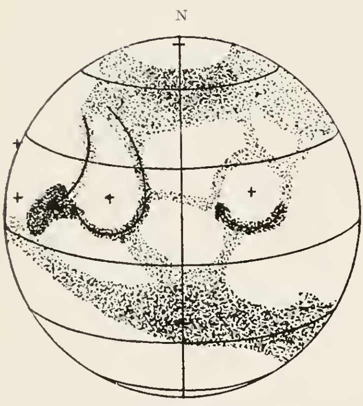


Fig. 3.

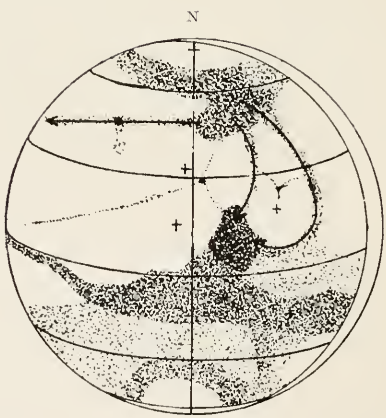


Fig. 4.

Figs. 3 and 4. By William H. Pickering, in *Popular Astronomy*, Jan., 1918.

PLATE V. Drawings of Mars.

Uranus and *Neptune* as abodes of life: we do not see how they can have anything in the nature of solid surfaces. *Venus* and *Mars* are the planets most nearly equal in size to the Earth. *Mars* has a very light atmosphere, certainly, but we know nothing as to the extent of *Venus's* atmosphere, except that it has one. If Schiaparelli was right in his conclusion that the planet *Venus* always presents the same face to the Sun, as it probably does, then life on *Venus* would be difficult: one hemisphere would have eternal day with burning temperatures, and the other hemisphere eternal night with extreme cold. *Mars* and the Earth seem to have many resemblances. Seasonal changes occur in the aspect of *Mars* such as could reasonably be attributed to changes in vegetation; and if there is vegetable life there could well be, and probably is, animal life. However, the vegetable may be easily independent of the animal; the forests and prairies of the Mississippi Valley put on their green clothing in the spring of every year and changed to brown clothing in the fall of every year even better before the coming of "intelligent" man than after his appearance on the scene. The "canals" of *Mars* may be evidence of intelligent life on that planet; but unless we accompany them with some rather violent assumptions the canals could serve equally well as examples of the lack of intelligence on the planet. How would engineers on the Earth proceed to catch the water from the melting north polar cap of the Earth and use it for irrigation, not only south to the equator, but well down into the southern hemisphere? How would they reverse the process and use the waters from the south polar cap to irrigate not only as far north as the equator but well into the northern hemisphere—it being assumed that there are no oceans to interfere? Would intelligent engineers insist on running their canals absolutely straight for thousands of miles, or would they follow the contours? As the surfaces of the Earth and the Moon are exceedingly unlevel, is it reasonable to assume that *Mars,* half-way between the Earth and the Moon in size, has a level surface? *Mars* probably has animal life, but in my opinion we have not the proof of it.

I think it is impossible for an intelligent and thoughtful mind to contemplate the orderly solar system, completely isolated from other systems, its great Sun in the center, the tiny planets and the infinitesimal asteroids revolving around the Sun in the same direction and nearly in a common plane, the moons revolving around the planets, all of the planets and asteroids around the Sun from west to east, and nearly all of their moons around their planets from west to east, without saying to ourselves: the members of the solar system have had a common origin; the materials in the Sun, the planets and moons have had a prior existence under other conditions; and the operation of the laws of nature has developed the system to its present state, and will guide its further development to the state which the future has in store for it. Kant's hypothesis would have the development proceed from a great collection of matter in a chaotic state—the same matter which, transformed and redistributed, now composes the system. Laplace's hypothesis would develop the solar system from a rotating parent nebula. Chamberlin would have the antecedent nebula spiral in structure. This phase of the subject would demand a full hour for adequate treatment, and we must be content to say that all astronomers believe the solar system to be the product of evolution.

Are there other solar systems than ours? Are there planets revolving around the other stars, as our planets revolve around our Sun? Is there life on planets in other systems? We do not know. We are powerless to answer these questions at present. If we should transport our astronomers and their most powerful instruments to *Alpha Centauri*, the solar system's nearest neighbor, they could not look back and see the planets which attend our Sun. They would see our Sun by naked eye as a first-magnitude star, but our greatest planet, *Jupiter*, would be a star of the twenty-first magnitude, and their telescopes at *Alpha Centauri* would have to be at least twenty-five feet in diameter in order to show *Jupiter* as a stellar point of light, just on the limit of vision; even though the flood of light from our Sun did not interfere with the observation. The fact is that *Jupiter*, as seen from *Alpha Centauri*, would never be more than five seconds of arc from our Sun, and the glare of sunlight in the Centauran telescope would hopelessly drown the image of *Jupiter*, even though the diameter of the telescope were much greater than twenty-five feet. The latter difficulty would resemble that of trying to see a glow worm that is two feet to the right or left of a powerful searchlight located sixteen miles from the observer.

Although we have not been able to secure direct and positive evidence in favor of other planetary systems, and although we see no promise of such evidence in the future, it would be unreasonable to believe that such planetary systems do not exist. It would be contrary to the simple probabilities if our Sun, one of several hundred millions of suns, were the only Sun attended by planets, and our Earth were the only planet that was the abode of life. We are not able to prove that we have neighbors scattered throughout the great stellar universe, but we are justified, I think, in believing that they are there.

WHAT WE KNOW ABOUT COMETS[1]

By W. W. Campbell

The startlingly sudden appearance of some great comets, the rapid growth of others to enormous sizes and their equally rapid disappearance have naturally excited the interest and, only too often, the fears of the human race. We are removed less than two centuries from the long-prevailing theological view that comets are flaming fire-balls hurled at the Earth by an angry God, to frighten and punish a sinful world. Up to the time of my childhood the opinion was widespread among civilized peoples that comets are the forerunners of famine, pestilence and war. Did not the great comet of 1811 herald the war of 1812; the comet of 1843 the war of 1846; and Donati's comet of 1858 our Civil War? Even in the twentieth century the fear that a comet may collide with the Earth and destroy its inhabitants comes to the surface, here and there, every time a comet is visible to the naked eye. This fear is not lessened by the highly sensational descriptions of such encounters by professional writers who have that little knowledge which has been called a dangerous thing.

The Earth has undoubtedly encountered comets' tails scores and scores of times since the advent of man, and with no baneful effects; and in the light of present-day knowledge of the structure and chemical composition of comets there is no danger whatever that our atmosphere will be poisoned by such an encounter. It is true that a collision between the Earth and the head of a comet *could* happen, but we see no reason to question the accuracy of the estimates made by mathematical astronomers that such encounters will not occur more than once in fifteen or twenty million years, on the average! It is by no means certain that such an encounter, should one ever occur, would be a serious matter for the Earth. Its effects might be confined to a brilliant shower of meteors, such as the peoples of the Earth have observed many times. Geologists

[1] Delivered December 8, 1916.

PLATE VI. Halley's Comet, May 1, 1910: Head and Beginning of Tail.

Photograph by H. D. Curtis.

are of the opinion that the outcropping strata of the Earth which they have been able to study have required a period of approximately one hundred million years for their formation. These strata, embracing the entire land area of the Earth, have given only one bit of evidence that the Earth's surface has been affected by a collision with an outside body. In central Arizona is a cup-shaped hole in the ground, about three quarters of a mile in diameter and several hundred feet deep, which has been formed, with little doubt, by the descent of a great meteorite, or of a great cluster of small meteorites: thousands of small iron meteorites have been found in and all around the hole, and there are no evidences of volcanic activity in the crater and its immediate surroundings. Geologic and geographic surveys of the Earth have revealed no other case of collisional effects[2] in the records of a hundred million years. Man himself has lived upon the Earth certainly many tens of thousands of years, and there are no traditions extant concerning injuries to earth or to man from comets. Why then should anybody worry about possible injury from a comet in his short span of three-score years and ten?

The answer to our first question, where do comets come from, involves the question of their relationship to the solar system and to the great stellar system. It is essential that every auditor should understand certain prominent features of the solar and stellar systems; and, at the risk of repeating what many members of the audience already know, I shall devote a few lines to a description of these systems.

Widely scattered throughout a great, but finite, volume of space occupied by our stellar system are tens of millions of stars. It is estimated that our largest refracting telescopes could show us about seventy million stars, and that the reflecting telescopes could photograph possibly two or three times as many. Our own Sun is just one of these scores of millions of stars. It seems very large, very bright and very hot because we on the Earth are relatively close to it. It is our own star. Revolving around it are many planets, of which our Earth is one. Probably the other stars in many cases, possibly in all cases, have planets revolving around them in the same way.

[2] Neglecting the insignificant cavities produced by isolated small meteorites.

We do not know that this is a fact because the nearest star, excepting our own star, is so far away that we should require telescopes at least twenty-five feet in diameter to see planets revolving about it, even though such planets be as large as *Jupiter* and *Saturn*, the largest planets revolving around the Sun.

Now the Sun and its planets and their moons are the chief members of an orderly system which we call the solar system. Ninety-nine and six-sevenths per cent of all the materials in the solar system is in the Sun, and only one-seventh of one per cent is divided up to form the planets and their moons: *Mercury*, *Venus*, the Earth and its one moon, *Mars* and its two moons, the more than eight hundred minor planets which move in the zone lying just outside of the orbit of *Mars*, the giant planet *Jupiter* and its nine moons, the planet *Saturn* with its ring system and its nine moons, the planet *Uranus* and its four moons, and the outermost known planet *Neptune* and its one moon.

It is a most interesting fact that all of these planets revolve around the Sun in the same direction, which astronomers have agreed to call from west to east, or in the "direct" sense. Motion from east to west is called "retrograde".

Another remarkable fact is this: the orbits of all these bodies lie nearly in the same plane. If we call the distance from the Sun to the Earth unity, then the distance from the Sun to the outermost planet, *Neptune*, on the same scale is thirty units, and the diameter of the solar system on that scale is sixty units. If we had a great box sixty such units in diameter and only one unit in thickness the solar system could be placed within this box and all of the eight major planets and their moons and nearly all of the minor planets would perform their motions within the box. A few of the minor planets would dip a little out of the box, above or below.

The solar system is very completely isolated in space. If the distance from the Sun to the Earth is one and from the Sun to *Neptune* thirty, then the distance to the next nearest star of which we have any knowledge, *Alpha Centauri*, is 275,000. A ray of light traveling with a speed of 186,000 miles per second would travel from the Sun to the Earth in eight and one-third minutes, to *Neptune* in four and a half hours, but it would require four and a half years to reach the Sun's nearest neighbor, *Alpha Centauri.* The stars in the great stellar system are distributed more or less irregularly, but their average distance apart is of the order of six or seven or eight light-years.

All of the stars are in motion, and our own star, the Sun, is no exception to the rule. It is one of the well-established facts of astronomy that our solar system is traveling through space in the general direction of the boundary line between the constellations *Lyra* and *Hercules* with a speed of approximately twelve and one-half miles per second.

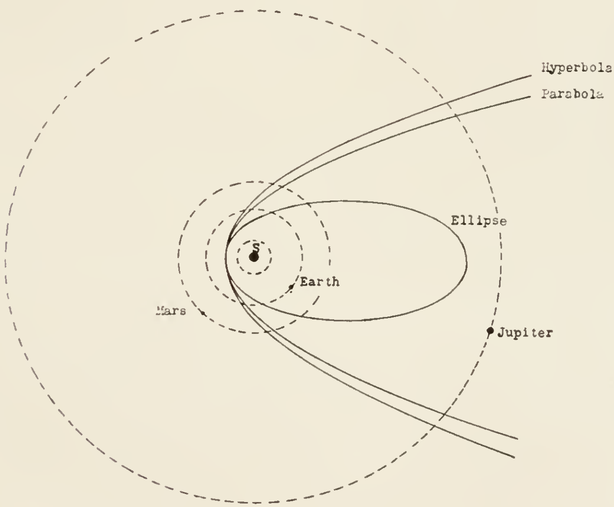


FIG. 1. CHARACTERISTIC FORMS OF ORBITS.

It is well known that the orbits of our planets are ellipses which do not differ greatly from the circular form. The comets, on the other hand, move in very elongated orbits around the Sun. The orbits of some comets are easily recognized as ellipses, but for the great majority of comets the orbits differ but little from the parabolic form. The parabola, as many of you know, is on the dividing line between ellipses and hyperbolas. The ellipse is a closed curve, and a comet moving around the Sun in an elliptic orbit should return again and again to the neighborhood of the Sun; but a comet following a parabolic or hyperbolic path, subject merely to the attraction of the Sun, can pass through the vicinity of the Sun only once, for the parabola and the hyperbola are not closed curves, and the branch upon which the comet approaches the Sun and the branch upon which the comet recedes from the Sun never come together, no matter how far out from the Sun they be drawn.

There have been two hypotheses as to where the comets come from. Sir Isaac Newton thought of them as moving in elongated ellipses. It was the view of Immanuel Kant 160 years ago that comets are bona fide members of the solar system, just as the Earth and *Neptune* are: that their orbits are all ellipses, but very elongated ellipses. He said that the comets travel out a great distance from the Sun, but that they must eventually return because they are moving in ellipses. Kant's view of the subject was essentially a mere opinion, though the opinion of one of the greatest philosophers of all time, who gave careful consideration to every known fact. Up to Kant's day, and for many decades later, comet observations were crude in comparison with present-day standards. Most comets were observed for only a few weeks, and the true characters of the very elongated orbits could not be affirmed.

Half a century later the great Laplace championed the view that the comets belong to the stellar system and not to the solar system; that comets are travelers through interstellar space; that the wanderings of a chance few comets bring them within the sphere of influence of our Sun; and that we see those which come into favorable position near the Earth. Halley's celebrated comet was the only one then known to return again and again to the region of the Sun, and it was thought to be a captured wanderer. In Laplace's time also the comets were still inaccurately observed, over short periods of time, and in nearly every case a parabola seemed to represent their motion satisfactorily. This Laplacean view that comets are wanderers through the great stellar system and are only chance visitors to the solar system was the prevailing one throughout the nineteenth century. Evidences to the contrary began to appear as early as 1860, but so firmly rooted was the hypothesis, that only in the twentieth century have astronomers in general been convinced that the comets are members of the solar system. Several lines of evidence, all in good agreement, have brought us to this conclusion.

1. Since the solar system is traveling through the stellar system in the direction of the constellations *Lyra* and *Hercules*, with a speed of twelve and a half miles per second, if comets come in from interstellar space we should *meet* more comets coming from the *Lyra-Hercules* direction than there are comets *overtaking* us from the opposite part of the sky, for precisely the same reason that if we are traveling very rapidly by automobile from San Diego to Los Angeles we should meet more autos than would overtake us and pass us. Now the comets do not show that preference. As early as 1860 Carrington studied the directions of approach of all the comets, 133 in number, which up to that time were considered to have parabolic or hyperbolic orbits. He found that only sixty-one[3] of these comets met the solar system, so to speak, whereas seventy-two[3] comets overtook us—extremely strong evidence that the comets are traveling along with us, just as all of our planets are traveling with the Sun while revolving around it. Many later astronomers, especially Fabry, using the more plentiful and more accurate data now available, have confirmed this conclusion that there is no tendency for comets to meet us, as we rush through interstellar space, rather than to overtake us. It is a fact, however, that the observed comets have not had their directions of approach distributed uniformly over the surface of the sphere. Their deviations from reasonable uniformity appear to be due in small measure to a preference of comets to travel in planes making small angles with the ecliptic, with motion around the Sun from west to east as in the case of the planets; but the chief discrepancies arise from the heterogeneous circumstances under which comets are discovered.

Nearly all discoveries of comets made by means of telescopes prior to forty years ago were made in the northern hemisphere, at observatories situated in latitudes north of +40°. The southern hemisphere is still very much in arrears

[3] The disparity in the numbers is thought to be purely accidental.

in the matter of comet discoveries, though the discrepancy is not now so great as it once was.

There is more searching for comets in the northern hemisphere during the northern summer and in the southern hemisphere during the southern summer than in their respective winters. There is also a better chance for northern observers to discover comets when the Sun is farthest north in June and for southern observers when the Sun is farthest south in December. These facts lead to the discovery of comets, prevailingly, which come to perihelion in certain favored regions; that is, in the regions of the sky where the Earth is at those times.

It is advantageous at this point to call attention to other sources of lack of homogeneity in comet data.

Prior to the invention of the telescope, three centuries ago, about 400 comets had been made matters of historical record. These were naked-eye objects which forced themselves upon the attention of observers. They were the especially large comets which came close to the Earth or to the Sun. They were imperfectly observed, and for only a small proportion of them do we know even their approximate orbits.

Since the invention of the telescope, about 450 comets have been discovered, and the half of these have been found in the last fifty years. What we may call the golden age of comet discovery included the two decades, 1888 to 1908, when 100 comets, an average of five per year, were discovered. Four American observers, Swift, Brooks, Barnard and Perrine, announced the arrival of thirty-seven of these 100 comets.

All of the early comets were visible to the naked eye. Only a small fraction of recent comets, perhaps one in four, become bright enough for the unassisted eye to see the head, and perhaps one in eight or ten for the unassisted eye to see the tail. Computed comet orbits have become increasingly accurate, partly because of greater telescopes, which enable these bodies to be more accurately observed and observed through longer arcs of their orbits.

2. Another decisive argument for the theory that comets are at home in the solar system is this: Schiaparelli showed in the early '70's that, owing to the Sun's motion through the

Fig. 1—Donati's comet, 1858, Oct. 5; head and beginning of tail; brilliant stellar nucleus near center of head; envelopes surrounding nucleus on side toward the Sun. White circle to the left represents comparative size of the Earth.

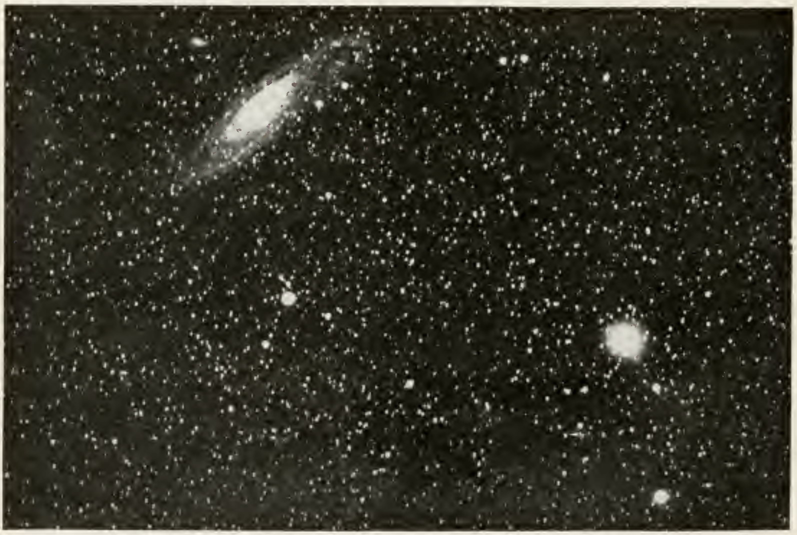


Fig. 2—Holmes's comet of 1892; no tail was visible in the telescope; long-exposure photographs (Barnard, 3 hours, Nov. 10, 1892) recorded an extremely faint tail extending down to lower right corner of the picture. The great spiral nebula in *Andromeda* was recorded on the photograph—upper left corner of picture.

PLATE VII.

stellar system, if the comets come from distant interstellar space, a very large proportion of them should move around our Sun in hyperbolic orbits, and many of these orbits should be *strongly* hyperbolic. Schiaparelli's conclusions have been confirmed and extended by several mathematical astronomers, notably by Louis Fabry. Fabry concluded: If the Sun travels through the stellar system and the comets come to the Sun from interstellar space, then the comets should all move in hyperbolas—differing from the parabola the more as the velocity of the Sun through space is the greater.

What are the facts of observation? Of 347 comet orbits fairly well determined

(a) 60 are certainly elliptic;
(b) 275 are approximately parabolic;
(c) 12 or fewer are slightly hyperbolic;
(d) None are strongly hyperbolic.

Now it has been shown by Thraen, Fayet and Fabry in the last two decades that several of the twelve orbits thought to be hyperbolic were not really so, but that they owed their reputations to poor or insufficient observations, or to errors in the computations, and that all of the genuine hyperbolas save one acquired their hyperbolicity after the comets concerned came under the disturbing influences of our planets. Five years ago (1911) Strömgren was able to show that the one outstanding hyperbolic orbit was caused, in the same way, by the disturbing attractions of the planets. The original, undisturbed orbit of every one of the so-called hyperbolic comets was, therefore, an ellipse. Fayet has further shown that a very great majority of the orbits which had been observed to be sensibly parabolic when the comets were near the planets and Sun were clearly elliptic when the comets were still far out from the Sun; that is, as these comets, moving in elliptic orbits, came in toward the planets and Sun, the attractions of the planets made their orbits approach closely to the parabolic form. There is no reason to doubt that far out in the domain of the Sun the comets all approach in elliptic orbits; but that when the attractions of one or more of our planets upon them become appreciable, some of the orbits are changed into shorter ellipses, others are changed into ellipses so long that it is difficult to distinguish them from parabolas, and many orbits are changed to the hyperbolic form. Those comets whose orbits are thus thrown into the hyperbolic form will leave the solar system and travel out through the stellar system.

3. A statistical study of comet orbits made by Leuschner a decade ago bears upon this question. He found that prior to 1755 ninety-nine per cent of all comets were *said* to move in parabolic orbits, but that only fifty-four per cent of comets between 1846 and 1895 were *said* to move in orbits approximately parabolic; and, secondly, that of comets under observation less than one hundred days, sixty-eight per cent were *said* to be parabolas, whereas of those observed from eight months to seventeen months, only thirteen per cent have orbits approximately parabolic. These facts point to the conclusion that when comets are observed inaccurately, as of old, and in only a short section of their orbits, parabolic orbits satisfy the observations within the limits of the errors unavoidably attaching to those observations; but that when comets are observed accurately and for a long stretch of time, nearly all are found to be moving in ellipses. Most of the ellipses are of course extremely long ones.

If comets starting substantially at rest came from a very great distance away from our Sun, say one-hundredth the distance of the nearest star, which we think is decidedly within the sphere of our Sun's attraction, they would move in ellipses so elongated that we could not hope to distinguish them from parabolas. Their periods of revolution would be nearly one hundred and fifty thousand years. Yet they would be members of our solar system, subject to the Sun's attraction, and unless disturbed by some other body or bodies, they would return again and again to the center of the system.

The work of Carrington, Schiaparelli, Fabry, Fayet, Strömgren and Leuschner and of many others has left no room for doubt that comets are bona fide members of our solar system. The materials composing the great majority of comets spend most of their time in regions far removed from the Sun and its planets, as our little distances in the planetary system go, but close to the Sun in terms of the magnificent distances which separate our Sun from the other suns. They are moving in closed orbits around our Sun and traveling through space along with our Sun.[4]

Besides the comets which go out on extremely elongated orbits to great distances from the Sun, there are about fifty elliptic comets which are closely related in one sense to some of our planets. About three dozen are in the so-called *Jupiter-*

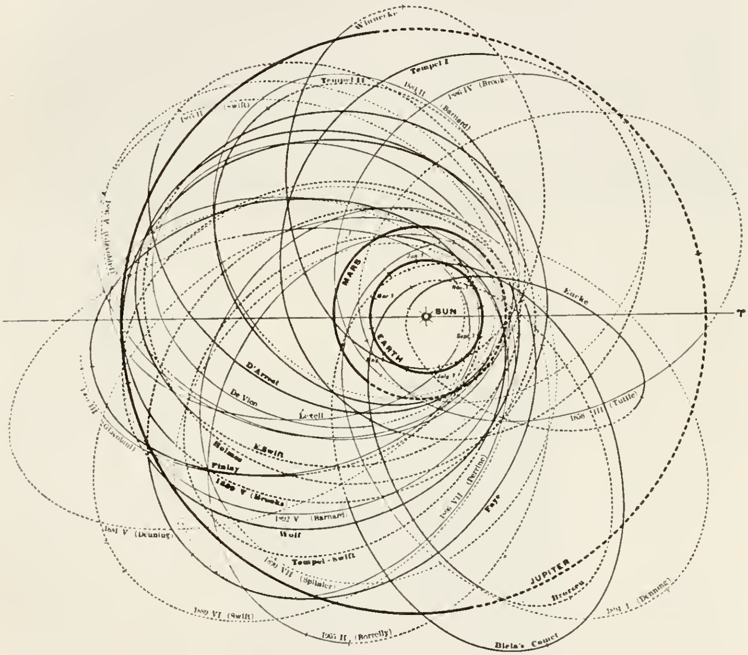


FIG. 2. JUPITER'S FAMILY OF COMETS (UP TO 1893).

family of comets. The orbits of all those discovered up to 1893 are represented in Fig. 2. It is seen that the outer parts of all of them—the aphelia—are in the vicinity of *Jupiter's* orbit. Similarly, there are a few comets related to *Saturn's* orbit, a few to the orbit of *Uranus,* and six comets to the orbit

[4] Those who would like to look more thoroughly into this question are strongly advised to read Schiaparelli's paper on "Orbites cométaires, Courants cosmiques, Météorites," in *Bulletin Astronomique,* 27, 194-205 and 241-254, 1910. It embodies some points of view slightly different from those presented by me. The technical contributions by Fabry, Fayet and Strömgren are extensive and of a high order of merit; and students of comets cannot afford to neglect them.—W. W. C.

of *Neptune*, one of the latter being Halley's comet. The *Jupiter* comets have periods lying between three and nine years, and the *Neptune* comets complete their circuits in from sixty to eighty-one years.

What has been the history of these short-period comets? H. A. Newton and other investigators have shown that it would be impossible for great numbers of comets, such as have been observed, to move through the solar system, without a certain proportion having their orbits changed into short-period elliptic orbits. It is the accepted view that the short-period comets have been captured, so to speak, by the combined attractions of the Sun and one of the planets in each case. The chances of capture by the planets are greatest when the approaching bodies are moving in orbits which lie in planes most nearly coincident with the plane of the planetary system, and when their motions around the Sun are from west to east. Newton's analysis of the problem led to the conclusion that five or six times as many captured comets should move in the direct sense, west to east, as in the retrograde sense, east to west. Now the only comets with periods less than one hundred years which are revolving around the Sun in the retrograde direction are Halley's comet, period seventy-six years, and Comet 1866I, period thirty-three years. The three dozen members of the *Jupiter*-family revolve from west to east without exception. That the motion in the short-period orbits is so universally from west to east finds the most probable explanation in the view that the cometary materials, when they were farthest from the Sun, long before they approached the region of the planets and the Sun, already had a slow motion from west to east, the motion of the parent mass of matter from which the solar system itself was developed. The French astronomer, Faye, on the assumption that comets have originated in the outer parts of a rotating mass which has developed into the solar system, came to the conclusion that comets should move prevailingly in the direct sense when their orbit planes do not differ greatly from the orbit planes of the planets, but that those whose orbit planes make great angles with the plane of the solar system should show no preference for the direct over the retrograde motion. These theoretical results are in good accord with the observed facts.

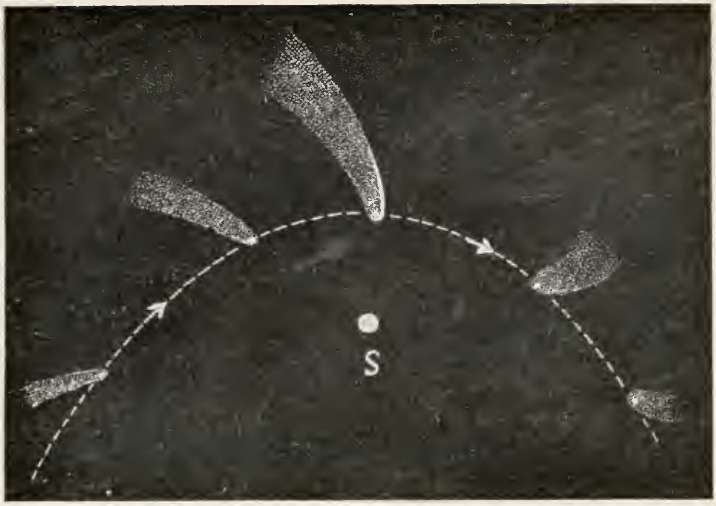


FIG. 1—Comets' tails lag behind the line joining the Sun (S) and the comets' nuclei. Orbital motion is carrying the nucleus of the comet to the right.

FIG. 2—Diagram illustrating the three principal types of tails of comets. Orbital motion is carrying the nucleus to the left. The Sun is below.

PLATE VIII.

Our second question is, What are comets?

Comets have certain characteristic features:

1. There is always a head, or coma as it is sometimes called, a shining mass of hazy, nebulous matter. The head is sometimes circular in outline, more frequently elliptical or nearly so, but again it is oval on the edge facing the Sun and merges insensibly into the tail on the side opposite the Sun (Plates VI and VII). The sizes of comet heads vary enormously. One less than ten thousand miles in diameter would be most unusual and generally would escape discovery. The head of the great comet of 1811 was at one time more than a million miles in diameter. The head of the great comet of 1882, which many of us enjoyed seeing, was for a long time about one hundred and fifty thousand miles in diameter. It is a curious fact that the heads of comets in general contract in size as they approach the Sun and expand as they recede from the Sun. Encke's periodic comet, which has been observed on many returns, frequently had a diameter of two hundred and fifty thousand miles or more when the comet was at a great distance from the Sun, whereas the diameter of the head reduced to ten thousand or fifteen thousand miles when the comet was nearest the Sun. Before the disappearance into distant space the head resumed its original dimensions. A satisfactory explanation of the contraction and expansion of the heads of comets has not been found.

2. Near the center of the head of the comet there is usually a brilliant, star-like point which we call the nucleus (Fig. 1, Plate VII). This is the point upon which accurate measures are made when it is a question of determining the position and the orbit of the comet. In general the nuclei are most sharply defined for those comets which have come in from great distances upon orbits nearly parabolic, and the nuclei are frequently hazy, poorly defined, and sometimes entirely lacking, in the comets composing *Jupiter's* comet family. Occasionally there is a double, a triple, or a quadruple nucleus, a division undoubtedly connected with the disintegration or breaking up of the comet into smaller masses. The size of the nucleus varies greatly, apparently from a few miles up to several thousand miles in diameter.

3. Most comets have tails. They frequently develop to enormous dimensions. When a comet is observed at a great distance from the Sun, only the head and nucleus are usually visible. The tail develops with close approach to the Sun. The tail of the comet of 1882 was at one time more than one hundred million miles in length; that of 1843 was at one time two hundred million miles. As comets recede from the Sun, the tails diminish in extent and usually disappear long before the head and nucleus are lost to sight. Several of the *Jupiter* comets do not have visible tails (Fig. 2, Plate VII). They appear not to possess in abundance the materials which go to form comets' tails.

4. When comets approach relatively close to the Sun the heads frequently throw off a series of concentric shells or envelopes. The materials composing these envelopes appear to be expelled from the head and toward the Sun at high speed, but these speeds of approach to the Sun seem to be gradually overcome and the materials turned away from the Sun to assist in forming the tails (Fig. 1, Plate VII).

The tails of comets, it is well known, point away from the Sun. However, the popular view that they point *exactly* away from the Sun is seriously in error. In general they lag behind the line passing through the Sun and the comet's head (Fig. 1, Plate VIII). There can be no doubt that they point away from the Sun because of some repulsive force, originating in the Sun, which acts upon the minute dust particles or gas molecules released from the comet's head. It takes time for these particles to travel out millions of miles from the head, and, while they are moving out, the head is moving forward in its orbit. The nucleus obeys the gravitational attraction of the Sun absolutely, so far as observation has gone, and we have no reason to suspect that it is subject to an appreciable repulsive force. The particles composing the outer regions of the head and the particles composing the tail are doubtless attracted by the gravitation of the Sun and are at the same time driven away by the repulsion of the Sun. What the particles will do under the action of the two opposing forces depends upon the ratio of these forces. If the repulsive force is vastly stronger than the attracting force the particles will travel out from the head with great and increasing speed and form a tail pointing nearly away from the Sun; that is, it will lag behind very little. If the attracting and repelling forces acting upon another group of particles are not very unequal those particles will form a second tail having considerable lag. If the repulsive force is very weak with reference to the Sun's attractive force upon a third group of particles, they will form a short tail that lags very far behind. The forms and positions of comet tails were studied extensively by Bredichin, who found that there were three classes of tails, corresponding to three fairly definite ratios of repulsive to attractive forces, as indicated by three different degrees of lagging behind the line joining the Sun and the head (Fig. 2, Plate VIII).

Bredichin determined that the long slender tails, observed in a few comets, which lag behind only slightly are the result of a repulsive force twelve to fifteen times as intense as the attractive force. He found another class of comet tails, of medium lag, for which the repulsive forces were from 2.2 to 0.5 times the attractive forces. Another class of tails, short and bushy, with very strong lag, were explainable on the assumption that the repulsive forces were relatively weak, from 0.3 to 0.1 of the attractive forces.

In some comets only one of these three classes of tails is present, and again in one and the same comet all of the classes may be present at the same time.

That there is outward motion of the tail materials admits of no doubt. It is not uncommon for the tail materials of one night to be driven off into space, scattered and lost to sight, and for an entirely new tail to take its place by the following night. A comet's tail is constantly forming and moving out. The tails of Comet Rordame (Plate IX) photographed by Hussey on two successive nights, July 12 and 13, 1893, have no points of resemblance. The streamers composing the tail on one night are fairly straight, regular, and rather faint. The tail of the following night is very much broken, there are several fairly well-defined nuclei, and it is brighter than the tail of the 12th. Two photographs of this comet were fortunately made on the second night, with a time interval of three-quarters of an hour. A comparison of the positions of the three nuclei on the two plates showed that they had moved outward from the head with great speed during the interval. The nucleus nearest the head had traveled out with a speed of forty-four miles per second, the next nucleus with a speed of fifty-two miles per second, and the one still farther out with a speed of fifty-nine miles per second. Here are two photographs of Comet Brooks (Plate X) made on October 21 and October 22, 1893, by Barnard. The structure of the tail on the first photograph is not at all the structure on the second. The tail of the first night has been scattered to invisibility and an absolutely new tail has replaced it. The outward motion of well-defined tail structure has been measured for many comets. Here is a series of measures made by Curtis upon points in the tails of Halley's comet.

AVERAGE VELOCITIES OF RECESSION, FROM THE HEAD, OF MATTER IN THE TAIL OF HALLEY'S COMET

Date, 1910	Mean Distance from Head	Average Velocity
May 23	800 miles	0.6 miles per sec.
May 27-28	400,000 miles	8 miles per sec.
May 25-26	930,000 miles	12 miles per sec.
June 2-3	1,360,000 miles	20 miles per sec.
May 28-29	1,730,000 miles	23 miles per sec
June 6	2,200,000 miles	27 miles per sec.
May 26-27	2,500,000 miles	24 miles per sec.
May 30-31	6,600,000 miles	45 miles per sec.
June 7-8	8,400,000 miles	57 miles per sec.

The points to be measured were not well defined, and the measures could not be accurate, but it is clear that high speeds and accelerated speeds prevailed. The tail materials start out slowly from the head, and increase their speeds with the distance from the head, as we should expect of motion resulting from the action of a continuous force which meets with no sensible resistance.

In Plate XI are reproductions of photographs of Halley's comet made by Curtis on June 6 and June 7, 1910. A semi-detached part of the tail, seen on the photograph of June 6 about an inch above the head, is visible about two and a half inches above the head on the photograph of June 7. This structure was first observed by Curtis shortly after it had emerged from the central part of the head on June 4, and it

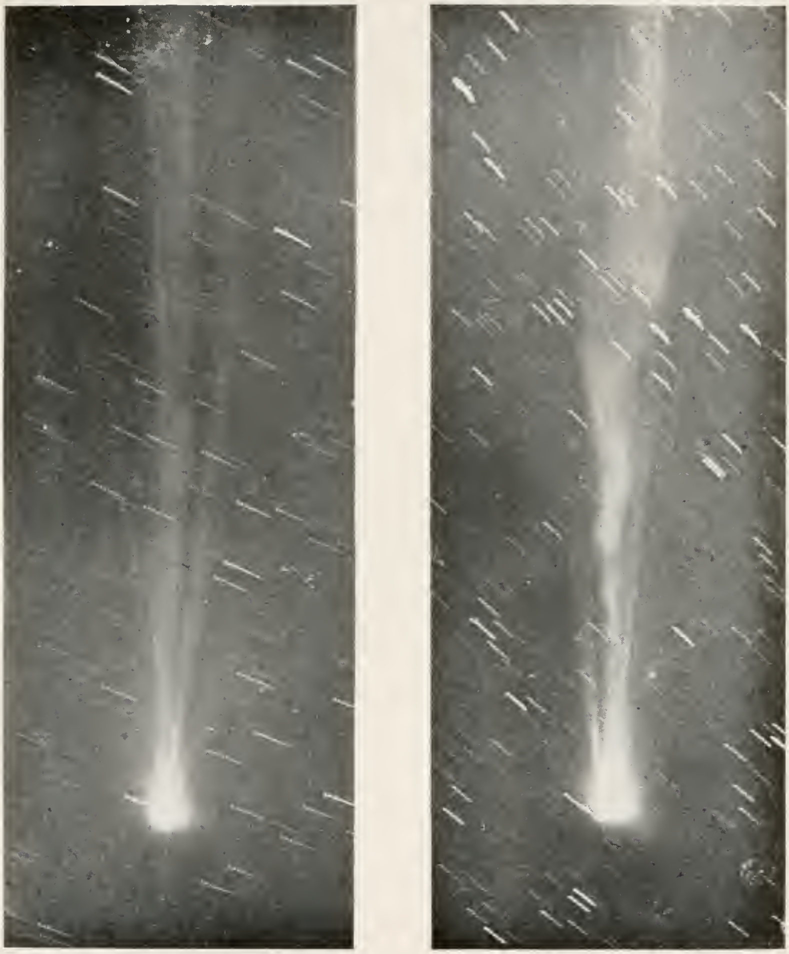


PLATE IX. Comet Rordame on July 12 and July 13, 1893.

Photographs by W. J. Hussey.

The camera followed the nucleus of the comet, and the stars "trailed."

was recorded on the photographs secured by a great many observatories in the following four days, as the rotation of the Earth brought the comet successively into position for observation at the different observatories. The times when the lower point of the structure had certain positions are indicated in Fig. 3. The tail did not seem to lag behind the position of the radius vector—the line passing through the Sun and the comet's nucleus—because the observers on those days were nearly in the plane of the comet's orbit and the lag of the tail was toward the observers. The velocity with which the structure moved out in the tail was strongly accelerated with the passing of time, as may be seen from the chart. The constant loss of materials dispelled along the tail would seem to require that comets in general grow fainter with time. This is the logical conclusion, and the observational evidence for it is undoubted in many of those comets which return again and again to the region of the Sun. Nearly all of the *Jupiter* comets have a hazy, washed-out appearance. Several of them do not develop tails, as if their supply of tail materials had already been exhausted by expulsion as former tails. Others of them develop only very short tails, and several short-period comets have entirely disappeared. To this phase of the subject we shall return.

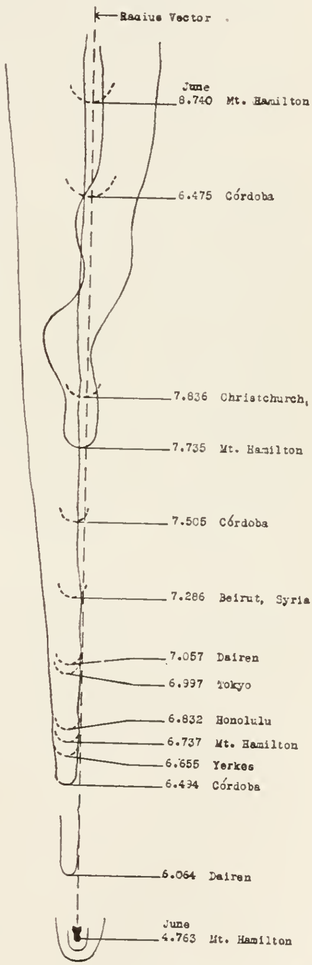


Fig. 3. Successive Positions of the Inner End of a Detached Tail of Halley's Comet, June 4-8, 1910.

As to the nature of the repulsive force responsible for comets' tails: It was long thought to be electrical, arising from a strong electrical field about the Sun and from electric charges of the same sign on the particles composing the tail. The idea is in part purely speculative, but the giving of serious consideration to it is justified because of the fact that much of the light of comets seems to arise from electrical conditions in them. The idea may be wrong in toto, or an electric repulsive force may be one of two or more forces which are acting. It can hardly be the only force involved.

Clerk-Maxwell half a century ago, from pure theory, and Lebedew and Nichols and Hull some fifteen years ago, from experimental evidence admitting of no doubt, showed that when light energy falls upon a surface it presses against that surface; very feebly it is true, but it will cause the body pressed upon to move if that body is not too massive. In this respect light-pressure repulsion and electric repulsion should act much alike. These repulsions are effective in proportion to the surface areas of the bodies acted upon, whereas gravitation pulls those bodies with a force proportional to their masses. Now the surface of a body is proportional to the square of its dimensions, whereas gravity acts in proportion to the cube of its dimensions. The smaller a body is, the more surface it has in proportion to its mass. Electric and radiation-pressure repulsions will therefore act more efficiently upon very small particles than upon large ones. A cube of water one centimeter on each edge would be drawn by the Sun's gravitational action ten thousand times as strongly as the pressure of the Sun's rays falling upon that body would repel it. But a cube of water only 0.001 of a mm. on each edge would be in equilibrium under the Sun's gravitational attraction and the Sun's light-pressure repulsion. A cube of water less than 0.001 mm. would actually be driven rapidly away from the Sun. The equilibrium diameter for little spheres of water, according to Nichols and Hull, is 0.0015 mm. Now as light energy is traveling along with a speed of 186,000 miles a second, we should expect particles of matter considerably smaller than the equilibrium size to travel away from the Sun with great and rapidly increasing speeds. These speeds would be the greater for particles smaller and smaller until a certain limit of size

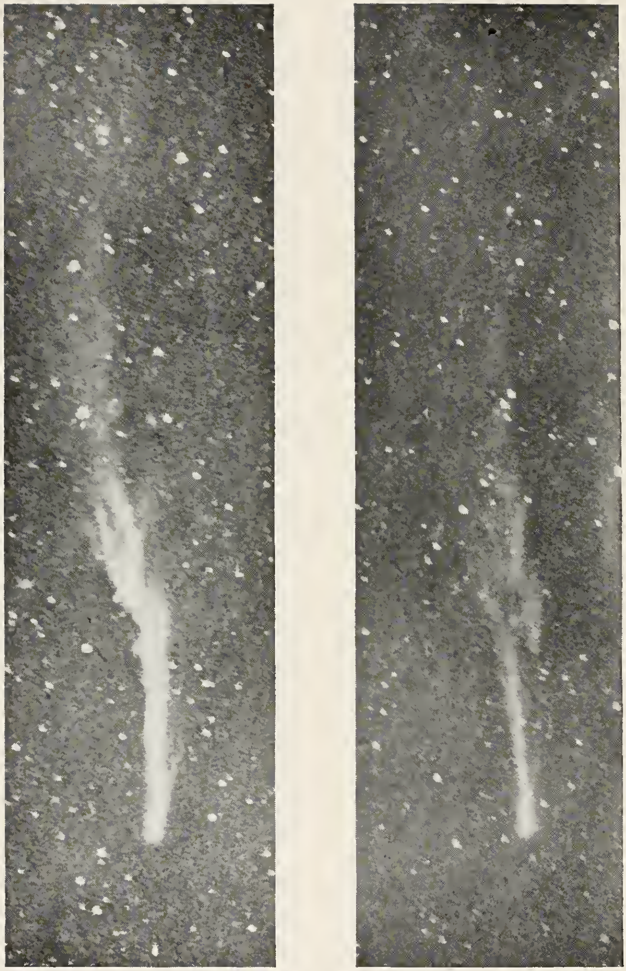


PLATE X. Comet Brooks on Oct. 21 and Oct. 22, 1895.

Photographs by E. E. Barnard.

with reference to the wave-length of light is reached, after which the light would be diffracted without transmitting so large a proportion of its repulsive energy to the particles. These limits of efficiency were determined by the lamented Schwarzschild.

The resistance of cometary particles is evidently also a function of the specific gravity of the particles. The figures which we have quoted are for water, density 1. We can scarcely doubt that radiation pressure is an important force, perhaps the chief force, perhaps the only force responsible for the driving out of the materials of comets' tails. Particles of solid matter or gas molecules of three different classes of sizes might be responsible for the three main classes of comets' tails. More probably materials of three different classes of density compose the three classes of tails. Bredichin called these three classes the hydrogen, the hydrocarbon and the iron tails. The atomic weights of these three substances give to their atoms or molecules about the right mobility, under equal pressure upon all, to explain the lags of the three classes of tails. Unfortunately it is far from certain that hydrogen exists in comets, and iron has been reported for only one comet.

The hoods or envelopes (Fig. 1, Plate VII) which form the outer strata of the heads of comets which come close to the Sun are very interesting. It is the prevailing view that, when a comet approaches the Sun, the solar heat falling upon that surface of the comet which faces the Sun generates or liberates the gases and vapors which have been contained in or between the more solid parts of the comet; and being liberated, in effect, under pressure, the materials at first travel toward the Sun with considerable speed. The Sun's repulsive force acts upon these jets and, overcoming the forward motion of the materials, it eventually turns them back along the tail. Those phenomena have been observed many times.

There is a great variety of comet spectra, indicating as great a variety of cometary contents or conditions. In some cases the spectrum seems almost wholly continuous, as in Holmes's comet of 1892; in others the light, when passed through the spectroscope, falls almost wholly into isolated bright lines or bands, as in Morehouse's comet of 1908. Other spectra are a combination of continuous and bright-line light (Fig. 1, Plate XII). The spectrum of the nucleus seems to be always continuous, or continuous except for absorption lines. In some of the brighter comets the nucleus spectrum as photographed contains the well-known absorption lines visible in the Sun's spectrum. These observations indicate that the nucleus is shining, at least mainly, by reflected sunlight. In most comets the continuous spectrum is too faint to let us photograph it and thus to prove the presence or absence of the solar absorption lines. The continuous spectrum in many comets extends also to the head, or at least to the inner strata of the head. This may or may not mean reflected sunlight. It may mean some other form of luminescence which yields a continuous spectrum. The greater parts of the heads of comets and those parts of the tails of comets which are close to the heads nearly always, and perhaps in every case, give a characteristic spectrum of bright bands, which were for several decades called the hydrocarbon bands. Observations of recent years have made it probable that this spectrum does not indicate a combination of hydrogen and carbon, but that it is either one of the low-pressure carbon vapor bands or that it results from one of the compounds of carbon and oxygen, preferably from carbon monoxide. The lines and bands of cyanogen—a nitrogen compound—and of carbon are present without any question in the heads and inner tails of many comets. Several observers have reported that the so-called hydrocarbon spectrum of the heads and inner tails extends far out into the tails. This may have been true for the cases reported, but recent observations are casting doubt upon the presence of that spectrum in the outer extensions of comet tails. Improved methods of photographing comet spectra were applied to the bright comets, Daniels of 1907 and Morehouse of 1908, especially by Deslandres, Evershed and Chrétien, with the result that their tail spectra were proved to be very different from the prevailing spectra of comets' heads and inner tails. Fowler has succeeded in duplicating the tail spectra of these two comets, in his laboratory, with remarkable agreement (Fig. 2, Plate XII), by photographing a cathode spectrum of carbon monoxide in a tube reduced to pressure not exceeding 0.01

mm. At higher pressure than this he obtained the so-called hydrocarbon spectrum, but it was not certain, and in fact it was improbable, that there was any hydrogen in the tube. The presence of carbon and nitrogen in comets is certain, the presence of oxygen is probable, and the presence of hydrogen is doubtful.

The comets which have approached very close to the Sun turned to a yellowish orange in color and remained so while in the vicinity of the Sun, because the yellow light of sodium then developed strongly in them, apparently by virtue of the intense heating of the cometary matter by the Sun's rays. This happened with the Wells comet of 1882, the great comet of September and October, 1882, the brilliant comet in January, 1910, and others. When the September, 1882, comet was only a few hundred thousand miles from the Sun, Copeland and Lohse observed not only the sodium lines but half a dozen other bright lines which they concluded were well-known iron lines.

What is the origin of the light which gives bright lines and bands? The sodium lines certainly, and the iron lines if actually observed, were no doubt due to the vapors of those elements having been rendered incandescent under the intense heat or other influence of the Sun. Strangely enough, when the brilliant sodium comets approached the Sun, the carbon bands, which had previously been prominent, disappeared and remained invisible until the comets had receded to a considerable distance from the Sun and the sodium lines were no longer in evidence. These observations, it should be said, were made by visual means. The photographic observations of recent years have been much more efficient in detecting the sodium lines and carbon bands when these are faint. The carbon light could scarcely be generated by heat action, for if so the carbon bands should have been in evidence during the time that the comet was passing nearest to the Sun. Much more probably the bright-line spectra of the head and tail are of electrical origin, or fluorescent. This phase of the subject is technical, and to some extent speculative, and we can not profitably pursue it further on this occasion.

A certain proportion of the light of many comets is slightly polarized. The interpretation of this phenomenon is that a fraction of the light of the heads and of the inner tails of comets is sunlight diffracted by minute dust particles or gas molecules in the comet structure.

Returning to the subject of the disintegration and disappearance of comets:

A small comet was discovered by Montaigne in 1772. A comet was discovered by Pons in 1805. A comet was discovered by Biela in 1826. Biela computed the orbit of his comet and found it to be moving in an ellipse of period six and a half years, and he proved that the three comets discovered respectively by Montaigne, Pons and himself were identically the same comet. Biela's comet was rediscovered in 1832, almost precisely in its expected place. The next return was missed because the body was not in good position for observing. It was rediscovered in 1845, when it was seen to consist of two comets moving side by side on orbits almost identical. In 1852 both comets were reobserved, but farther separated than they had been in 1845. The comet was searched for at the proper times for several later returns, but it was never seen again.[5]

Kirkwood published in 1872 a list of eight comets which had divided in a similar manner and disappeared.

A number of other comets have completely disappeared, though their orbits were very well determined.

This brings us to another interesting phase of our subject.

The *Perseid* meteors were with us again last August. Many of them have been seen every year for several decades. They are usually most numerous on the nights of August 9, 10 and 11. Predictions concerning meteors are somewhat risky, but so faithfully have the *Perseids* come every August that I have no doubt an observer on those nights of August, next year, from midnight on to daylight, will see dozens of meteors whose paths traced backwards would pass through a small area in the constellation of *Perseus*. In 1866 Schiaparelli computed the orbit of the *Perseid* meteors and noticed that it was essentially identical with the orbit of Comet 1862III. Here are the elements of the two orbits:

[5] One of the components of the Biela comet may have been observed for a few hours from Madras in 1872.

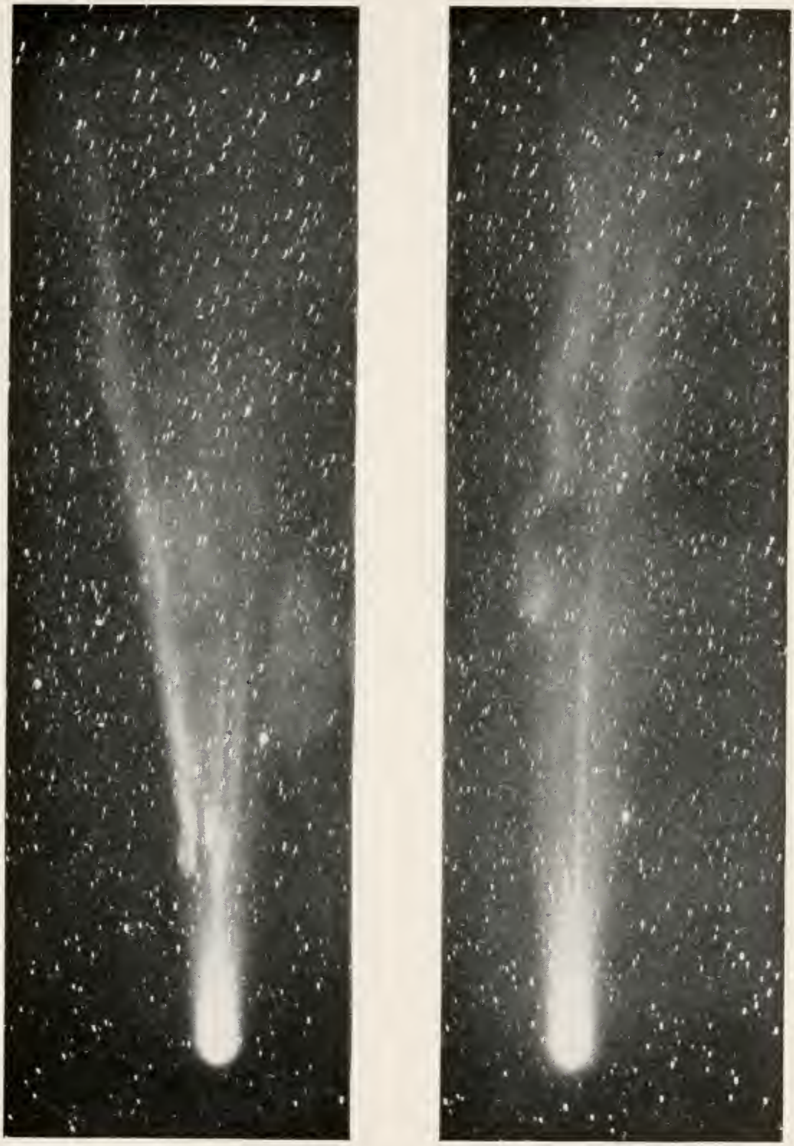


PLATE XI. Halley's Comet, June 6 and June 7, 1910.

Photographs by H. D. Curtis.

Orbits of	Meteors of August 9, 10, 11	Comet 1862III
Perihelion passage	July 23.62	August 22.9
Longitude of perihelion	343° 38′	344° 41′
Ascending node	138 16	137 27
Inclination	63 3	66 25
Perihelion distance	0.9643	0.9626
Period of revolution	105 years?	123.4
Direction of motion	retrograde	retrograde

The difference in the two perihelion times does not mean that their orbits were different even to the minutest degree, but only that, moving on the *same* orbit, they reached the point nearest the Sun at slightly different times; that is, the meteors traveled over the orbit a little in advance of the comet. The revolution period assigned to the meteors is subject to considerable error because it is not possible to observe the paths of the meteors with great accuracy.

There were rich and startling showers of meteors on November 12, 1799, and on November 12-13, 1833. H. A. Newton examined the literature of meteoric falls and found that many similar showers had been observed at intervals of thirty-three years running back several centuries to 902 A.D., "the year of the stars," and he confidently predicted that another great shower would occur on November 13-14, 1866. His prediction was abundantly verified. Early in 1867 Schiaparelli and Le Verrier independently computed the orbit of these meteors, and Schiaparelli and Oppolzer independently found it identical with the orbit of Comet 1866I. Here are the elements of the two orbits:

Orbits of	Meteors of November 13	Comet 1866I
Perihelion passage	November 10.092	January 11.160
Longitude of perihelion	56° 25 .9′	60° 28 .0′
Ascending node	231 28 .2	231 26 .1
Inclination	17 44 .5	17 18 .1
Perihelion distance	0.9873	0.9765
Eccentricity	0.9046	0.9054
Semi-major axis	10.340	10.324
Period of revolution	33.250 years	33.176 years
Direction of motion	retrograde	retrograde

It is impossible to doubt that these November meteors and the comet referred to were traveling in the same orbit.

The so-called *Lyra* meteors are visible about April 20 each year. It was noticed in 1867 by Weiss that the orbit of the *Lyra* meteors is essentially identical with that of Comet 1861I.

Biela's comet, to which we have referred, when last seen in 1852, as a double comet, was expected to return in 1866 and again in 1872, but it was not seen then, nor later. A meteor shower of moderate intensity was observed on November 27, 1872, moving in the orbit of the lost comet.

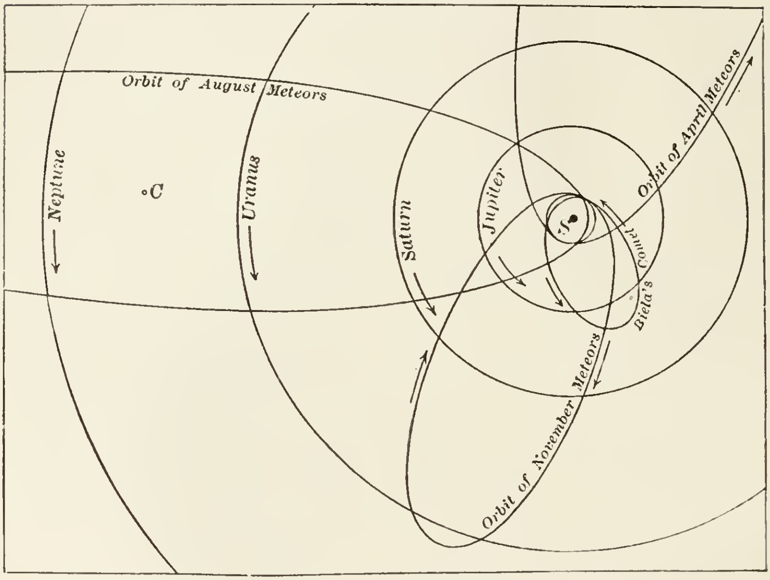
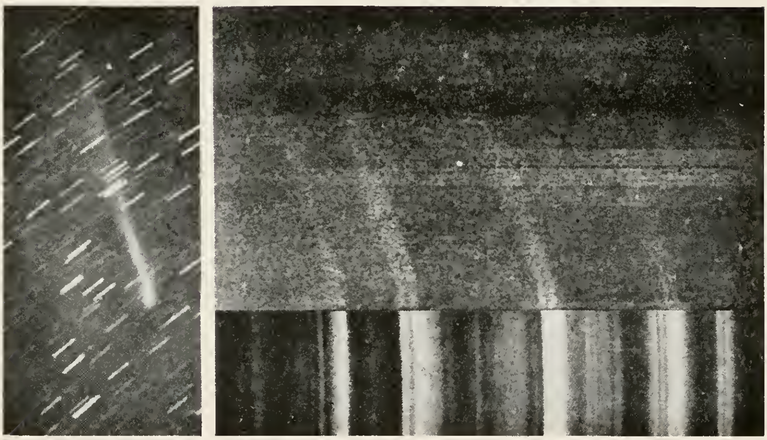


FIG. 4. ORBITS OF METEORIC SWARMS, WHICH ARE KNOWN TO BE ASSOCIATED WITH COMETS.

Not to dwell upon the remarkable identities of the orbits of the four meteor swarms, respectively, with the orbits of the four comets (Fig. 4), two of which have disappeared, and the other two, of relatively long periods, which may never return, we express the prevailing opinion of astronomers in saying that the meteor streams have actually resulted from the disintegration of the four comets. Alexander Herschel has prepared a list of seventy-six meteor streams whose orbits agree fairly closely with the seventy-six comet orbits. A certain proportion of the suspected identities probably represent

Fig. 1—Spectrum of Comet Daniels, 1907.

a *b*



c

Fig. 2—(*a*) Ordinary photograph of Comet Morehouse. (*b*) Spectrum photograph of Comet Morehouse made at same time as (*a*). (*c*) Fowler's spectrum of carbon monoxide, whose principal bands match the principal spectrum images of the comet's tail.

PLATE XII.

facts. It is interesting to note that even as early as 1861 the truth of the situation was expressed and printed by Kirkwood:

> May not our periodic meteors be the debris of ancient but now disintegrated comets whose material has become distributed around their orbits?

It was in this connection and at that time that Kirkwood was able to make a list of eight comets, each of which had divided into two or more parts and had wholly disappeared from the sight of observers.

The cause of the disintegration of comets is not far to seek. A comet's nucleus is thought to be a collection or cluster of small bodies, such as have been observed to collide with our atmosphere and to produce the meteor showers. They are held together, so to speak, while they are far away from the Sun, because of their own very small but sufficient attraction for each other; but when they come within our planetary system, and especially when they come relatively close to the great planets *Jupiter* and *Saturn*, the Sun and the planets attract the nearer particles of the comets more strongly than they do the farther particles. The nearer particles forge ahead on smaller orbits, the farther particles lag behind on larger orbits, and in the course of centuries the cometary material is strewn along a great stretch of the orbit. Other separative forces—of magnetic or electric natures, for example—may develop amongst the particles composing the nucleus as a comet approaches the Sun. The intensity of the reflected light in all parts of the scattered comet structure becomes too small to let us see the remains of the comet, except as the remnants collide with the Earth's atmosphere. There is certainly no reason to doubt that a very great many of our shooting stars are the remains of disintegrated comets. Tens of millions of little meteors enter our atmosphere every twenty-four hours and with rare exceptions are consumed by the heat of friction with the atmosphere when they rush through it at tremendous speeds. The gases from the combustion enter the atmosphere, and the ash and other unconsumed parts fall down to the Earth's surface in due time. Accumulated meteoric dust is found in the perpetual snows at the tops of high mountains, and Sir John Murray found it in the ooze brought up from the depths of the oceans. Whether the meteorites which penetrate our atmosphere and are found and placed in our museums are parts of ancient comets can not safely be asserted, but it seems entirely possible that some of them are. However, it is not certain that any meteorite found on the Earth has come from a meteor stream of recognized cometary origin. It is pretty well established that many of the sporadic meteors which plunged into our atmosphere were traveling on hyperbolic orbits.

We discover only a certain proportion of the comets which come close to the Sun and to the Earth. The numbers which course through the planetary system and remain undiscovered by the observers on the Earth must be exceedingly great. The supply of cometary material in the remote outskirts of the planetary system must be enormous. This material is probably in the nature of remnants of the nebula or other mass of matter from which the Sun, its planets and their moons developed. This idea is to a certain extent speculative; but that the cometary material is now out there in abundance we can not doubt. Much of it naturally consists of matter in the solid state; and, the Sun's attraction at that great distance being almost zero, neighboring masses could slowly come together as a collection of small solid masses, such as seem to compose the nucleus of a comet. Such a nucleus could attract and attach to itself any dust particles and molecules coming within its sphere of attraction. These might well, and probably would, include a collection of finely divided matter that had already been driven off in the tails of comets which in earlier ages had visited the Sun. The materials thus collected would be attracted by the Sun, a few of the collections would eventually pass comparatively close to the Sun, a few of the latter would be discovered as comets, and a part of the finely divided material contained in them would be driven off again as comets' tails into space, possibly to return many times in the bodies of comets coming later into the Sun's neighborhood. Certain of these bodies would come so close to the planets as to have their orbits transformed from very long ellipses into very short ellipses. Those comets would be disintegrated and their materials be widely scattered. We have seen that the

Earth has collided with such materials, and the Earth is growing slowly, very slowly, through the deposition of the remains upon its surface. Probably a little of the same materials goes likewise to other planets of the solar system and adds slowly to their masses. However, an insignificant proportion of the materials scattered in this manner through the solar system is thus accounted for, and the remainder doubtless revolves around the Sun in ellipses, probably contributing its share of reflected sunlight to the faint glow near the Sun known as the zodiacal light.

We have seen that devoted students of comets have learned much concerning these interesting travelers. Many mysteries have been removed, but many questions remain for the astronomers of the future to answer. We should especially like to know more of the physical conditions existing in comets, more about their chemical contents, and more as to why and how they shine by their own light. Perhaps the most valuable result of cometary investigation has been the emancipation of civilized peoples from unreasoning and groundless fears of these bodies, which come and go in obedience to the same simple laws that govern our every-day affairs.

A TOTAL ECLIPSE OF THE SUN[1]

By Robert G. Aitken

The first lecture of the present course gave a general account of our solar system as a whole, emphasizing particularly the harmonies in the motions of its component bodies and its isolation from other stellar systems. The second lecture described in detail what we know about one special class of objects within our system—the comets. It has seemed to me appropriate that our third lecture should be devoted to the Sun itself, the most important object in the universe for us—the source of heat, light, mechanical and electrical power, and, in the material sense, of life itself on our little globe.

But the phenomena of the Sun as revealed by our modern studies are so multifarious and raise so many intricate and interesting problems that it is quite impossible to treat them all in a single lecture. It is necessary to select, and I have chosen to place the emphasis in what I shall say this evening upon those phenomena which are more or less directly associated with a total eclipse of the Sun.

There are special reasons for this choice: No other natural phenomenon is so impressive, so startling, so fascinating, as a total eclipse of the Sun; many important advances in our knowledge of the Sun have had their origin in eclipse observations; the present year (1917) is a year of eclipses—seven, the maximum possible number, occurring within it; a total eclipse of the Sun will be visible in the western part of this country next year—June 8, 1918—for the first time in twenty-nine years; and, finally—a point of particular interest to us who are gathered here—our Society, the Astronomical Society of the Pacific, may be said to owe its existence to a total eclipse of the Sun. This was the eclipse of January 1, 1889, which, beginning at sunrise in the North Pacific Ocean, entered California near Point Arena at about 1:45 p. m., and swept across the State northeastwardly in a path some eighty miles broad, to end at sunset in northeastern Canada.

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[1] Delivered January 12, 1917.

The Lick Observatory, which had begun active work only six months earlier, sent a party headed by the late Professor Keeler to a favorable station on the central line of the shadow path. Near by were expeditions from other American observatories, and a strong party from the Amateur Photographic Association of the Pacific Coast, under the energetic leadership of Mr. Charles Burckhalter of the Chabot Observatory. This party of amateurs secured many very successful photographs, which were later discussed by Professor Holden, and the results published in Volume I of the *Lick Observatory Contributions*. It was the cordial coöperation of amateur and professional observers on this occasion, and the interest in astronomy revealed and stimulated by it among our people, that led to the formation of our Society.

The questions which I think you would like to have me discuss in this lecture are: (1) What causes an eclipse of the Sun or of the Moon, and why do we so seldom see a total eclipse of the Sun? (2) What do astronomers hope to discover at the time of a total eclipse that they cannot find out by studying the Sun at other times? (3) Just what do they do to get ready for an eclipse and during the few minutes of its duration?

It does not require a vivid imagination to picture the terror inspired among primitive peoples by a solar eclipse. To see the Sun in midday slowly but surely disappear without apparent cause (for the Moon is quite invisible until its disk begins to encroach upon the disk of the Sun), is sufficiently awe-inspiring even to those who understand the reason and who have made special preparations to observe the phenomenon; and it is easy enough to see how such myths as that of the dragon devouring the Sun came into being. Even in quite modern times an eclipse of the Sun was seriously regarded as a portent, "a sign and a wonder in heaven," and there is a quaint story concerning a total eclipse which occurred in our own colonial days while the General Assembly of Connecticut was in session. Many members were alarmed, some exclaimed that the Judgment Day was at hand, but one sturdy member called for candles, that they might proceed with their business and, if Judgment Day came, be found doing their duty.

Long before the dawn of recorded history, however, far-seeing men like the Babylonian and Chaldean watchers of the skies had learned to associate eclipses of the Sun and of the Moon with the motions of these bodies relatively to the Earth, and had indeed discovered an approximate method of forecasting eclipses by means of an eclipse cycle, for which we still use the name they gave—the *Saros*.

It is obvious that all the planets and satellites in our system, since they shine merely by reflected sunlight, must constantly be attended by shadows sweeping through space on the side turned away from the Sun, and that these shadows must be conical in shape (since the bodies casting them are approximately spheres), with bases equal to the cross-sections of the bodies intercepting the Sun's light, and lengths depending upon the sizes and distances of these bodies from the Sun. Every night we walk in the Earth's shadow, and, from a mountain height, like that of Mount Hamilton, or from the deck of a ship far out at sea, we can watch that shadow sweeping up the eastern sky as the Sun sinks farther and farther below the western horizon.

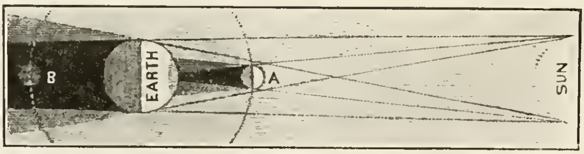

Fig. 5. Shadow and Penumbra of Earth and Moon. *A* marks the position of the Moon in a solar eclipse, *B*, in a lunar eclipse. An eclipse is total for points in the shadow cones, partial for points within the penumbrae.

A beautiful example of such a shadow is that afforded by the passage of one of *Jupiter's* larger satellites across the planet's disk. The shadow can be seen by our telescopes only when it falls upon the planet, and then it appears as a nearly round black dot which travels across the bright planet from east to west (Plate II). If we were on *Jupiter* within that shadow-spot, the Sun would be eclipsed for us.

Since the Moon revolves about the Earth from west to east once every month, it must be in conjunction (pass between the Earth and Sun) once each month—at new moon—and half a month later at full moon, be in opposition—on the opposite side of the Earth from the Sun. If the Moon's orbit were precisely in the same plane as that of the Earth, that is, if the Moon's apparent path among the stars were precisely the same as that of the Sun, there would be an eclipse of the Sun at every new moon and one of the Moon at every full moon.

If, further, the Moon and Earth were perfect spheres and were revolving in perfect circles, all eclipses of the Sun would be exactly alike, and similarly those of the Moon. As a matter of fact, none of these conditions is realized, and no two eclipses are quite alike.

The Moon's orbit is tilted at an angle of about 5° to that of the Earth, hence it generally happens that the shadow of the Moon at new moon passes above or below the Earth, and that of the Earth at full moon above or below the Moon. It is only when the Sun at new, or full moon, is near one of the lunar nodes—the name we give to the two points where the two orbits apparently intersect—that an eclipse can occur. An eclipse of the Sun *must* happen when the Sun at time of new moon is within 15⅓° of the node, and *may* happen, under special conditions, when it is as far as 18½° from the node. The limits for eclipses of the Moon are somewhat smaller. Now since the Sun appears to make the circuit of the heavens once each year, it travels less than 30° in a lunar month. Hence at least one new moon must occur while the Sun is still within 15⅓° of the node, on one side or the other, and six lunations later the same thing must happen at the other node. Therefore there must be at least two eclipses of the Sun each year. Because the limits for an eclipse of the Moon are smaller, it occasionally happens that a year will pass without any lunar eclipse.

Suppose a total eclipse of the Moon to take place very early in the year, as happened this year, on last Sunday night (January 7, 1917). The Moon on this occasion was a little west of its descending node, and the Sun near the opposite or ascending node. Two weeks later, at new moon on Monday, January 22, the Moon has overtaken the Sun at a point east of the descending node but well within the eclipse limit, and a partial eclipse of the Sun results. Five new moons after this the Sun is west of the descending node and within the eclipse limit, giving another partial solar eclipse on June 18-19; two weeks later, on July 4, it is close to this node, and the Moon, at full, is near the ascending node, and the result is another total eclipse of the Moon; two weeks later still, at new moon on July 18, the Moon has overtaken the Sun again just before it reaches the eclipse limit east of the descending node, and a very small partial solar eclipse takes place,—three eclipses within a month's time. Finally, on December 13, Sun and Moon are in conjunction so near the ascending node that an annular eclipse of the Sun results. Two weeks later, on December 27, comes the last eclipse of the year, a total eclipse of the Moon—seven eclipses within the year. This, as has been said, is the maximum possible number, but it occasionally happens that five out of the seven are eclipses of the Sun, and only two of the Moon. The last year with five solar eclipses was 1823 and the next one will be 1935.

I have mentioned partial, total and annular eclipses of the Sun. A partial eclipse is, of course, one in which only part of the Sun's disk is covered by that of the Moon, and needs no comment except that every solar eclipse is a partial one for some stations on the Earth. When at eclipse time the line joining the centers of the Sun and Moon passes through any part of the Earth also, which happens when conjunction takes place within 10° of the node, the eclipse is central. If the Moon's shadow reaches the Earth, it is total, viewed from points within the shadow path; but if the shadow cannot reach the Earth the Moon's disk will be a little smaller than that of the Sun, and a narrow rim or annulus of sunlight will surround it when it is projected on the Sun's disk.

The actual length of the Moon's shadow and the distance of the Moon from the Earth are continually varying because the orbits of the Earth and Moon are ellipses, not circles. The following table gives, in round numbers, the average, the greatest and the least values at time of new moon:

Distance from Moon to Earth's Surface		Length of Moon's Shadow		Difference
Average	235,000 miles	Average	232,000 miles	— 3,000 miles
Greatest	249,000 miles	Shortest	228,000 miles	—21,000 miles
Least	218,000 miles	Longest	236,000 miles	+18,000 miles

It follows that the Moon's shadow cannot always reach the Earth's surface, even at the time of a central eclipse, and that, when it does, the cross-section of the shadow cone where it intersects the surface may vary from a mere point to a circle about 168 miles in diameter. Some central eclipses, therefore, are annular, not total, and a total eclipse may be as brief as a fraction of a second or may last nearly eight minutes. Eclipses lasting as long as six minutes are the exception, however, and the majority last only about two or three minutes.

Another point should be noticed while we are discussing the mechanism of eclipses. The Moon revolves about the Earth from west to east, hence the Moon's shadow at the time of a total eclipse always touches the Earth first at a point where the Sun is just rising, sweeps on eastwardly and leaves the Earth at a point where the Sun is just setting. Meanwhile the Earth itself is turning on its axis from west to east, thus shortening the path along which the shadow travels to about 120° of longitude. Further, the Earth rotates on an axis perpendicular to the equator, and the angle between the planes of the equator and the ecliptic is about 23½°. Hence, since the plane of the Moon's orbit makes an angle of 5° with that of the ecliptic, we see that the Moon at the node is moving sometimes at an angle of more than 28° to the equator, sometimes at one only a little over 18°, and this motion will be toward the north at one node and toward the south at the other. The shadow path on the Earth's surface at eclipse time is therefore a curve tending in a general northeasterly or southeasterly direction, the actual figure depending upon the angle between the Moon's orbit and the equator, and the latitude in which the eclipse occurs (Fig. 6).

Any given total eclipse is visible as such only from stations in the comparatively narrow shadow path—ordinarily less than 100 miles wide—and in general this path crosses any given spot on the Earth's surface only at long intervals. For example, the last total eclipse visible from points in the British Islands occurred in 1724, the next one will not take place until 1927. The area within which the eclipse is visible as partial is, of course, much wider, extending indeed several thousand miles on either side of the shadow track.

I have said that the ancients had discovered that an eclipse returns after a period of about eighteen years, a period to which they had given the name *Saros*. In one sense every eclipse is the return of its predecessor, but in another sense the statement just made is appropriate and the *Saros* is a cycle of considerable interest.

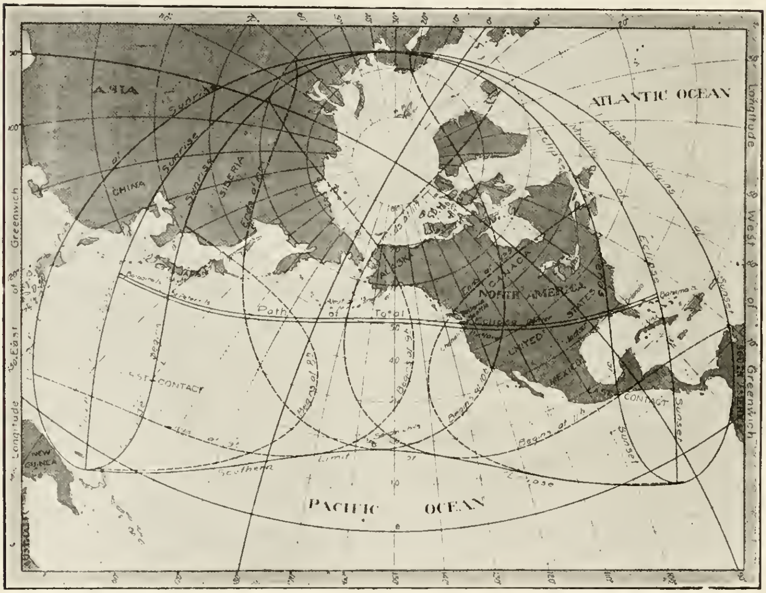

FIG. 6. TOTAL ECLIPSE OF JUNE 8, 1918.

The nearly parallel lines across the center mark the shadow path; the longer, closed curves indicate within what wide limits the eclipse was visible as partial.

The Moon makes the circuit from new moon back to new in what we call our ordinary month, 29.53059 days, but it requires only 27.21222 days—a *draconic* month—to pass from node around to the same node again because the nodal points are constantly retrograding, slipping westward along the ecliptic, an effect due to what we call perturbing forces that we cannot stop to discuss tonight. For the same reason—this retrogression of the nodes—the Sun passes from a node around to the same node in 346.6201 days instead of in 365¼ days.

Now let us multiply the first period by 223, the second by 242, the third by 19. We shall have, with sufficient accuracy for our purpose, 6,585.32, 6,585.35 and 6,585.78 days respectively, and these values amount to eighteen years, eleven days (ten days if five leap years are included) and the three fractions given. After this interval, which is known as the *Saros*, the three bodies will again stand almost precisely in the same relation to each other, and if an eclipse takes place at a given date, one *Saros* later another will occur under almost the same conditions. Almost, not quite. Because of those three differing fractions of a day, the Sun and Moon will be a little farther west with respect to the node at the second eclipse, causing slight changes in the direction and length of the shadow, and the Earth will have turned nearly one-third way farther round on its axis, causing the center of the second eclipse to fall correspondingly farther west on its surface. This second eclipse we consider as a "return" of the earlier one, for though many others have taken place between the two, the positions of Sun and Moon with respect to the node, and hence the circumstances of these eclipses, were quite different.

To see how this cycle may be used in making approximate forecasts of eclipses, let us compare the eclipses which occurred one *Saros* ago with those which are taking place in the present year:

(1)	Total eclipse of Moon, (Duration of totality,	1898, December 27. 1^h29^m	1917, January 7. 1^h28^m)
(2)	Partial eclipse of Sun, (Magnitude of eclipse,	1899, January 11. 0.715	1917, January 22. 0.725)
(3)	Partial eclipse of Sun, (Magnitude of eclipse,	1899, June 7. 0.608	1917, June 18-19. 0.473)
(4)	Total eclipse of Moon, (Duration of totality,	1899, June 22-23. $1^h1.5^m$	1917, July 4. $1^h1.5^m$)
(5)	Partial eclipse of Sun,	. . . . . .	1917, July 18. (Magnitude, 0.086)
(6)	Annular eclipse of Sun, (Center of each eclipse track near the South Pole.)	1899, December 2.	1917, December 13.
(7)	Eclipse of Moon, (Almost total in 1899, magnitude = 0.996; just total in 1917, magnitude = 1.011, duration of totality = 16.5^m.)	1899, December 16.	1917, December 27.

Each lunar eclipse of the earlier period, it is seen, is repeated this year, the date falling eleven days later, the duration of totality being about the same. The three solar eclipses of the earlier year are followed this year, eleven days later in the year, by eclipses resembling them closely, the point of greatest eclipse, however, falling this year about 120° of longitude farther west. In addition, a new cycle begins this year with the very small partial eclipse of the Sun on July 18.

Let us illustrate the recurrence of a single eclipse at *Saros* intervals by considering the cycle to which the eclipse of June 8, 1918, belongs. Like all eclipse cycles this one began as a very slight partial eclipse, when the Sun was almost at the limit of distance *east* of the Moon's node at the time of new moon. Since, for this family of eclipses, the new moon was near the ascending node, the point where its orbit crosses the ecliptic from south to north, the penumbra brushed the Earth near the South Pole at this first eclipse—on March 10, 1179. Eighteen years later, on March 20, 1197, the Sun was a little nearer the node at new moon, and the Moon's disk cut off a little more of the Sun's light. This continued after every *Saros,* the magnitude of the eclipse increasing each time, until June 4, 1323, when the eclipse became central and annular for a short track near the Earth's South Pole. Annular eclipses continued after each succeeding *Saros,* twenty-eight of them, their paths falling ever farther north, until April 14, 1828. By this time the Sun, at new moon, had passed the node, and at the same time the Moon was nearer perigee (the point in its orbit nearest the Earth) and hence the tip of the actual shadow cone touched the Earth at the middle of the eclipse time at a station in East Africa, 18° north of the equator, completely hiding the Sun there for a few seconds. The conditions at the next return were similar, the eclipse in April 25, 1846, being annular along the eclipse track except just east of Cuba, in 25° north latitude, where it was total. The three following returns, May 6, 1864, May 17, 1882, May 28, 1900, were total, the shadow paths spiraling ever northward. The shadow cone on June 8, 1918, will touch the Earth at sunrise in the Pacific Ocean in 130° east longitude and 26° north latitude, at noon will cross a point in the Pacific at 152° west longitude and 51° north latitude, will enter the United States in southwestern Washington at about 2^h 55^m, Pacific Standard Time, sweep a path across the country toward the southeast, tapering in

PLATE XIII. The 40-Foot Camera, Flint Island.

width from a little over seventy miles in Washington to less than forty-five miles in Florida, and end at sunset, in the Atlantic east of Cuba, in west longitude 75°, north latitude 25°.

At subsequent returns it will spiral ever farther north, remaining total until the return of August 23, 2044. Then for more than two hundred years it will recur as a partial eclipse, disappearing at length above the North Pole when the Sun at new moon has passed beyond the eclipse limit west of the node.

The actual calculation of an eclipse path and the other attending circumstances, such, for example, as the precise time and duration of totality at a given station within the path, are far too technical matters to be dealt with tonight. Suffice it to say that the calculation can be made with such accuracy that we might easily select now a station for the eclipse, say of August 23, 2044, and set up our telescopes there with the full assurance that the eclipse would occur within a few seconds of the predicted time and that our telescopes would need but very slight adjustments by the observers of that distant day. Whether they would succeed in making the observations planned is another matter. Perhaps by that time our successors will have learned how to control the Earth's atmosphere so as to insure a clear sky at the critical moments. At present we can not do this, and therefore the intending observer, in selecting a station for his observations, carefully studies all the meteorological data available, and when the path of totality makes choice of stations possible, gives the meteorological factor almost the highest weight. Of course, he desires a position where the eclipse will be of maximum duration, for at best it is all too short, but if weather conditions there are highly unfavorable, and are far more promising at a point where the eclipse time is shorter, the latter will be preferred. Often it happens that the shadow path lies mainly across the ocean, touching land only at the edges of the continents near sunrise and sunset, and perhaps crossing an island or two. It may easily happen that at every possible station at such an eclipse the chances for clouds are so great that no observer will care to risk the time and expense an expedition thither would involve.

Unfortunately an accurate forecast of the state of the atmosphere at eclipse time is impossible even at the most promising station, a fact that laymen sometimes find it hard to understand. For example, our eclipse observers returning from the eclipse of May 28, 1900, in Georgia, recounted with glee the skepticism of a leading citizen of a small town there who had from the first been doubtful of their ability to foretell the occurrence of the eclipse. When he heard their anxious discussions as to the probabilities of cloudiness at the important time, his doubt was deepened to conviction. "These young men try to tell me they know the Sun is going to be eclipsed and they can't even tell me if the sky is going to be clear!"

Better-informed people may well ask, since the duration of an eclipse is so short and the chances of observing it are at best uncertain, why astronomers should devote weeks and months of time to preparation, and travel sometimes half around the world to watch the phenomenon. Let me answer by tracing in a summary way the development of our knowledge of the Sun during the last eighty years. It is not necessary to go back farther, for, broadly speaking, we may say that little more was really known about the Sun in 1840 than had been discovered by Galileo and his contemporaries and their immediate successors in the early days of the telescope two centuries before.

The Sun was an enormous globe whose composition and physical condition were unknown. From its intensely hot surface, known as the photosphere, light and heat were radiated. From time to time spots appeared on this surface and by observation it was found that they were confined to two broad zones, one on either side of the Sun's equator, that they were often surrounded by areas of extreme brightness—the faculæ—and that the Sun turned on its axis once in twenty-five or twenty-six days. Total eclipses of the Sun had been observed when the shadow paths were conveniently placed, but principally to note the precise times of contact of the disks of the Sun and Moon for the purpose of improving the lunar and solar tables. The corona was noted of course, it could hardly have escaped the notice of even the earliest witnesses of an eclipse, and there are occasional references to rosy or scarlet or flame-colored appearances close to the Moon's disk during totality, but these features attracted strangely little scientific attention.

One discovery of capital importance had been made, though not at an eclipse. Fraunhofer, in 1815, had found that the solar spectrum, produced by passing a beam of sunlight through a narrow aperture or slit and then through a prism, is crossed by a series of fine dark lines which always fall in the same positions with respect to the colors of the spectrum, but their significance was unknown.

The real impetus to further advance in solar studies, we may say, was given by the eclipse of July 8, 1842. The Moon's shadow on that occasion swept across Europe, and many prominent astronomers occupied stations on the shadow path. The corona was strikingly beautiful and, fortunately, at least three large brilliant flame-colored protuberances, now known as prominences, were visible. What caused them, and what was the corona? These questions were now for the first time generally discussed, and it was soon apparent that astronomers were divided in their opinions. Some held that they were solar appendages, others that they belonged to the Moon, while a third group argued that they were not objective realities at all, but were optical phenomena produced by diffraction of the Sun's light at the irregular mountainous circumference of the Moon's disk. Eclipses of the Sun were now looked forward to with interest, and in the next thirty years a number occurred that were well observed. Moreover, new instruments were made available to study their phenomena.

Photographic processes had been so far perfected that they could be systematically applied at the Spanish eclipse of July 18, 1860. In the preceding year, 1859, Kirchhoff had shown that the Fraunhofer lines could be explained on the assumption that the light from the Sun's photosphere passes through a gaseous layer or envelope which, while intensely hot, is cooler than the photosphere itself. This layer of gases would "absorb" light of precisely the wave-lengths it was itself capable of emitting. Hence the positions of the lines should not only tell us the composition of the gaseous layer, but when the photospheric light is cut off, as for example, by the interposition of the Moon's disk at the time of total eclipse, the lines themselves should flash out as bright lines. Precisely this phenomenon was observed by C. A. Young at the eclipse of December 22, 1870. He was watching the Fraunhofer lines in his spectroscope as the Sun gradually disappeared behind the Moon's advancing disk, and just as the last rays of photospheric light were cut off he saw them suddenly flash out as bright lines. In a second or two they were gone—covered by the advancing Moon. But the existence of the "reversing layer" above the photosphere had been fully established by this actual observation of the "flash spectrum."

Meanwhile the photographic camera and spectroscope had definitely proved: (1) that the prominences and the inner corona were real and belonged to the Sun, for the Moon's disk clearly traversed them in its motion; (2) that the prominences were vast masses of luminous gases—hydrogen, helium, calcium—rising from a continuous layer (the chromosphere) of such materials surrounding the Sun; (3) that the corona was at least partly gaseous, for its spectrum showed a bright line of green light due to some element not even yet identified but called "coronium"; but (4) that it shone also in part by reflected sunlight, for Fraunhofer lines were present, and the light was partly polarized.

If an astronomer had been fortunate enough to observe successfully every total eclipse that has occurred from 1860 to the present year, he would, in all, have had less than two hours' time of actual observation, yet it is clear that this short space of observing time has advanced our knowledge of the Sun beyond the dreams of astronomers a century ago.[2]

Total eclipses of the Sun must still play their part in advancing our knowledge of the forces that are in action upon the Sun, and of the relations between corona, prominences and sun-spots, though we may not now hope to discover new enveloping layers. The corona has been seen and photographed only at the time of total eclipse, in spite of strenuous efforts made by the most skilful observers, and it now seems that the attempt to study it at other times is hopeless. For Abbot, using that extremely delicate electric thermometer which we

[2] A general description of the Sun as we know it was given at this point in the spoken lecture; this is here omitted, for a better account will be found in Dr. St. John's lecture on a later page.

call the bolometer, an instrument that can reveal the variation of 0.000,000.1° C. of heat radiation, has shown that the sky radiation even 20° from the Sun is more than ten times greater than that of even the bright inner corona, and that the latter is therefore beyond the reach of any existing form of instrument except at times of eclipse.

Eclipses, too, afford the best if not the only opportunity to study other questions not strictly related to the constitution of the Sun; for example, whether or not there exists a planet of any notable size within the orbit of *Mercury,* and whether the force of gravity has the power to deflect light, as postulated by the modern theory of relativity. The former question was prominent in the plans of recent eclipses but has now been quite definitely settled in the negative, mainly by the observations by Lick Observatory expeditions. The latter will certainly hold a prominent place in the program for the eclipse of June 8, 1918.

Thanks to the liberality of generous friends—the late Colonel Fred Crocker, Mrs. Phebe A. Hearst, and, particularly, Mr. W. H. Crocker, all members of our Society—the Lick Observatory has from the first been able to take a prominent part in solar eclipse work. Since the California eclipse of January 1, 1889, of which I spoke at the beginning, eclipse expeditions have been sent out at the expense of one or another of these three friends of the observatory in nine different years, and in only two of these years—1896 and 1914 did clouds prevent success.[3] Other eclipses have occurred

[3] Eclipse Expeditions from the Lick Observatory, University of California.

Date	*Place*	*Donor*	*In Charge of*
1889, Jan. 1	Bartlett Springs, Cal.	The University	Keeler
1889, Dec. 22	Cayenne, French Guiana	Chas. F. Crocker	Burnham & Schaeberle
1893, Apr. 16	Mina Bronces, Chile	Mrs. Phebe A. Hearst	Schaeberle
1896, Aug. 9	Yezo, Japan	Chas. F. Crocker	Schaeberle (clouds)
1898, Jan. 22	Jeur, India	Chas. F. Crocker	Campbell
1900, May 28	Thomaston, Ga.	W. H. Crocker	Campbell
1901, May 18	Padang, Sumatra	W. H. Crocker	Perrine
1905, Aug. 20	Cartwright, Labrador	W. H. Crocker	Curtis (clouds)
1905, Aug. 20	Alhama, Spain	W. H. Crocker	Campbell
1905, Aug. 20	Aswan, Egypt	W. H. Crocker	Hussey
1908, Jan. 3	Flint Island, South Pacific	W. H. Crocker	Campbell
1914, Aug. 21	Brovary, Russia	W. H. Crocker	Campbell & Curtis (clouds)
1918, June 8	Goldendale, Wash.	W. H. Crocker	Campbell & Curtis

within this period, but the prospects of good weather were too poor to justify an expedition. Doubtless a party will be sent from the Lick Observatory[4] in June, 1918, to a suitable station—perhaps in southern Idaho or eastern Oregon, where weather conditions are unusually promising and where the total phase on June 8 will last a little less than two minutes.

Let me illustrate what such an expedition means, especially when the site chosen is out of the regular lines of travel, by giving some details of the expedition from the Lick Observatory, which it was my privilege to accompany, to observe the eclipse of January 3, 1908.

The Moon's shadow on that date touched the Earth at sunrise in the Pacific Ocean in longitude 155° east, latitude 11° north, swept eastward and left the Earth at sunset on the western coast line of Costa Rica. Two small islands were the only land points in the shadow path, both out of the usual lines of steamer travel. There was no choice between them, either in point of climate or in point of accessibility, or, better, inaccessibility; but at Flint Island, about 450 miles northwest of Tahiti, in 10° 7′ west longitude, 11° 25′ south latitude, the eclipse occurred nearer noon, and hence when the Sun stood higher in the sky (an advantageous factor) and the total phase lasted considerably longer than at Hull Island, which is about 700 miles north of Samoa. Flint Island was therefore selected as our station.

Mr. W. H. Crocker made generous provision for the expedition, the U. S. Navy Department courteously detailed a gunboat, the *Annapolis*, to take the party from Papeete, Tahiti, the nearest steamer port, to the island and back; and plans for the instrumental equipment and for the observing program were begun more than a year in advance of the date of the eclipse.

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[4] Note added November, 1918. The Crocker Eclipse Expedition from the Lick Observatory occupied a station at Goldendale, Washington, on June 8, 1918, and added another to the Observatory's list of successfully observed eclipses. The circumstances were even more dramatic than at the eclipse on Flint Island which I have described in the lecture.

"The sky had clouded late on the night of the 7th," writes Dr. Campbell, "and we may say that it remained completely clouded until toward midnight of the 8th, with the important exception that a small rift occurred exactly at the critical time and place. The clouds uncovered the Sun less than one minute before the beginning of totality and they again covered the Sun a few seconds after the end of totality. The small region of unclouded sky containing the totally eclipsed Sun seemed to be absolutely clear . . ."!

The observing program, which conformed closely to the forecast made in the

Fig. 1—The channel through the reef.

Fig. 2—Surf-boat used in landing eclipse equipment.

Fig. 3—Palm-thatched huts in the cocoanut grove.

PLATE XIV. Flint Island.

Ever since the eclipse of 1893, the chief photographic telescope used on our expeditions has been of the tower form devised and used at that time by Astronomer Schaeberle of the Lick Observatory, at Mina Bronces, Chile. Obviously it is not possible to transport to eclipse stations such massive instruments as those used in fixed observatories at the present day; and the small portable equatorials used at eclipses before 1893 give images of the Sun too small to permit satisfactory study of the finer details of the coronal structure. What is wanted is an instrument of very long focus which will give a solar image four or more inches in diameter, and which will, at the same time, be easy to transport and erect. These requirements the Schaeberle form of telescope, especially as improved in its mounting by Campbell, meets admirably.

Its essential parts are a lens of 40-foot focal length, giving an image of the Sun 4½ inches in diameter; a tube consisting of a frame-work of lengths of gas-pipe, screwed together and braced by stout wire, and a cover of black cloth; and a plate-holder moved by clockwork. The geographical coördinates of the station being known, we can compute the precise position in the sky which the Sun will occupy at the time of totality, and we can therefore mount the lens rigidly at the top of a suitable tower in such manner that at the time of eclipse the light from the corona will shine down the tube and fall centrally upon a photographic plate exposed in a dark-room at its lower end. *The tube is not attached either to the lens or to the photographic plate* but simply serves to connect the two in order to keep stray light from falling upon the plate. The lens is firmly fixed in position in advance and it must be adjusted with precision. If it is not properly set it cannot be changed at the instant of eclipse; if such mistake should be made the telescope would be useless. Since the Sun's image changes its position slightly

closing paragraphs of my lecture, except that no spectroheliograph was used and that no "moving picture" record was secured, was carried through with excellent results. In particular, the photographs of the corona are the finest and most interesting ones taken at any Lick Observatory Crocker Eclipse Expedition. One of these is reproduced in half-tone as the frontispiece to the present volume. It is hardly necessary to say that much of the delicate detail of the coronal structure shown on the original negative has been lost in the process of reproduction.

It is impossible as yet to say what value the photographs taken to test the Einstein theory of relativity may have, because circumstances beyond the Observatory's control prevented the taking in advance of check photographs of the region of the sky in which the Sun would stand at the time of eclipse. The apparatus will be set up at Mt. Hamilton early this winter, when this region is again visible at night, and the necessary photographs will then be secured.

during the minutes of the total phase, because of the Earth's revolution about the Sun, it is necessary to move the plate at the same rate. This is accomplished by attaching a simple driving mechanism, actuated by clockwork, to the plate-holder. The whole apparatus can be compactly packed and can be erected with little difficulty.

On the expedition to Flint Island an instrument of this type was taken to secure large-scale images of the corona. Another lens of comparatively short focus, and differently mounted, was taken to secure additional photographs, especially of the outer extensions of the corona. Spectrographs of several different forms were designed and built to record the general spectrum of the corona, the spectra of the prominences, and the "flash spectrum". The equipment also included photometers to measure the intensity of the coronal light at varying distances from the Moon's apparent limb, polarigraphs to test its polarization, a duplicate set of telescopes—four in each set—to photograph the region about the Sun for the purpose of detecting an intra-Mercurial planet, if such existed (though earlier expeditions had made such existence doubtful), and an alt-azimuth instrument to determine time, latitude and longitude.

All of these instruments except the 40-foot telescope and the alt-azimuth instrument had to be mounted on polar axes driven by clockwork, that the light from the corona might pass through the various optical trains and fall continuously upon the same points of the photographic plates during the exposure times. In regular observatories such axes are of metal and are very heavy; for our eclipse mountings we fit metal bearings in the ends of the stout wooden packing boxes in which the instruments themselves are transported. These boxes then serve as polar axes; they are supported by wooden tripods, and the spectrographs or other pieces of apparatus are attached to their sides and they are rotated by means of long lever arms weighted with stone or sand, the rate of fall being controlled by a simple clock.

Every instrument was set up at Mount Hamilton, carefully adjusted, and fully tested before being packed. Moreover, the sky area in which the Sun would be at the time of eclipse was photographed with the intra-Mercurial camera to furnish comparison plates which would show all of the stars in the area.

In addition to the larger instruments, smaller pieces, chronometers, driving-clocks, tools, developing trays, chemicals, lanterns and a multitude of miscellaneous materials had to be provided. It was also known that the island was small and produced only cocoanuts, and experience on earlier expeditions had shown the desirability, in any event, of making the observing party while at the station as independent as possible of the country. It was therefore necessary to include camp cots, bedding, kitchen utensils, dishes, and food supplies sufficient to support the party during the month's stay on the island.

To plan and carry out successfully any eclipse expedition requires not only scientific ability but also good business judgment. In the particular case we are considering matters were complicated by the fact that once on the island we were shut off from any help from the outside world and the further fact that landing on Flint Island must be made by surf boat through a narrow passage blasted through the reef. All materials that could not safely be floated ashore had therefore to be packed in boxes that could be handled easily by two men at most.

At last everything was ready, and the party of six from the Lick Observatory, with thirty-five tons of freight, sailed from San Francisco for Tahiti (a 12-days' run) on November 22, 1907. At Papeete we spent three busy days transhipping our freight to the *Annapolis,* securing a supply of fresh fruit and other perishables and a surf boat for landing, and picking up our Tahitian carpenter, cook and laborers. On the evening of December 7th we sailed for Flint Island. Two days later, on the forenoon of December 9th, the island was sighted, a small kite-shaped patch of coral rock less than a mile wide from east to west and slightly over two miles long from north to south; 22 feet above mean sea level at its highest point, and surrounded by a flat coral reef beyond which could be seen a white beach, strewn with shells and broken coral, sloping gently upward to the edge of a grove of cocoanut trees. The channel blasted through the reef on the northwest side, which afforded the only possible landing, looked narrow indeed and to our unaccustomed eyes the surf seemed high. Often, we had been told, it was impossible to land at all and ships must lie off shore sometimes for days waiting for the surf to subside. To our great relief, the English manager of the cocoanut plantation which covers the island told us, when he came aboard, that the surf was really low, lower in fact than at any time in many months. Landing was forthwith rushed and by eight o'clock that evening all of our effects were on the beach and the *Annapolis* had headed again for Tahiti.

Now followed days of strenuous but delightful toil amid surroundings which made one dream of Captain Cook and Robinson Crusoe. Simple frames for huts were erected from lumber brought with us, and these the native laborers of the plantation covered, both roof and walls, with thatch woven from the fronds of the cocoanut trees. Canvas or colored calico hung from cord served as screens for the doorways. Tents were run up to shelter the instruments and the supply cases, and even while these tasks were in process, the alt-azimuth instrument was mounted upon a concrete pier and the first time observation secured on the night of December 11th. A meridian line was also run, sites chosen in the cocoanut grove where a few trees were missing, and foundations laid for all the instruments.

The weather was delightful, hot indeed in the Sun, but tempered by the constant sea breezes, and comfortable enough in the shade and at night. Rain fell daily, often three or four showers in a day. It was a novel experience to be interrupted in the course of time observations at night by a heavy rainfall and to resume observations in a perfectly clear sky within half an hour! Or to be at work by day at the adjustment of an instrument and to hear someone, who had noted a low cloud forming, shout, "Look out for rain." Then to seize tarpaulin or canvas, hastily cover the instrument, and be drenched by a tropical downpour before shelter, a few yards away, could be gained. Half an hour, sometimes only fifteen minutes, later, work would be resumed in bright sunlight and the ground under foot would be practically dry.

Fully a week before the day of the eclipse the instruments were all practically ready; there remained only those last fine

PLATE XV. The Intra-Mercurial Cameras and the Moving-Plate Spectrograph, Flint Island.

adjustments which make the difference between good and excellent results *and the rehearsal.*

The duration of totality was $3^m\ 52^s$; to utilize those precious seconds to the utmost, it was essential that every one should be so familiar with his particular duties that he would perform them mechanically, with precision and the maximum rapidity. This meant rehearsal and dress rehearsal, so to say, at that. For example; the program for the 40-foot telescope called for six photographs with exposure times ranging from 4^s to 64^s, the short exposures to record the bright inner corona, the long one, the faint outlying streamers. At each rehearsal, and there were many, the observer at this instrument had all six plate-holders at hand, put each in position in its order, went through the motions of exposing the plate, stopping the exposure, and putting the next plate in position, while another observer called off the passing seconds.

The morning of the eclipse dawned bright and clear and every one was on hand early; the twenty instruments were given their final inspection; the plate-holders, loaded the night before with the plates which till then had been kept in sealed tin cases, were put at hand; and then the horizon was watched with the keenest anxiety. Would rain defeat all of our preparations? The experience of the preceding days led us to dread it, and, in fact, at eight o'clock, three hours before the total phase began, heavy rain did fall. Thereafter the sky was alternately clear and cloudy, keeping us in constant suspense. Five minutes before the computed time of second contact (the beginning of totality), the observer at the chronometer called off the time, as had been planned, and as the word was on his tongue a dense black cloud passed over us, rain began to fall, and with it our hearts. Instruments were hastily covered, a native perched on the tower of the 40-foot telescope capped the lens, and we stood by, more in despair than in hope, as the seconds passed. The time-keeper cried, "two minutes before totality," in a rain still heavy but decreasing; somewhat more than a minute later the slender crescent of the disappearing Sun became faintly visible through thin clouds. These grew rapidly thinner, and two observers whose special duty it was, were able to note the precise second when the total phase of the eclipse began. Rain was still falling in scattered drops, but the instruments were quickly uncovered and the program was carried out as planned. Thin clouds covered the Sun during nearly half the total phase, but during the last half only a very slight haze could be discerned. Our relief and joy at this almost miraculous good fortune are more easily imagined than described, but our satisfaction was not really complete until it was found, upon developing them, that all of our photographs were excellent. The only harm the rain had done was in preventing our taking the photographs planned for the first few seconds of the eclipse.

The cloud which so nearly ruined the plans of the expedition swept over the island at a very low altitude and was quite limited in its area, hence the difference of only a few feet in the location of an instrument meant all the difference between a clear sky and a cloudy one. Thus, Dr. C. G. Abbot, of the Astrophysical Observatory of the Smithsonian Institution, who, with an assistant, had joined our party at San Francisco, had set up his bolometric apparatus (designed to measure the intensity of the heat radiation from the corona) on the beach near our landing place, perhaps 1000 feet northwest of our station. There the Sun stood in perfectly clear sky from about 15 seconds before the total phase began! An English party, headed by Mr. Frank McClean, on the other hand, had set up its instruments about 200 feet to the south of us. There the Sun was practically wholly obscured during the first half of totality, only the last half being observable.

It took us nearly a month to set up and adjust our instruments, but it required less than two days to take them down, pack them, and get them aboard the *Annapolis*, which had returned to the island on New Year's day. The photographic plates, too, had all been developed, dried, and packed with extreme care in sealed tin cases. It was well for us that such speed was possible, for the surf was rising steadily during those two days and at eleven o'clock on the morning of January 5th, when the last party left the island, the expert native boatmen found great difficulty in sending the boat through the surf. No one of the passengers is likely to forget the moments when it seemed an open question whether they would succeed or whether the boat would be flung broadside upon the outer reef.

Not every eclipse party can expect to have so many pleasant and romantic experiences as those we enjoyed on this voyage to the South Seas; but wherever the station may be, there is a fascination about even the most prosaic details of the preparation, and a joy in the actual observation of what is perhaps the most wonderful and beautiful of astronomical phenomena that afford ample compensation for all the time and trouble and hard work an eclipse expedition demands.

The American Astronomical Society has already appointed a special eclipse committee to make general plans for observing the eclipse of June 8, 1918, and it is quite certain that many American observatories will send out parties at that time. The shadow enters the United States on the coast of Washington in latitude $+46° 50'$ at $2^h 55^m$, Pacific Standard Time, as I have already said, and moving rapidly southeastward leaves the land on the coast of Florida shortly before sunset. But we must remember that sunset in Florida comes when the Sun in our longitude is still three hours or more above the horizon. The Moon's shadow actually sweeps across the country from the Washington coast to that of Florida in just forty-seven minutes. A number of cities lie close to the central line of the shadow path, among them Baker City (Oregon), Hailey and Montpelier (Idaho), Central City and Denver (Colorado), Jackson (Mississippi), and Orlando (Florida). Denver is the site of the Chamberlin Observatory, which possesses a twenty-inch refractor adapted for photographic as well as visual observations. Professor Howe and his associates can observe the eclipse, therefore, with their regular observatory instruments and need send out no expedition.[5] The most favorable locations for this eclipse are unquestionably on the line from southeastern Washington through Idaho and Colorado; the Sun during totality will be higher in the sky here than farther east, the eclipse will last longer, and the meteorological conditions are most promising.

The eclipse committee has made no report as yet, but it is safe to forecast the general nature of the observations that will be made, and their purpose. The corona will certainly be

[5] Unfortunately, the sky was cloudy at Denver on June 8, 1918.

the principal object of study. Large-scale and small-scale photographs will be taken, some with short exposures for the brighter portions, some with long exposures for the fainter regions. Intercomparison of these photographs will enable us to build up a true picture of the actual corona. Direct photographs, and others taken with the spectroheliograph, at observatories like the one on Mount Wilson, on the day of the eclipse and on the preceding and following days, will record the number and location of the sun-spots, faculae and prominences, and the distribution of hydrogen, calcium and other gases in the upper regions of the Sun; and the comparative study of these photographs with those taken by the eclipse expeditions, will, it is to be hoped, throw new light upon the constitution of the corona and upon its relations to the other solar envelopes.

Spectrographic observations will play an important part and spectrographs of several different types will be used, (1) to record the general coronal spectrum and the distribution of coronal light in the spectrum; (2) to determine the precise wave-lengths of the coronal lines, especially the green line of *coronium,* and to record the distribution of this gas at least in the inner corona; (3) to photograph the violet and ultra-violet coronal spectrum; and (4) to photograph the "flash spectrum".

Spectroheliographs may possibly be used to photograph the chromosphere, prominences and inner corona; bolometers will measure the intensity of the radiation of the corona at different distances from the Moon's limb, and special magnetic measures and meteorological observations will undoubtedly be made. Fairly successful "moving-picture" records have been secured at one or two recent eclipses. Several such records ought to be made at different stations on June 8, 1918.[6]

Two minutes is not a very long time, but a single expedition, well planned and thoroughly prepared to utilize every second to the utmost, can secure most valuable material. A number of parties working in coöperation, according to pre-arranged plans, should secure data that will mark a long step forward in our knowledge of the Sun.

As to observations not directly relating to the Sun, it is probable that search for an intra-Mercurial planet will not

[6] So far as I am aware, no such records were secured.

figure, except incidentally, but telescopes of the same type as those used in this search at recent eclipses—that is, batteries of four telescopes of about 11-foot focal length so mounted upon a single polar axis as to give simultaneous photographs of the entire region about the Sun—will undoubtedly be used to test the relativity theory now so prominent in theoretical physics. It is a consequence of that theory that a beam of light passing through a gravitational field should be deflected from its course just as a material particle traveling with the velocity of light would be. If, then, a star is so situated that its light in falling on the Earth passes close to the limb of the Sun, it should be bent in toward the Sun by about 0.9″. If it passes 20′ from the Sun, the deflection is less than half as great. If two stars are placed on opposite sides of the Sun, their light will be deflected in opposite directions and the effect will thus be doubled. Now stars so nearly in line with the Sun, even if bright, can be photographed only at the time of eclipse. Hence the plan is to take plates at eclipse time, measure the distance between star images suitably placed upon them, and compare the result with the distance between the same stars photographed with the same telescopes at an earlier or later season when the Sun is out of the way. If the attraction of the Sun has affected the direction of the light beam, the distance on the eclipse plates will be a little greater—the amount depending on the positions of the stars—than that on the other plates. The theory of relativity, while far too technical to be discussed here, is of such importance to our fundamental physical concepts that these tests, the only quantitative observational tests that can be made of it at present, will be of the greatest interest.

THE MOON[1]

By Robert G. Aitken

One Saturday evening, several years ago, I was standing in front of the Lick Observatory with a party of people who had come to look through the 36-inch telescope. The Sun was just setting behind the hills south of Mt. Tamalpais, and as it disappeared, the slender crescent of the Moon, less than two days past the new, appeared low in the sky south of the sunset point. One of the visitors, after watching it a moment, turned with the question:—"Why is it that the new Moon rises in the west, while the full Moon rises in the east?"

As soon as I recovered, I explained as tactfully as I could that the Moon whether full or new always rose in the east, but that when it was just past the new-moon stage it rose very near the Sun and after sunrise and therefore could not be seen until the Sun had set, by which time, of course, it was itself approaching the western horizon. But my tact or my explanation, or both, were unequal to the occasion, for when I had finished, the visitor replied with great dignity, "Well! That is the way it may do here, but in Humboldt County the new Moon always rises in the west!"

That any one should be so ignorant concerning the motions of the Moon, is certainly hard to credit; but my visitor differs only in degree from many a famous poet and novelist. I could quote a description of a sunset in a story written by one of the foremost "realist" fiction writers of New England, and published a few years ago in *Harper's Monthly Magazine,* in which a crescent Moon in the *eastern* sky adds to the beauty of the scene; or a passage from a novel which was a "best seller" not so very long ago and whose author had a reputation as a scientific man, in which the full Moon rises at midnight. Indeed all kinds of liberties have been taken with the Moon. Coleridge's lines in *The Ancient Mariner,*

[1] Delivered February 9, 1917.

PLATE XVI. The Moon, 9d. 2.5h. Old.

Photograph taken with the 36-inch refractor, Oct. 11, 1891, by E. S. Holden and W. W. Campbell.

> The horned Moon, with one bright star
> Within the nether tip

are classic; and we have all in our childhood recited or at least read *The Burial of Sir John Moore* with the line

> By the struggling moonbeam's misty light.

Some critic was unkind enough to look up the almanac and he found "that the Moon was new on the 16th of January, 1809, at one o'clock in the morning of the day of the battle of Corunna." The Moon was therefore invisible on the following day, and since the burial took place on the night after the battle, it was, in any event, below the horizon.

It would be easy to cite many other passages in which similar errors occur. Nor are these mistakes confined to writers in our own language. William Lyon Phelps, for instance, in his *Essays on Modern Novelists,* says that "the Moon, in German fiction, is not astronomical, but decorative. I have read some stories in which it seems to rise on almost every page and is invariably full. Even Herr Sudermann places in *Es War* a young crescent Moon in the eastern sky!"

Our modern civilization and our educational system are to a large extent responsible for this general ignorance of the apparent motions of the most familiar of all the objects in the night sky. Astronomy, in our country at least, is seldom taught in the schools and generally only as an elective in our colleges, and boys and girls can pass through all the grades to a university degree without acquiring the slightest information about the Sun, the Moon, the planets or the stars. And our crowded hurrying life with its insistent and ever growing demands upon our time affords ever less leisure for quiet observation and thought, and city lights too often hide from us the lights in the sky. That is why I am devoting the first part of this lecture to a simple account of the Moon as we see it in the sky.

It requires no observatory equipment, not even the smallest telescope, to gain a knowledge of the apparent motions of the Moon in the sky. It is only necessary to watch it with seeing eyes, as the ancients did, thousands of years before the telescope was invented. Any intelligent boy or girl can repeat these observations and verify what I am going to say, and I hope that many of you who hear me tonight will do so. When it comes to the real motion of the Moon the story is very different. To trace this motion in detail, to analyze it, and explain it on the Newtonian theory of gravitation, forms one of the most intricate and difficult problems of mathematical astronomy.[2] The trouble is that so many factors enter. If the Moon moved simply under the mutual attraction between it and the Earth, the problem would be the comparatively simple one known as the two-body problem. But the Sun's attraction is a powerful disturbing, or, in technical terms, perturbing force; *Venus* exercises a strong attraction; the other planets, in smaller degree, enter, each with a force determined by its mass and distance; even the fact that the Earth is not a sphere, but bulges at the equator, is a factor by no means to be neglected. The Moon, therefore, does not move in a simple elliptic orbit, but in a very irregular curve, following the line of the ellipse only in a general way, and it is so near the Earth, relatively speaking, that every departure from simple elliptic motion is detected in our observations. To account for the observed motion under the law of gravitation, taking all the disturbing factors into consideration, is a problem that has exercised the highest powers of great mathematicians from Newton's time to the present day. We may well be proud of the fact that three American astronomers—the late Simon Newcomb, the late George William Hill, and Professor Ernest W. Brown of Yale University—have taken distinguished parts in the solution of this great problem. Professor Brown's lunar tables, now being printed, are the most accurate ever constructed.

Returning, after this digression, to the Moon's apparent motion, the diurnal motion due to the rotation of the Earth on its axis is the first to be noticed. We see the Moon rise above the eastern horizon, circle the sky towards the west, and set below the western horizon. The points of rising and setting are not always the same nor does the Moon cross the meridian always at the same altitude, and the times of rising change from day to day. The observer will quickly learn to associate the times of rising and setting with the Moon's age and its phases. For a day or two at new-moon time he will not see it

[2] See Professor Leuschner's lecture, on a later page, for an excellent discussion of the motions of bodies in the solar system.

rise or set at all. Then, if he is sharp-eyed and the air is very clear, he will see it rise shortly after sunrise, a slender crescent. As the crescent grows from day to day, the time of rising becomes later and later until, when the crescent has rounded through the half-moon and gibbous phases to full moon, it rises in the east about the time the Sun is setting in the west. As it wanes again, first to the half-moon phase, and then, in the last quarter of the month, to an ever narrower crescent, the time of rising grows ever later until we see it rise for the last time in the month just before sunrise.

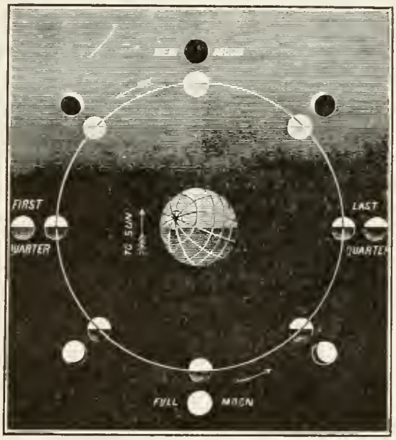

FIG. 7. THE PHASES OF THE MOON.

Of course this retardation in the time of its rising is due to the fact that the Moon is really moving about the Earth from west to east. Watch it for a few hours on any clear moonlight evening and you will find that in an hour's time it moves eastward among the stars about the distance represented by its own apparent diameter. Continue your observations and in due time you will learn that it requires approximately 27⅓ days to return to its original position among the stars so far as its eastward motion is concerned; but now it may be a little farther north or a little farther south than it was a month earlier. This is a little more than two days less than the time it requires to pass from new moon back again to new moon, and the reason is obvious when we recall the fact that because of the Earth's motion in its orbit the Sun also seems to move eastward among the stars. In a month's time it travels over nearly $1/12$ of its orbit, and the Moon must catch up with it before it can again reach the new-moon phase. It is also clear that the phases must in some way be related to the change in the Moon's position with respect to the Sun, for full moon always comes when the Sun and Moon are on opposite sides of the Earth, new moon when they are nearly in line on the same side.

Note the Moon's apparent size and you will find that it is always about the same but that it does vary slightly. At one time in the month it is a little larger than the average, at another a little smaller. But in making this observation be careful to watch the Moon when it is about the same distance from the horizon, for it always *looks larger* when near the horizon than when it is higher in the sky. This is an illusion, for the Moon is really nearly 4,000 miles farther away when it is on your horizon than when you see it overhead—a fact which you can readily demonstrate by a simple diagram—and actually its disk is then a little smaller.

After careful and long-continued observations of this kind the ancients were able to conclude, in the first place, that the Moon's orbit about the Earth—its apparent path among the stars—makes an angle of about 5° with the ecliptic. This explains why the Moon sometimes rises north of the east point, and sometimes south of it, for the ecliptic itself makes an angle of 23½° with the plane of the Earth's equator, and the Sun is south of the equator from the autumnal equinox (about September 21) to the vernal equinox (about March 21) and then north of it through the next six months. Let us note just here that since the Moon at full is always opposite to the Sun, the full Moon must be north of the equator during our winter months, when the Sun is south of it, and south of the equator during our summer months. The full Moon therefore "rides high" in the sky and gives us the most light in the winter when we have the least sunlight, and rides low in the sky in the summer. In our latitudes this is not a matter of great consequence, but if we were at the North or at the South Pole, it would be pleasant, at least, to have the Moon above the horizon continuously for the 14 days from the first quarter through full

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PLATE XVII. The Moon, 19d. 12.5h. Old.

Photograph taken with the 36-inch refractor, Aug. 30, 1893, by A. L. Colton and C. D. Perrine.

Moon to the last quarter every month during the long polar night.

Next, the ancients learned that the Moon's distance from the Earth varies by a slight amount, corresponding to the slight variation in its apparent diameter, and that this variation progresses in a regular manner, completing the cycle of its changes in the period of a month. This we now know is due to the fact that its orbit is not an exact circle but is flattened a little into the form of an ellipse. Of course they also learned that the Moon does not shine by its own light but only by reflected sunlight. This led to an understanding of the phases of the Moon.

A careful study of some of the prominent markings on the Moon's surface will soon convince any one that they always remain in approximately the same position with respect to the limb; that is, that the Moon always turns the same face toward the Earth. This means that the Moon must turn once on its axis—make one complete rotation—each month. That is a puzzling statement to many people when it is heard for the first time but it is easy to show that it is true, and that in no other way could the Moon keep the same face turned toward us. Try walking around a table placed near the center of a room, always facing the table as you walk, and see what happens! You will find that, in making the round, you have faced each wall of the room in succession; that is, you have yourself turned once completely round during your walk.

I said just now that the Moon always keeps the same face turned toward the Earth. This is true in a general way but the statement is not quite exact. The Moon's equator is inclined 6½° to the plane of its orbit, consequently at one time in each month its north pole is tipped 6½° toward us, and two weeks later its south pole is similarly tipped. Therefore we see a little beyond first one pole and then the other each month. This slight variation we call the *libration in latitude*. Further, since the Moon's orbit is an ellipse its motion in its orbit will be variable, being slower when it is farthest from the Earth and faster when it is nearest; but its motion of rotation on its axis is perfectly uniform. This produces what we call the *libration in longitude* and permits us to "see alternately a few degrees around the eastern and western edge of the lunar globe." Finally, the Moon when it rises and when it sets is practically on a plane passing through the center of the Earth while we are about 4,000 miles above that plane; therefore we look a little past the western limb of the Moon as it rises and a little past its eastern limb as it sets. The net result is that 41/100 of the Moon is always visible, 41/100 is never visible, and the remaining 18/100, along the limbs, is sometimes visible and sometimes not.

The Moon is so near the Earth that its distance can be measured with very great accuracy. One method of doing this is, in principle, precisely like that which a surveyor employs to determine the distance to an inaccessible object. The surveyor measures off a base line of suitable length from both ends of which the object is visible. At each end he then measures the angle included between the other end of the line and the object. This gives him a triangle in which he knows the size of three independent parts—one side and two angles—and from these he can readily compute the other parts. In the case of the Moon we measure its distance from the zenith at two stations having nearly the same longitude but widely separated in latitude, the observatories at Greenwich, England, and at the Cape of Good Hope, South Africa, for example. Knowing the latitudes of our stations we have for our base line the length of the line between them drawn through the Earth's crust, and the measures of the Moon's zenith distance supply our angles. Then we calculate the distance from each observatory to the Moon and from these values the distance to the Moon from the Earth's center. The mean value has been found to be 238,862 miles; but it is easier to remember the value 240,000 miles, a round number that is sufficiently exact for any one except the specialist. Having the Moon's distance, our measures of its apparent angular diameter can be converted into miles. This leads to the figures 2160 miles, a little more than one-fourth the diameter of the Earth.

Several of the satellites of *Jupiter* and of *Saturn* are fully as large as or even larger than our Moon, but the planets themselves are so much larger than the Earth that the contrast between planet and satellite is very much greater. Our Moon, in fact, ought really to be called the Earth's companion rather than its satellite. Viewed from *Venus* or from *Mars* it would easily be seen without the telescope, forming with the Earth a beautiful double star.

It is its nearness to us, however, rather than its size, that makes the Moon the only body except the Sun which exercises a direct influence upon our lives here on the Earth. I am speaking now from the strictly utilitarian point of view. Planets could be completely destroyed and the stars hidden from our sight and in one sense our lives would go on without the slightest inconvenience, though our intellectual and spiritual loss would be immeasurable. But let the Moon be annihilated! Immediately the effect would be felt in nearly every shipping port in the world. The ships in dock could not get out; the ships outside could not get in; and the maritime commerce of the world would be thrown into dire confusion, for the Moon is the principal factor in producing the tides. The Sun also raises tides on the Earth but its effect is only half that of the Moon.

We cannot enter now upon the story of the tides; that would make a lecture in itself. But I want to take up one point very briefly. If the Moon raises tides upon the Earth, then the Earth must likewise exercise a tidal strain upon the Moon and because the Earth's mass is so much the greater of the two, this strain must be about 20 times that exerted by the Moon upon the Earth. We think of the tides as a phenomenon connected with the ocean, but a moment's reflection will make it clear that the pull of the Moon, under the law of gravitation, is just as strong upon the solid crust of the continents. The waters of the ocean are freer to move, that is all. Now it can be shown mathematically that when a body rotates upon its axis in the same direction as its motion in its orbit, and the rotation time is shorter than the revolution period, such a tidal force acts as a brake to slow up the rotational motion until the two periods are equal. It is thought by most astronomers that the Moon originally rotated much faster than it does now and that the cumulative effect of the Earth's tidal action upon it through the ages is responsible for the fact that now its rotation time equals its revolution period, in other words, for the observed fact that it now keeps the same face always turned toward the Earth.

The Moon has been credited with many other influences upon us, malign as well as benevolent. Our words *lunacy* and *lunatic* preserve the idea once universally held that moonlight can affect the minds of men; countless wise sayings embalm the belief that the Moon affects the weather; and others, the belief that the planting of various crops, to result in fruitful harvests, must be timed to the right phase of the Moon. These are all superstitions, worth as much or as little as Tom Sawyer's method of curing warts. Not one of them has a basis of fact, but they cling tenaciously to men's minds and still influence the actions of some. In a certain region of the San Joaquin Valley. for instance, no farmer, even today, plants his cabbages without first consulting an almanac to see whether "the Moon is right"!

Consider the Moon and the weather. We are told that changes in the Moon's phases—at the quarters, full and new—bring changes in the weather. Now, in the first place, the Moon could only affect the weather by variations in the amount of heat it radiates to us. There is a variation in this respect, it is true, for not only is the illuminated surface at the quarter phase only half that of the full Moon but, because of the rough surface of our satellite, this surface sends far less than half—only one-ninth or one-tenth as much light and heat as the full Moon. But even the full Moon sends so little that it can have no appreciable effect; in fact it sends only 1/465,000th as much as the Sun. Taking the phases into account, it is found that in *thirteen seconds* we receive as much light and heat from the Sun as we do from the Moon in a whole year! Evidently, then, the Moon's heat is quite unimportant to us; a light cloud passing in front of the Sun deprives us of more heat than the Moon ever sends us. In the second place, storm centers travel across the Earth, generally from west to east in our latitudes, and can often be traced clear across the continent, or even half-way around the globe in the course of a week or two. If the storm begins with a change in the Moon at one station, it clearly will not begin with such a change at another station some hundreds of miles east or west of the first one. Finally, records kept at many stations for long periods of time—a hundred years in some instances—show no relation whatever between Moon change and weather change, though chance coincidences are of course frequently found.

Now let us look at the Moon itself as it is revealed to us by the telescope. Our first surprise is to find the surface so extremely broken and rugged; the next is that we can see the details of all the features so clearly. Visitors to the Lick Observatory often ask how near the great telescope brings the Moon to us. This, of course, depends upon the magnifying power we use. With a power of 1000, which is as great as can be used to advantage under ordinary conditions in studying the surface of a planet or of the Moon, it is, in effect, brought within about 240 miles of the Earth's surface. But this does not give quite a fair idea of the distinctness with which we see the lunar surface details, because when we view an object like a mountain 240 miles distant on the Earth we are looking at it through a much denser layer of our atmosphere. On a clear winter's day at Mount Hamilton, for example, we can see the Sierras stretching from the far northeast to the far southeast and can readily make out some of the prominent landmarks about the Yosemite Valley, 180 miles due east of us, without the aid of glasses. But we cannot see them so well defined as we see the Moon's features through our telescopes. Objects on the Moon having a diameter of 1,000 feet are easily seen and those with half or even one-third that diameter would hardly escape detection. Small inequalities of the surface, or an ordinary house, a single tree or animal or plant would be invisible. Rugged as the Moon looks to us, its actual surface is probably rougher still.

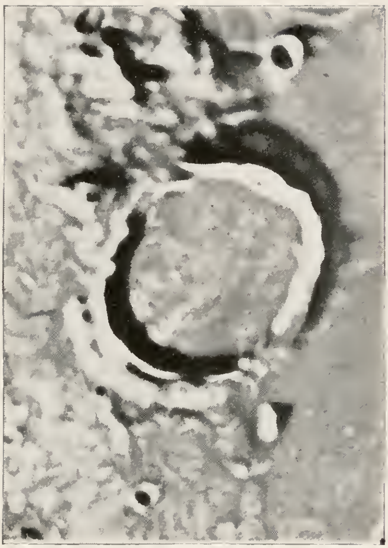
On that side of the Moon which is visible to us, there are no less than ten mountain ranges of considerable extent, numerous isolated peaks, some 10,000 cracks or "rills" and more than 30,000 "craters" which have been mapped and, for the most part, named. There are also the large dark areas which from Galileo's time have been known as *maria* or seas, though we have long been aware that they are dry. The system of nomenclature dates back to Riccioli, who, in 1651, published a lunar map on which several hundred mountains and craters were named for distinguished astronomers and mathematicians. The names *Alps* and *Apennines* and a few others date back still farther—to 1645, when Hevelius constructed the first satisfactory map of the Moon.

It is not my purpose to describe the lunar surface in detail, for the most complete and vivid description I could possibly give would fail to convey to you any adequate conception of its beauty as viewed through a good telescope. What little I shall say will be said in the hope that it may lead many of you to a direct study of our companion world. Contrary to a somewhat general impression, a very large and expensive telescope is not required. A good lens with an aperture of three or four inches, driven by clockwork if possible, or mounted upon a simple tripod, and supplied with eye-pieces ranging in magnification from 50 to 150 or 200 diameters, is capable of yielding valuable results in many fields of astronomical work and is certainly amply large for observations of the Moon undertaken primarily to gratify one's love of the beautiful.[3]

The time to view the Moon for this purpose is when it is crescent in the first quarter, or still in the early gibbous phase in the second; or, if you do not object to keeping late hours, when it is again waning to a crescent after the full-moon stage. At full, the Sun's light falls upon its surface so nearly vertically that there are practically no shadows and hence no contrasts. Color differences, of course, exist even at the full-moon phase, and are, indeed, conspicuous to the unaided eye. The large dark areas are, in general, low ground, the so-called *maria,* or seas; the bright portions are higher ground. The

[3] The two photographs shown in Plates XVI and XVII have been selected for reproduction because together they show the entire visible surface of the Moon (neglecting the effects of libration) at phases well suited for general telescopic views. Many observers would, however, regard the views at phases respectively a day or two earlier and a day or two later as still finer. The large crater near the center of the terminator edge (sunrise line) at the right, in Plate XVI, is Copernicus; to the left of it and below stands the crater Eratosthenes at the head of the lunar mountain range known as the Apennines. A gap in the range nearly opposite a group of three craters, Archimedes (the largest), Autolycus and Aristillus, in the *Mare Imbrium* (at the right), separates the Apennines from the Caucasus Mountains and opens into the *Mare Serenitatis* (at the left). The lunar Alps extend toward the right from the lower end of the Caucasus range to the great crater Plato near the terminator. Note especially the narrow, nearly straight Valley of the Alps to the left of Plato.

In Plate XVII, Copernicus is the great crater a little to the right and below the center of the illuminated disk. Note the complicated system of ridges and bright streaks radiating from it. The prominent crater near the top of the photograph is Tycho. Bright streaks radiating from it are also visible, but this crater and its wonderful system of bright streaks are best seen at the full-moon phase, when they form the most conspicuous and indeed almost the only well-marked features of the lunar landscape.



ARCHIMEDES.
Aug. 15, 1888.

ARCHIMEDES.
Aug. 27, 1888.

PLATE XVIII.

Note the changes in aspect produced by the change in the angle of incident light.

floors of many craters are also dark, whereas the remarkable systems of streaks radiating from such craters as Copernicus and Tycho, and most of the crater peaks and walls, are bright, some of them intensely brilliant.

But it is only when the sunlight falls slantingly upon them that the details of the Moon's surface are brought out in strong relief. Mountain ranges, isolated peaks, ringed plains, craters large and small, and canyons, cracks or rills are now distinctly recognizable. It will be noted that the shadow outlines are extremely sharp; there are no half-tones, no gradations between the deep blueblack shadows and the bright sunlit areas.

As the phase of the Moon changes, the angle of incidence of the Sun's light grows larger or smaller and the shadows change their dimensions, their forms and their positions. The result is a change in the appearance of craters and peaks that has frequently misled observers into thinking they were viewing true physical changes on the Moon's surface. Observation continued over many lunations will generally dispel this idea. It will also convince you that there is at no time any evidence for the existence of clouds above the surface of the Moon to obscure the view, and no appearance of "weathering" or erosion on any of the rugged mountain slopes or crater walls.[4]

Now the sharpness of detail, the absence of clouds and of any appearance of weathering lead to the inference that there is no water and no air upon the Moon. This inference we have every reason to regard as correct; certainly there is no water on the Moon's surface and if any atmosphere at all is present, which is very doubtful, it must be extremely tenuous—less than a thousandth part as dense as that of the Earth.

It is a fact readily verified by any patient and careful observer that when the Moon occults a star, the star disappears instantaneously at the Moon's advancing limb and emerges from the Moon's receding limb with equal suddenness. It is also true that the diameter of the Moon calculated from the duration of occultations agrees very precisely with the value

[4] Not all students of the Moon will subscribe fully to these statements. Claims have been made from time to time by trained observers entitled to respectful hearing that evidence of erosion is not altogether lacking and that (as is noted on page 93) physical changes have been observed in certain craters. Even were selenographers not divided in opinion as to the validity of these claims, the statements made above would hold for the Moon's surface in general.

obtained by direct measurement.[5] But even a very tenuous atmosphere would bend the star's rays and absorb more and more of their light the nearer the rays approached to the surface or limb of the Moon. Hence the star would disappear gradually and the duration of an occultation would be considerably less than that predicted from the Moon's measured diameter.

This is perhaps the best argument to prove the practical non-existence of a lunar atmosphere. But others are not lacking; the fact, for example, that at an eclipse of the Sun the Moon's limb is perfectly dark and sharp upon the Sun's disk; or the argument, based upon what is known as the kinetic theory of gases, that the Moon's mass is too small to enable it to retain an atmosphere even were it to be endowed with one. But we need not carry the discussion further, for astronomers are agreed upon the fact that the Moon is essentially a dead world: a world without air, without water, without vegetation and, indeed, without soil, unless this term be given to volcanic ashes or the "cosmic dust" of fallen meteors. As some one has said, the Moon is a world without weather and where nothing ever happens.

The most distinctive and conspicuous markings upon the Moon are the almost innumerable craters. They are found all over the visible disk, though they are not at all uniformly distributed; toward the south pole the surface is fairly honeycombed with them, whereas the broad belt of the chief dark areas or *maria* north of the center is relatively smooth. In size they range from "craterlets" barely visible in the most powerful telescopes to the great ringed plains 100 miles or more in diameter. One writer even regards the lunar Carpathian, Apennine and Caucasus mountains as but the fragments of a former huge crater wall which had a diameter of 800 miles. Generally the bounding wall is approximately circular and is compound, "composed of shorter ridges which overlap one another, but all trend concentrically". The inner

[5] Direct measurement gives slightly the larger value, but this is due chiefly to *irradiation*. Measures of a bright disk like that of the Moon or of one of the planets are always a little in excess of the true values. An excellent illustration of the irradiation effect is found in the appearance of the Moon three or four days after new Moon; the bright crescent appears distinctly larger in radius than the dark portion feebly visible by reflected earth-light, a fact embodied in the phrase "the new Moon holding the old Moon in its arms".

PLATE XIX. Walled Plains on the (Sunset) Terminator.

The upper, double walled plain, with triple central peak and a bright rill connecting the peak and wall at the right is Petavius. Below is Vendelinus. Note the small craters on the walls and floor of Vendelinus.

plain or floor is lower than the neighboring outer plain, often thousands of feet lower. Theophilus, for example, a crater 64 miles in diameter, is 19,000 feet deep. The crater walls, as a rule, slope very steeply to the inner floor and much more gently to the outer plain. Frequently one or more mountain peaks tower abruptly from the inner plain of a large crater to a height of even 11,000 feet as in Copernicus, or 16,000 feet as in Theophilus; but these peaks never, according to Neison, reach the altitude of the crater walls. Finally, the craters overlap one another in almost every conceivable way, forming complicated groups and chains, and smaller craters are numerous on the floors and walls of larger ones.

Now you will ask, as does every intelligent visitor to the Lick Observatory after seeing the Moon through the telescope, "What caused the craters?" I wish I could tell you! But if I am to be perfectly honest I shall be obliged to confess that I do not really know. The question of the origin of the various lunar surface features is one on which astronomers are still in doubt. It is perhaps not difficult to conceive of the formation of the mountain ranges, lofty as some of them are, and of the valleys or canyons and of the smaller craters, at least, by forces similar to those which have produced corresponding features upon our Earth, especially when we consider the fact that, because of the Moon's smaller mass, a given force acting against gravity there would be about six times as effective as here. But the bright lines or rays running out from some of the craters are unlike anything familiar to us on the Earth's surface, and there are great difficulties in the way of accounting for the craters themselves. Of the many theories that have been proposed at one time or another we need here examine only the two which at the present time command the serious attention of astronomers, the classic "volcanic" theory and the "meteoric" theory.

Probably the term *craters,* which was early given to these formations because of their superficial aspect, has been the source of unconscious prejudice in many minds in favor of the volcanic theory; just as the unfortunate translation of Schiaparelli's Italian term *canali* by our English *canals* has unquestionably been a powerful factor in creating the widespread belief in the artificial origin of these well-known markings on *Mars*. Be that as it may, it is safe to say that a majority of astronomers favor the volcanic theory, or, to use broader terms, the theory that all of the observed configurations of the lunar landscape are the result of the action of forces originating in or on the Moon itself. Confining our attention to the craters, using this term generically to include both large and small formations, we find that this theory encounters a number of difficulties.

In the first place, the craters are so numerous and many of them are of such vast dimensions compared with the volcanic craters upon the Earth. The objection as to disparity in number is perhaps fairly met by the assumption that the lunar craters were formed many ages ago and that all traces of the corresponding early volcanic activity on the Earth have been obliterated by later processes of erosion and sedimentation. It is not so easy to explain the relative size of the larger lunar craters; and the facts that the material in the surrounding walls and peaks is generally not sufficient to fill the crater bowls and that there is little or no evidence of lava flows increase the difficulty. It is certainly hard to believe that the craters on the Moon were formed by such explosive forces as those which are responsible for the formation of Vesuvius, and approximately 95 per cent of all known craters upon the Earth. Craters of the subsidence type, like those on the Hawaiian Islands, as W. H. Pickering and others have shown, bear a much closer resemblance to the lunar formations; but even here the resemblance is far from perfect and neither type of terrestrial crater has any features similar to the huge central peaks which so frequently rise from the floors of the larger lunar ones. These peaks are in no sense secondary crater-cones; they are to all appearance true mountain peaks.

But if there are difficulties in the way of fully explaining the lunar markings by the action of internal forces, the objections to the meteoric theory are of even greater weight. The bombardment must obviously have been a terrific one by meteors of tremendous size, and since the Earth and Moon revolve about the Sun together in the same general path, craters of meteoric origin should be correspondingly large and numerous upon the Earth. As a matter of fact, however, the largest meteoric mass found upon the Earth could have produced but a puny crater compared with those upon the Moon; and the only crater upon the Earth, so far as known, that was probably formed by a falling meteorite is the celebrated "meteor-crater" in Arizona.[6]

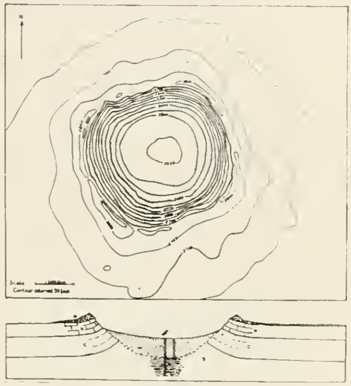


Fig. 8. Crater Mound, Arizona.
A photograph of the model prepared for Professor C. K. Gilbert is shown in *a* (left); a photograph of the topographic map, and a cross section of the mound are shown in *b* (right).

Again the objection to the number is met by assuming that the lunar craters were formed in the early history of the Earth-Moon system, and it is also argued that at that time meteors of far greater mass than any known in historic times may have been encountered. If this were so, it would seem that there should be more than a little indication of their former existence in the rock strata which have been explored upon the Earth, for in view of their number and enormous masses it is hardly conceivable that all traces of them would disappear after they had buried themselves deep in the ground, even after the lapse of geologic ages. So far as I am aware, however, geologists have found no evidence of such huge falls. Indeed it must be said that, while the explorations that have been made of the Arizona crater-mound seem reasonably conclusive as to the method of its formation, the meteoric mass believed to be responsible has not been discovered.

[6] This is known also as Coon Butte and is situated some miles east of Cañon Diablo near Sunshine Station on the Atchison, Topeka and Santa Fe Railroad. It is a bowl-shaped hole approximately three-quarters of a mile in diameter, whose walls rise about 150 feet above the plain. "The bottom of the crater is about 570 feet below the rim, or more than 400 feet below the general level of the plain outside." For an interesting description of this crater, see the article by Elihu Thomson, from which I have just quoted, on "The Fall of a Meteorite," *Proc. Amer. Acad. Arts and Sci.*, 47, 719, 1912.

An even more forcible objection to the meteoric theory, and one that to my way of thinking is insuperable, arises from the predominantly circular form of the lunar craters, large and small. Such forms imply that if the craters were produced by meteors these must have fallen vertically. But it is plain that a majority of meteors, traveling more or less swiftly through space and colliding with a spherical body like the Moon, must strike the surface at a large angle to the vertical, and that numerous encounters must be mere glancing blows. Hence we should expect to find craters and scars of all forms ranging from circular pits to long and narrow valleys, the oval pit being perhaps predominant. Observation, however, has revealed only two lunar markings which at all suggest an origin in a glancing blow from a meteor, the remarkable Valley of the Alps, and the valley near Rheita; and forms intermediate between these and the circular craters are conspicuously lacking. This objection has never been satisfactorily overcome.

The systems of bright rays or streaks about Tycho, Copernicus and one or two other large craters are puzzles, whatever theory of crater formation we adopt. They run in nearly straight lines over craters, cracks, peaks and seas alike, sometimes for hundreds of miles; and at no phase angle do they cast shadows. Hence they are neither elevations above, nor depressions below the surrounding surface. Many explanations of their nature and origin have been offered but no one of these is at all satisfying.

I have stated the objections to the theories rather than the arguments in their favor because the objections must in some way be removed before either theory can be accepted as satisfactory. Some recent work by Professor R. W. Wood, however, may be referred to here which to a certain extent seems to favor the theory of origin by volcanic or other internal forces. He has photographed the Moon in light of different wave-lengths, first in yellow light, then in violet and finally in ultraviolet light, and the three sets of photographs show some marked differences in appearance. For example, a large dark patch just above the crater Aristarchus appears on the ultraviolet picture, which is practically invisible in the

PLATE XX. COPERNICUS.

Drawing by Professor E. L. Weinek.

From the negative taken at the Lick Observatory on July 28, 1891, 15ʰ 49ᵐ 16ˢ P. S. T.

yellow one and only faintly visible in the violet one. Professor Wood took two specimens of volcanic tufa of about the same color, one of which photographed light and the other dark in rays of ultraviolet light. Placing a small chip from the dark specimen upon the light one he secured effects exactly reproducing those shown by the Aristarchus spot. Analysis then showed that the dark chip contained iron and traces of sulphur. Experimental photographs of many rock specimens having iron stains failed to give these effects, but by taking the specimen of tufa which had photographed light in the ultraviolet picture and forming on a spot on its center a very thin deposit of sulphur—so thin as to be invisible to the eye—he obtained photographs showing the spot quite black in the ultraviolet, gray in the violet and invisible in the yellow. This makes it appear probable that there is a deposit of sulphur near Aristarchus on the Moon. More extended work along this line is needed, however, before any theory of crater formation can be based upon it.

I have said that the Moon is a world where nothing ever happens. Some astronomers would take exceptions to this, and it is perhaps well to remind ourselves that a universal affirmative (or negative) is a dangerous form of statement. It is quite conceivable, for instance, that a large meteorite *might* strike the Moon at some time and that we *might* be able to detect the effect. Again, the surface is certainly subjected to extreme variations of temperature; there is no atmosphere to shield it from the direct rays of the Sun during the two weeks of the lunar "day," or to blanket it during the two ensuing weeks of the lunar "night". Doubtless some cracking of the surface must from time to time result; but it is questionable whether this could proceed on a scale large enough to become visible to us.

Physical changes have repeatedly been reported by expert observers in connection with a few of the craters and in particular with the relatively small crater Linné in the Sea of Serenity (*Mare Serenitatis*); but the general opinion is that the reality of these supposed changes has not yet been fully established and some selenographers assert, on the other hand, that "no eye has ever seen a physical change in the plastic features of the Moon's surface".

Very positive statements are also made by certain competent observers that slight color changes take place in the course of each month in the neighborhood of one or two of the craters. Further confirmatory observations are desirable before we accept these changes as demonstrated; and even then we may well hesitate to accept the explanations that have been offered; as, for example, that they are due to vapors, issuing from cracks in the surface, which are deposited as snow or hoar frost in the lunar night and evaporated in the lunar day; or that vegetation of a low order springs up, runs the cycle of its life history in each lunar day and perishes in the cold of lunar night.

My conclusion is that we have still much to learn of the nature and origin of the surface markings on the Moon, though it is the nearest body to us in space. It may be a dead world, but it will long continue to be an interesting object of study.

Fig. 1—The Diffuse Nebulosity, Messier 8, in Sagittarius.

Fig. 2—The Diffuse Nebulosity, N. G. C. II 5146.

Fig. 3—The Dumb-Bell Nebula.

PLATE XXI.

THE NEBULAE[1]

By Heber D. Curtis

In the four lectures of the Stahl series which have preceded this one you have heard about that portion of the universe to which our own little Earth belongs, you listened to what astronomy has to say regarding the planets of our solar system and whether they may possibly be inhabited or not, learned something of those mysterious wanderers in our system which we call the comets, studied the surface of that cold and lifeless satellite of ours, the Moon, and the fact was brought home to you that the mighty Sun was only our own particular star, and not a very great or important star at that except for its position as the center of our solar system. In the present lecture we shall consider the nebulae, a remarkable class of objects in the universe without, a universe so vast, of such incomprehensible extent, that our own solar system is but an atom in comparison.

Though the task is apparently a hopeless one, it may be an advantage if we make the attempt at the start to realize the vastness of this outer stellar universe of which our solar system forms so inconspicuous a part. We can all form some conception of the distance around the Earth, say twenty-five thousand miles, and we can then have some sort of an idea of the distance of the Moon as about ten times as far away. But neither the layman nor the professional astronomer can form any adequate conception of the distance of the Sun, ninety-three millions of miles from our Earth. Nor can we have any idea of the distances of the stars from the fact that, at the distance of the average naked-eye star, ninety-three millions of miles looks to us of about the same size as a fifty-cent piece in Los Angeles, viewed from San Francisco. Out in this ocean of space a measuring rod a million miles in length is all too short; it would be like trying to measure the distance to Los Angeles with a foot rule. Something a million times larger than this would

[1] Delivered March 9, 1917.

be better, so the foot rule which the astronomer ordinarily uses is the distance traveled by light in one year, which he calls a light-year. A light-year is nearly six trillion miles; that is, take a length of a million miles and lay it down as a measure six million times, end to end. The light-year is not quite six trillion miles, but we need not be particular about a few billion miles, more or less. It takes light, then, over four years at the rate of 186,500 miles a second, to reach the very nearest of the stars, so such a star is said to be four light-years away. We feel certain that some of the celestial objects are so far away that it takes light a hundred thousand years to make the journey, in other words, we see such objects not as they actually are tonight, but as they were one hundred thousand years ago. But enough of such brain-staggering figures. It is sufficient if we from these facts comprehend a little more clearly that this stellar universe is something wonderful and mighty, far beyond the power of the mind of man to grasp.

What we term the factor of space-distribution is of considerable importance in all theories of the nebulae, that is, the way in which these are arranged with reference to the great mass of the stars, so, at the start, a word or two with reference to the "geography" of the stellar universe will be in place. We can see for ourselves on any clear night that most of the stars appear to be grouped near the Milky Way, and our telescopes and photographs show that this is really the case; the stars are not arranged regularly all through space, but the great majority of the thousand million or so of stars are grouped in a relatively flat disk, so that the shape of the stellar universe, when we consider the stars alone, is much like that of a thin pocket watch, with our Sun fairly near the center.

Another point which will be of importance later in the lecture is what we may term the factor of space-velocity. All these apparently fixed celestial objects are really moving in all directions at very high rates of speed. Thus we may not speak of the part of space occupied by our solar system, but simply of the part of space which it now occupies, for the Sun and all his retinue of planets is moving through space at the rate of about twelve and a half miles in every second of time. This seems inconceivably rapid to us, but our Sun is, even at this rate of speed, quite a slow coach compared with many of the stars. Thus, when the Egyptians commenced to study the heavens five thousand or more years ago, we and our solar system were two trillion miles from where we are tonight. At that rate it would take us fifty or sixty thousand years to reach the very nearest of all the other stars, provided we were going exactly in that direction, which we are not. When you leave the hall at the close of this lecture the Sun and all our system, and all of us with it, will have traveled about forty-three thousand miles from the place where they were when you sat down. If I should happen to talk ten minutes too long we should be seven thousand miles beyond the corner where we should have got off!

But neither the two trillion miles which our system has traveled since the days of the Egyptians, nor the equal or greater movements which all the stars have made in that interval, have made any essential difference in the general appearance of the heavens, for two trillion miles is not a very long way as distances go in the outer world of space. The Egyptian saw his night sky tilted at a different angle and had a different pole star than our own, because of a progressive change in the position of the Earth's axis, but the constellations looked practically the same then as they do now; though all the stars are moving at these rapid rates of speed, it takes much longer than five thousand years for these motions to show so as to be very perceptible without a telescope and accurate measures.

Now out in this limitless ocean of space we see just two great classes of objects, the stars, and the nebulae; while our subject is the nebulae, the stars will, of necessity, be occasionally mentioned as well. As for the stars, our great telescopes and the photographic plate tell us that there must be a thousand million or so, separated from each other and from us by trillions and quadrillions of miles. But there is a smaller number of objects of an entirely different class from the stars, objects which in a telescope look like very faint luminous clouds, which is the reason they have been given the name "nebula" from the Latin word for cloud. There are several hundred thousand of these nebulae, ranging in apparent size from mere specks to great masses covering a sky area larger than that covered by the Moon. Only a very few of them are large enough or bright enough to be seen without a telescope, and even in the largest telescopes the best of them prove generally to be very disappointing objects to the layman, as they are so faint and indistinct. Their full beauty and wonderful structure is brought out only by photographs of several hours' exposure made with a large reflecting telescope, and the illustrations shown were made in this way by the Crossley reflector at the Lick Observatory.

In looking at reproductions of the nebulae it is well to try to keep in mind that these remarkable objects are really of enormous size; perhaps the following illustration will assist in forming this impression. We shall not be very far wrong in the statement that the diameter of the average star is from half a million to a million or more miles. Now the thing which is most apt to disappoint the average observatory visitor as he looks through a great telescope at a star is that it still looks like a star, a mere point. He sees the star much brighter than it would appear to the naked eye, but expects to see something very large, filling the whole field of the telescope, and is at some difficulty to comprehend why the brightest star should still look like a point in the mightiest telescope; it is hard for him to realize that the star is so far away that even a million miles under high magnifying power looks like a point without size. If half a million or so of miles has no size at all, so to speak, at stellar distances, how mighty must a nebula be which covers a space equal to that covered by the full Moon? It will then be evident that many of these bodies must be billions or trillions of miles, even many light-years, across from edge to edge.

While the nebulae take a great variety of form, there are but three main classes, and the following table will show the main features of each class.

THE GREAT DIFFUSE NEBULAE

Enormous masses of luminous matter; filmy, cloud-like, and generally very irregular. Occur in or near the Milky Way and where the stars are thickest. Frequently associated with "young" stars, never with "old" stars. Speeds low; almost at rest in space. Fairly numerous.

THE PLANETARY NEBULAE

Generally small, clear-cut, bright, and with a central star. They are gaseous bodies. Comparatively rare objects; fewer than 150 known. Tend to congregate in the Milky Way. Average speed much higher than that of the stars.

THE SPIRAL NEBULAE

Several hundred thousand in number; generally spiral in form. Congregate about the poles of the Milky Way where stars are fewest, and never found in the Milky Way. Speeds enormous, averaging several hundred miles a second. Their light is generally the same as average star-light.

The great diffuse nebulosities are wonderful structures and Fig. 1, Plate XXI, shows a typical object of this class. In some cases, as in the nebulosity around the *Pleiades,* there is good reason to believe that the light from these nebulosities is in some way, perhaps by reflection, caused by the bright stars with which they are associated. But in the majority, as the Great Nebula in *Orion,* Messier 8, the *Trifid* Nebula, and others, the light which comes to us from them tells us very clearly, when analyzed in our spectroscopes, that these are truly gaseous bodies. They contain the gases hydrogen, helium, and something which, for lack of better knowledge, we call "nebulium". Just how they shine we do not fully know; we have evidently to do here with matter in a very rare and perhaps primordial state, and it may be that their light is in part due to some form of electrical excitation. As far as their actual density is concerned they must be exceedingly rare bodies. Among our reasons for this belief is the easily calculated fact that were the substance of the enormous nebula in *Orion* anywhere nearly as heavy or as dense as ordinary air the great mass would weigh so much that it would be drawing all the neighboring stars, and our Sun as well, swiftly toward it by its gravitational power. Sometimes the region immediately around one of these diffuse nebulosities is singularly devoid of stars. Fig. 2, Plate XXI, shows this in a striking manner. The best explanation appears to be that around the inner luminous part of such a nebula there lies a great mass of dark matter which obliterates the stars in the background. These diffuse nebulosities are often found associated with stars and in every such case the star is one of the class which, from the character of the light it sends us, is believed to be a "young" star; never do we find this diffuse nebulosity associated with stars of "old" types. Bearing in mind that these diffuse nebulosities are always found in or near the Milky Way where the stars are thickest, we can see that there are very good reasons for supposing that the great diffuse nebulosities may well be regarded as the primordial stuff from which stars are made.

Though the second class of nebulae, the planetaries, is so small a one, it is nevertheless of very great interest. Fig. 3, Plate XXI, shows a typical object of the class. Their light shows them to be of gaseous constitution; they are nearly all rather small and oval or round, and most of them show a central star. They tend to congregate in the Milky Way and where the stars are found in greatest numbers. Many of them are of exceedingly complicated structure, and, because of recent discoveries with the spectrograph, we know that they are revolving. But they are a very puzzling class. We do not know as yet how they can take these complex forms and show certain motions, as they do, under the ordinary laws of gravitation alone; perhaps other forces, such as radiation pressure, come into play as well. We would like to think of them as in that stage of nebular condensation and stellar evolution which comes just before true stars are formed.[2] But there are several difficulties in the way of accepting this theory. In the first place, the planetaries are comparatively rare objects; out of so many hundred thousand stars in all stages of development it is very strange, in fact inexplicable, that there should be fewer than one hundred and fifty at this particular early stage. Then, too, their space velocities are very much higher than that of the average star. Why should the planetaries stand so decidedly apart in this respect, and how can this gap be bridged over? Though but a theory as yet, perhaps the most acceptable hypothesis, because of their high speeds and small numbers, is that the planetary nebulae are to be regarded as a somewhat sporadic case in stellar evolution, arising through some collision or cataclysm, and not to be regarded as cases typical of the general run of stellar development.

When we pass on to the third subdivision, the great class

[2] They are very closely allied in spectrum with a comparatively rare class of stars known as the Wolf-Rayet stars.

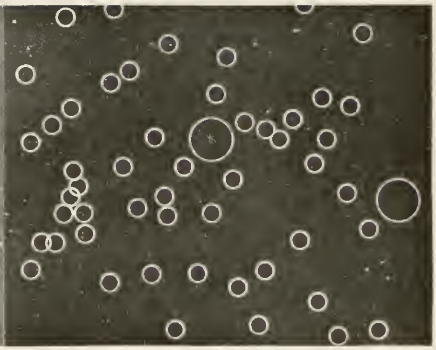
 

Fig. 1—*At left*, region in the Milky Way showing ten to twenty thousand stars, one planetary (N. G. C. 6563), and no spirals.

Fig. 2—*At right*, region near N. G. C. 2507, some distance from the Milky Way, showing few stars and fifty-three small nebulae, indicated by rings. The area of each half is somewhat larger than that covered by the full Moon.

Fig. 3—*At left*, is a drawing of the Spiral Nebula, Messier 101, made by Hunter in 1851 with the 6-foot reflector of Lord Rosse.

Fig. 4—*At right*, a photograph of the same nebula.

PLATE XXII. Photographs of Spiral Nebulae by H. D. Curtis; Drawing of Messier 101 by S. Hunter.

of spiral nebulae, we are on much less certain ground. Prior to the introduction of photography there were fewer than ten thousand nebulae known. It was Director Keeler, of the Lick Observatory, who first really showed the great power of photography and the reflecting telescope in the depiction and discovery of nebulae. Some of the very largest of this last class of nebulae had, it is true, been seen visually to be of spiral form, but Keeler's photographs showed, first,—that the great majority of the nebulae were spirals in form, and, secondly,—that their numbers were far greater than had before been supposed. Fig. 1, Plate XXII, shows a small part of the Milky Way where the stars are very closely packed so that they seem almost to touch one another, though in reality trillions of miles apart. In such regions as this we never find a single spiral nebula. Fig. 2 is from a negative taken some distance from the Milky Way. The area covered is somewhat larger than would be covered by the disk of the full Moon, and it will be noticed that the stars are comparatively few in number. But many nebulae are seen on the original negative; these are too faint and too small as a rule to show in the cut, so the position of each one is indicated by a small ring. Most of these small nebulae are probably spirals. It may be seen, then, that the spirals occur in great numbers in certain definite parts of the sky: the estimates as to their total number range from two hundred thousand to half a million. A recent count of the small spirals occurring on all available regions of the Crossley photographic plates taken from 1898 to 1918 indicates that at least 700,000 small spirals are within reach of large reflecting telescopes. It should be emphasized, also, that they never occur in the regions where the stars are thickest, but seem to avoid these regions, congregating near the poles of the Milky Way. Figs. 3 and 4, Plate XXII, will serve to show how immeasurably photography has improved our knowledge of the nebulae. The first is a copy of a drawing made by Mr. Hunter in 1851 with the six-foot reflector of Lord Rosse, and the other a photograph of the same object. It will be evident that there is simply no comparison between the two, and that the beautiful and delicate structure of the photograph was entirely invisible in a powerful telescope. The human eye is a wonderfully delicate instrument, but it can see a faint object no better or more clearly after gazing at it for an hour than it could in the first few seconds; the photographic plate, on the other hand, keeps adding up the impressions of each second or fraction of a second it is exposed to the object, and thus with long exposures can show us objects far too faint for the human eye alone, though aided by the greatest telescope in existence.

Though the general characteristics are the same, the spirals exhibit a great variety of form. Sometimes there are but two prominent whorls, as in Fig. 1, Plate XXIII; at other times the structure is much more complicated, as in Fig. 2. Occasionally the spiral whorls will lie so close together that a ring appearance is shown, but in most cases the structure is more open. Most frequently the spiral appears like an elongated oval (Fig. 3), because it is essentially a flat, disk-like structure, and seen at an angle, but occasionally it lies so nearly straight across our line of sight that it appears to be almost round (Fig. 4, Plate XXII). Then again we see quite a number almost exactly edge on and can get a vivid idea of the fact that the spiral is not a sphere in general outline, but flat and lens-shaped. Many of these edgewise spirals show a very interesting phenomenon. Figs. 4, 5, and 6, Plate XXIII, show this very clearly. There is very evidently a great band of absorbing matter all around the circumference of these spirals, which cuts off all view of the matter in the nebula in a lane running along its length. Fig. 6 shows this in a most striking manner; the dark lane is so clear-cut that it appears almost like a streak of black paint along the image of the nebula.

Now what has modern astronomy to say as to the constitution of these beautiful objects, the spiral nebulae? May we think of them as representing a certain early stage in the evolution of the stars, or in the formation of such a system as our own solar system? Do they, as was long held by astronomers, give us ocular evidence in support of some sort of nebular hypothesis, and are they the existing representatives of that primeval stage when our own solar system was an extended, whirling mass of primordial gas? Is it possible to regard them as in the first of the stages so well put by Tennyson in "The Princess"?—

Fig. 1—The Spiral Nebula, N. G. C. 7479.

Fig. 2—The Spiral Nebula, Messier 51.

Fig. 3—The Spiral Nebula, N. G. C. 253.

Fig. 4—N. G. C. 891.
Fig. 5—N. G. C. 7814.
Fig. 6—N. G. C. 4594.

PLATE XXIII.

This world was once a fluid haze of light,
Till toward the center set the starry tides
And eddied into suns that, whirling, cast the planets.

From the form of the spiral nebulae we feel certain that they must be in rotation; we have some slight evidence of this in the fifteen or twenty years during which they have been under photographic observation, and the temptation is a strong one to place these great rotating spirals as a first stage in the evolution of stars or solar systems. The majority of astronomers still believe that our solar system was formed in accordance with some sort of nebular hypothesis, though, for a number of weighty technical reasons impossible to detail here, the well-known nebular hypothesis of Laplace, in just the form in which he put it forward, is no longer accepted.

But, tempting as such a theory of the spirals is, there are a number of very strong objections to it, objections which depend largely upon the two factors of space velocity and space distribution, which were mentioned briefly at the beginning of the lecture. We may sum up in the following table what we know at present of the space velocities of the various classes of objects in the stellar universe.[3]

THE FACTOR OF SPACE VELOCITY

Diffuse Nebulosities; velocities low.

The Stars: velocities appear to increase with stellar age.

Class B:	average	speed	8	miles	per	second
Class A	"	"	14	"	"	"
Class F	"	"	18	"	"	"
Class G	"	"	19	"	"	"
Class K	"	"	21	"	"	"
Class M	"	"	21	"	"	"

The Planetary Nebulae; average speed 48 miles per second.

The Spiral Nebulae; average speed 480 miles per second.[4]

[3] The stars are divided into a relatively small number of types or classes in accordance with the character of the light they send to us. Classes B and A are the bluer stars, in whose light hydrogen, helium and other gases are prominent, and are generally supposed to be the youngest stars; Classes F and G are yellower, more like our Sun, and show the presence of many metals; Classes K and M are redder and thought to be stars of relatively advanced age. While other arrangements of these classes, as indicating relative star ages, have been put forward, the generally accepted order of stellar age is as given in the table.

[4] The speed given for the spiral nebulae is somewhat uncertain, as this has been observed for a comparatively small number of spirals as yet. The assumption is also made that their motions are in all directions. Future work may change the value, but it seems certain that it will remain very large.

It will be seen that, as far as their space velocities are concerned, the great diffuse nebulosities fit in well as a starting point in the evolution of the stars, and we have seen that these are, if associated with stars, always connected with those classes of stars which are believed to be the youngest. On the other hand, the planetaries do not fit in, unless we should place them at the end of the stellar progression, or, as is perhaps better, regard them as exceptional cases. And the spiral nebulae do not fit in at all; their almost unbelievable velocities place them in a class entirely apart from the great mass of the stars.

Taking up the even more important factor of space distribution, the following table will show roughly the apparent location of the spiral nebulae with reference to the universe of stars which we call our galaxy.

THE FACTOR OF SPACE DISTRIBUTION

100,000 ± Spiral Nebulae
Distance unknown

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The Milky Way and stellar universe
is believed to be roughly lens-shaped and about
3,000 by 30,000 or more light-years in extent. In this space
occur nearly all the stars, nearly all the diffuse nebulosities, nearly all
the planetary nebulae, nearly all new stars,[5] nearly all
clusters, nearly all the variable stars, etc., but
NO SPIRAL NEBULAE.

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100,000 ± Spiral Nebulae
Distance unknown

The factor of space distribution is then entirely at variance with the hypothesis of the spiral nebula as a starting point in the formation of stars or of our own solar system.

The spirals are intrinsically so very faint that it is a matter of great difficulty to secure spectroscopic observations which

[5] Except the new stars recently found in spiral nebulae which are referred to later.

will throw additional light on their composition, and this work has been done for only a few of the brightest members of the class. Here we find a very puzzling fact. The light which these objects send to us, when analyzed in our spectroscopes, tells us that they are, in general, not gaseous, but of such constitution that their light is just the same as would be expected to come from a great cloud of stars. The future may possibly bring to light new facts which will enable us to give some other explanation, but our present evidence, so far as it goes, leads to the belief that the spirals are composed of great clouds of stars so infinitely distant that we can not make out the individual stars, much as our own Milky Way, which is seen in the telescope to be made up of millions of closely packed stars, to the unaided eye appears as a faint, nebulous, luminous band across the sky.

This characteristic of their light, then, together with their peculiar distribution, as a class, apparently apart from our stellar system, has given rise to what is known as the "island universe" theory of the spiral nebulae, namely, that these objects are really separate galaxies or universes of stars. There are some difficulties in the theory, but we have at present very little evidence to make any other theory of the spiral nebulae a more probable one. On this theory, too, could we be transported out into space a distance of hundreds of thousands or millions of light-years, to where the spirals are situated, and look back from that point at our own particular Milky Way and stellar universe, it would perhaps appear to us as a spiral nebula. The attempt has been made to depict our stellar universe as a spiral in general arrangement, with the Sun located fairly near to the center of the spiral.

Why, it may be asked, should our galaxy be situated thus in such a peculiar way, about half-way between two great groups of other universes at enormous distances from us, with no other universe relatively close to our own, and with none at all visible around the edge of our own, that is, beyond the circumference of our Milky Way? This peculiar arrangement is indeed a puzzle on any theory of the spirals. Perhaps the only explanation which can be suggested is that outside our Milky Way and nearly in its plane is a great ring of absorbing matter somewhat like those which are found in certain edgewise spirals (Figs. 4, 5, and 6, Plate XXIII), and that this matter cuts off from our view all other universes which we would expect to lie beyond and in line with our Milky Way. Then, too, the analogy of our Milky Way as a spiral must not be expected to prove too much. Nearly all spirals have a well-defined concentration at the center, marked either by an almost stellar nucleus or by an almost spherical enlargement of the nebular mass around the center, as is well seen in numerous photographs of edgewise spirals. There is pretty certainly no such great concentration of stars at the center of our own galaxy, supposing that it is to be regarded as a spiral. However, there are a number of very flat spirals which show no such mass concentration at the center, but they are scarcely typical of the class.

As a substitute for the Kant-Laplace nebular hypothesis Professors Chamberlin and Moulton have recently propounded what has been called the planetesimal hypothesis as an explanation of the spiral nebulae and the evolution of our solar system. The theory postulates, in brief, that a spiral nebula would be formed as a result of the disruptive tidal effects produced by the close approach of two massive stars. It has been well worked out and appears very plausible in what may be termed its mathematical and mechanical aspects; it does not seem impossible that our solar system might thus have been formed from a diminutive spiral nebula. But the theory can as yet offer no explanation for the fact that the light sent us by the spirals seems to be the same as that from a cloud of stars, nor for their phenomenal space velocities. Why, too, if the spirals are formed from close stellar approaches, should we find them where the stars are fewest, and never occurring where the stars are thickest and where, if at all, close stellar approaches should be common?

It must be admitted that the evidence at present available, upon which any satisfactory theory of the spiral nebulae may be based, is exceedingly scanty, and the confession must be made that in this class of objects modern astronomy finds one of its most perplexing problems.

A promising line of evidence has been recently developed

North

FIG. 1—The Spiral Nebula N. G. C. 4527.

Left: May 8, 1901.
Right: April 16, 1915, showing Nova.

North

FIG. 2—The Spiral Nebula N. G. C. 4321.

Left: April 19, 1901, showing Nova A.
Right: March 2, 1914, showing Nova B.

PLATE XXIV. NOVAE IN SPIRAL NEBULAE.

Crossley Reflector Photographs.

by the discovery of novae in the spiral nebulae. More than a dozen such new stars have been found in spirals, nearly all within the last year or two; two of these, the nova in the *Andromeda* Nebula, and Z *Centauri,* were moderately bright; the others have been from the 14th to the 19th magnitude at maximum. So far as can be decided for such faint objects, these novae are apparently similar in all respects to the new stars which have appeared in our own galaxy in historic times to the number of 26.[6] The line of argument based on the occurrence of these novae in spirals is one which is easily followed, though a striking analogy is by no means a rigid proof. If the spirals are in truth island universes, composed in each case of a thousand million or more stars, we should expect to observe in them occasional new stars, such as are observed in our own galaxy. Moreover, the average magnitude of the new stars in our own system has been about the fifth, while those seen in the spirals will average about the fifteenth magnitude or fainter; that is, approximately, ten thousand times less brilliant. If we assume that we have sufficient of each type of nova to afford a fair average, and assume in addition that such novae, whether in our own system or in the spirals, are bodies of the same order of size, and that questions of absorbing matter in space may be neglected in the problem, we may then postulate the spirals as $\sqrt{10,000}$ or one hundred times as far away, on the average, as the novae which have appeared in our galaxy. Now all these latter are Milky Way objects and probably at an average distance from us of at least ten thousand light-years. On this line of argument the spirals would be distant from us one million light-years (more probably ten or one hundred times this distance, as the fainter novae in spirals would escape detection). Our own galaxy, if we assume its diameter as thirty thousand light-years, would appear only 10′ in diameter if viewed from a distance of ten million light-years.

The peculiar grouping of the spirals, in that they are apparently so definitely arranged with reference to the plane

[6] It must be noted, however, that eleven novae have been found in the great *Andromeda* Nebula alone, and nearly all of these within the last two years (1916-1918). If they are intrinsically as bright as the novae which have appeared in our own galaxy, and are similar to them in their origin and in other respects, this is a remarkably large number.

of our own Milky Way, has convinced some astronomers that they must necessarily be connected with our own galaxy, on the ground that so definite a relationship, even though it is a "relationship of avoidance," demands such a connection. But such a "relationship of avoidance" loses its force if the cause lies within our own system. Such a cause is rendered possible of acceptance for our own galaxy, regarded as a spiral, in the phenomenon of occulting matter seen in so many edgewise or nearly edgewise spirals.

It is perhaps worth while here, at the risk of some repetition, to summarize the arguments bearing on the place of the spirals in cosmogony.

A. Regarded as members of our own galaxy.
   1. They must be relatively close; all evidence is against this.
   2. Spectrum difficult of explanation.
   3. No reason can be assigned for their apparent avoidance of the Milky Way regions.
   4. It is difficult to place them in any scheme of stellar evolution; they are never found where the stars are thickest.
   5. Their tremendous speeds place them in a class apart from all other galactic objects.

B. Regarded as separate galaxies (island universes).
   1. They are probably from ten million to one hundred million light-years distant; this is in accord with the negative results thus far secured for their distances, proper motions, and apparent rotation.
   2. The spectrum appears to be about what would be expected for a vast congeries of stars.
   3. Their apparent grouping at the poles of the Milky Way, and their avoidance of its plane, appear reasonable, if we assume occulting matter in the peripheral regions of our own galaxy similar to that seen in so many spirals, which would serve to cut off from our view spirals near the plane of the Milky Way.

4. The occurrence of novae in the spirals would be expected if the spirals are individual galaxies.
5. Their great velocities are less difficult of explanation, and accord well in order of magnitude with those found for the Magellanic Clouds, which may perhaps be similar structures, relatively close to us.

It is certainly a wonderful, a brain-staggering conception, more tremendous even than any other of the mighty ideas and facts of astronomy, that our own stellar universe may be but one of hundreds of thousands of similar universes. It is a familiar saying that, "An undevout astronomer is mad". This can not be interpreted too literally; there are many astronomers who are certainly not mad, but who could not, by any stretch of the imagination, be termed devout, in the ordinary acceptance of that term. But, in a larger sense, the saying is a true one. Familiarity with these mighty concepts most certainly does not breed contempt, does not dull our awe at the mightiness of the universe in which we play so small a part. It is very doubtful if any of those who are seriously studying the heavens ever lose their feeling of reverence for this supremely wonderful universe and for Whoever or Whatever must be behind it all.

ASTRONOMICAL DISCOVERY[1]

By Heber D. Curtis

The usefulness of a science to the world, and its intrinsic value as a pure science, are not necessarily measured by its capacity for growth, nor by the number and the relative importance of the discoveries which can be credited to its pursuit. But our estimate of its vitality, its charm as a field of research, and that allurement which the scientifically militant mind feels in the presence of problems awaiting solution, are all in great measure dependent upon such considerations.

It is not easy to make a definite and precise statement which shall include all the elements entering into a discovery. Into the detection of a new truth there may enter any or all of such factors as increased instrumental equipment, refined methods of manipulation, more powerful analytical processes, patience and perseverance, pure inspiration, or even pure chance. The discovery of the sun-spots, or that of the companion to *Sirius,* may be assigned as a direct result of the use of new or improved apparatus; the first stellar parallax was primarily due to Bessel's manipulative skill; fifteen years of patient search was involved in the discovery of the asteroid *Astraea*; Keeler's work on *Saturn's* rings may well be regarded as pure inspiration combined with great technical skill; the discovery of *Uranus* was largely chance. ". . . the only safe conclusion seems to be that there are no general rules of conduct for discovery." (Turner)

It would be quite possible, then, to limit our treatment of the subject exclusively to instruments, the purely mechanical adjuncts of discovery, and to describe the improvements in our telescopes, meridian circles, zenith telescopes, micrometers, cameras, spectrographs, and photometers. Such a view-point, though partial and inadequate, would be a legitimate one, for certainly, in the final analysis, all astronomical discovery

[1] Delivered April 6, 1917.

PLATE XXV. The 36-Inch Refractor, Lick Observatory.

depends upon such tools. Without the telescope, astronomy could have advanced but little beyond the pre-Galilean epoch. Science, like civilization itself, is a matter of tools.

It would be equally permissible to approach the subject from the standpoint of processes, emphasizing the astronomer's methods of handling his tools, rather than the tools themselves. In such a treatment there would be involved a discussion of the accuracy necessary in astronomical processes, the search for minute sources of error, the methods of measuring exceedingly small quantities, and the patient accumulation of details. This course would lead directly to a consideration of the nature of an astronomer's work, as an element in discovery. The objection may perhaps be raised that the routine of astronomical work has little to do with discovery. The objection is not a valid one. As a matter of fact, the work of the scientist is discovery, as closely as it is possible to define so elusive an entity. Discovery is coterminous with scientific work; all research has discovery for its aim, if not for its result. Discovery is merely scientific work which has the good fortune to produce definite results.

I have preferred not to limit myself to either of these points of view, though utilizing some material from each one. There are certain well-marked differences in the older and the more modern epochs of astronomical discovery, characteristic of other sciences as well. The attempt will be made to compare and to contrast the methods of astronomical discovery developed in the past half-century with those of earlier dates. Earlier discovery was generally, though not invariably, that of an isolated fact. The modern epoch has produced a vast number of individual discoveries, but counts its real progress in wider generalizations deduced from large numbers of separate discoveries; it deals with *classes* of objects, rather than with *units.*

For the nature of our science, its overwhelming subject-matter, has served to make modern astronomical discovery a process requiring the coöperation of many observers, or even many observatories, before sufficient evidence can be secured for some sweeping deduction which may rank as a discovery relating to a class, based upon hundreds of discoveries on the units of that class. The complexity and richness of our raw material becomes, to some extent, a disadvantage. What is the goal of astronomical discovery? In the widest sense, its purpose is to find out all that is possible about the universe, the mighty scheme that lies beneath it all, how came our Sun, the planets, and the stars into existence, what has been our past, and what is our probable future history. But such observations on a thousand million stars and nebulae would mean a program of work which is practically infinite, beyond the powers of all the observatories in the world, though they worked at the problem for thousands of years. All that astronomy can hope to do, on the observational side, is to secure the fundamental facts for as many representative objects as possible, and to fit these facts into a coherent evolutionary scheme.

There has been a tendency to underrate the apparently minute advances buried in the files of modern technical literature when such researches are compared with the confident, mighty journeys into unknown fields made by the pioneers of scientific discovery. It is true that much of modern scientific progress has resulted from a consideration of minute residual phenomena, or has depended upon measured quantities but little larger than the probable error of the methods employed. Argon, xenon, and neon, existing in our atmosphere in very small quantities, and the variation of latitude, form excellent examples of such "residual" discoveries. The radial velocities of the stars, and their distances, are determined by the measurement of exceedingly small quantities.

It is perhaps for such reasons that a mere superficial comparison of past and present advances in many fields of scientific endeavor is apt to leave the impression that modern research is a matter involving merely minute technicalities and the accumulation of statistical detail. Can modern astronomy, for example, afford instances of inventions or discoveries which can parallel such ten-league strides as were made by the invention of the telescope, the recognition of the law of gravitation, the finding of *Jupiter's* four major satellites, or the detection of the new planets *Uranus* and *Neptune*?

That the goal of a complete and perfect knowledge is unattainable is accepted as axiomatic; in the words of Tennyson:

> Yet all experience is an arch,
> Wherethrough gleams that untraveled world, whose margin fades,
> Forever and forever as I move.

But is the rapidity of scientific discovery gradually diminishing, approaching asymptotically to the limit of a perfect knowledge? Any adequate analysis of recent progress in any branch of science will indicate to the thoughtful observer that, so far from any approach to the stagnation of perfection, there never has been an epoch when scientific advancement has been more rapid, never a period of more revolutionary progress. Three decades ago there were many who felt that physics and inorganic chemistry were fast crystallizing into a form which, like trigonometry, might reasonably be regarded as approximately final; the permanent foundations had been laid. Small changes were naturally to be expected in the superstructure, but such fundamentals as the form of the atomic theory then current, the permanence of the chemical elements, and the invariability of the atomic weights were, like the atoms themselves, unchangeable entities. What chemist or physicist of that day could have imagined the annihilation of such basic hypotheses, could have conceived of the transmutation of the elements occurring in radioactive processes, or could have admitted the existence of isotopic forms of lead, identical in chemical constitution, but differing in atomic weight in accordance with the radioactive parent metals of which the leads are the eternally-old residue, still being created?

In considering, more in detail, the elements which enter into the processes of astronomical discovery, one must guard against certain all too prevalent misconceptions of the character of the work of the astronomer. The popular idea of an astronomer is that of a man sitting at one end of a telescope; the larger the telescope, the greater the astronomer; he is looking at something very interesting, preferably the planet *Mars*, and discoveries follow thick and fast. Nothing could well be further from the truth. Such misconceptions exclude, as well, those manifold astronomical activities which depend less directly upon observation, but are at least of equal value, and have given rise to discoveries of the highest importance.

For our sciences, not only as such, but in their internal development as well, form no exception to the familiar truth that this is an age of specialization. We no longer find men who will pretend to the entire sum of human knowledge, as did the scholastics of the Middle Ages; it was then actually possible for one brain to compass practically the entire store of accumulated fact. It has been said that with the death of Sylvester there passed away the last man who could with some reason be said to be thoroughly conversant with all departments of the one science of mathematics, as it existed in his day. So much has the field of this mighty science expanded since his time that it is now absolutely impossible for any single intellect to encompass the whole. Similarly, the chemist, the physicist, the biologist, or the engineer, must now perforce limit his mastery of his science, and the field of his creative work, to some comparatively limited sub-province. One astronomer may devote his entire life to the measurement of double stars, another to the determination of accurate stellar positions, another to the analysis of their light, still another to photography. One very important class rarely make a direct observation or look through a telescope, but carry out the extensive computations or the mathematical investigations, without which analytical sifting process the multitudinous observations of the practical astronomer would sometimes have little value for the progress of the science. Of this type were such men as Hansen, Poincaré, and Hill, honored for their mathematical discoveries, though their names may not be found in the more elementary astronomical text-books. Hill once stated that the twenty years of continuous work which Delaunay had devoted to the lunar theory was undoubtedly the greatest task one man had ever carried through single-handed; with the simple, unegotistic certainty of genius he added that he would give second place to the fourteen years which he himself had devoted to the mathematical theory of the motions of *Jupiter* and *Saturn*. Such men must surely rank as discoverers.

What is it, then, which constitutes a discovery, and how may it be defined? Can a distinction be made between Bond's discovery of the "crêpe" ring of *Saturn* (made on a night when

PLATE XXVI. THE 37-INCH MILLS REFLECTOR, SANTIAGO, CHILE.

haze obliterated all but the brighter stars!) and Euler's equation, which gives a remarkable relation between the times, the distances from the central body, and the length of the arc traversed in a parabolic orbit under the law of gravitation,[2] of the first importance in certain orbit computations? Can relative values be assigned to Herschel's discovery of *Uranus*, and to the method of determining stellar velocities in the line of sight by the Doppler-Fizeau shift of the spectral lines, which forms one of the most powerful methods of modern astronomy?

Such comparisons are futile: the race of discoverers is rather to be regarded as a pure democracy, where all have equal rank. Every advance has its value in contributing to our knowledge of the whole, whether the discovery is that of a comet or double star, a more powerful method of analysis of planetary motions, or a masterly deduction of evolutionary processes derived from a consideration of thousands of isolated facts. It is true that the effort involved, and the ability required, in different astronomical discoveries are sometimes so unequal that it seems impossible to give the results an equal weight. Given the invention of the telescope, and it would appear that the moons of *Jupiter,* the craters on the Moon, and the spots on the Sun, must be found immediately, as indeed they were; a bright comet or nova is frequently "discovered" by scores. On the other hand, it has taken several generations to accumulate such a knowledge of stellar positions and motions as to make possible the two-stream theory of star drift.

Whatever may be the differences in the older and the more recent fields of astronomical discovery, it will be found that one factor, and that the most important one of all, is the same in all present-day researches in any science as it was of old, and that is the element of unlimited patience, and close, unwearied application. Darwin put the secret very clearly, when he stated that his successes were chiefly due "to the love of science, unbounded patience in long reflecting over any subject, industry in observing and collecting facts, and a fair share of invention as well as of common sense."

A few typical instances will serve to illustrate the older field of more purely individual discovery.

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[2] This equation, in mathematical symbols, takes the form,—

$$6k\ (t_2 - t_1) = (r_1 + r_2 + s)^{3/2} \pm (r_1 + r_2 - s)^{3/2}$$

Herschel, in the course of his systematic survey of the sky, was one night surprised to find an object which seemed radically different from a star, in that its apparent size increased as he applied successively higher magnifications. He does not appear to have recognized an actual disk, but he satisfied himself that the object was not a star; he made careful record of the observation and the position of the suspected object, and was able later to note that it had moved. He announced the discovery as a comet. It was some time before it was realized that, instead of a comet, he had found a new major planet! Herschel named it *Georgium Sidus* the Georgian star, in honor of his royal patron, and it was later known as *Herschel*. Many years later the more fitting name, *Uranus*, supplanted both earlier designations. This discovery has often been referred to as one in which pure chance played a very large part; it has been described as "the finding of something by an observer who was looking for anything." The discovery was the result, however, of a definite and well-planned program of work. To make observations carefully, to keep accurate records, to leave nothing to chance, and to pass over no point of difference without seeking a reason for the discrepancy, are all fundamental factors in scientific discovery, and none of these essentials was omitted by Herschel. As a matter of fact, it has since been found that *Uranus* had previously been observed no fewer than seventeen times on various meridian-circle programs, the first recorded observation having been made in 1690, a century before Herschel's time.

In the early part of the nineteenth century there was a janitor at the Observatory of Marseilles who became deeply interested in astronomy; he taught himself all he could, and commenced to devote himself with unremitting patience to one very definite field of discovery. He found thirty-seven comets during his life, and rose to the position of director in another observatory. Through these cometary discoveries the name of Pons is today a fairly familiar one in astronomical literature, though there are few astronomers who could name the director at Marseilles under whom Pons, as a janitor, started his astronomical career.

Again, a country apothecary in a little German town began to watch, to sketch, and to keep an accurate record of sun-spots. He was provided with a little telescope but slightly more powerful than some modern binoculars. He kept assiduously at his self-appointed task for many years, and finally was enabled to announce from his own records, and to corroborate by analysis of older observations, that the sun-spots have a regular period, occurring in far greater numbers about every eleven years. To Schwabe, the country apothecary, and not to any of the more powerfully equipped observatories of his time, belongs the honor of the discovery of this fundamental solar phenomenon.

Many similar examples might be given of astronomical researches carried out with a minimum of instrumental equipment, plus a maximum of energy, patience, and manipulative skill. We recall how Barnard set up his little telescope, and commenced the untiring observational toil which has made him a valued member of the staff of two of America's largest observatories. Burnham, a reporter in the Chicago law-courts, bought himself a six-inch lens, which he mounted at the rear of his home. After his day's work, he spent most of his nights in observing and discovering double stars, becoming the world's leading authority in that field.

Telescopes,—even small ones,—are by no means a prerequisite in certain types of astronomical discovery. A little before the middle of the last century astronomers were puzzled by the fact that *Uranus*, then the outermost planet known, was deviating slightly from the path which computation had indicated for it. It was "out" from its computed position by about the angle subtended by the dots over the letter *i* on this page, when viewed from a distance of two feet; a seemingly minute discrepancy, but intolerable from the standpoint of accurate gravitational theory. Independently, and almost simultaneously, two men set themselves at the task of finding the reason for this irregularity. One of these was Adams, an Englishman of twenty-five, just out of college. The other, Leverrier, was a brilliant Frenchman of thirty-five, who had planned for a career in the French state tobacco administration; to this end he had specialized in chemistry, but he gave up this field when offered an opportunity to become a teacher of astronomy. It would be impossible to give a non-technical outline of the intricate calculations which these men carried through independently, to the same conclusion, that *Uranus* was being pulled slightly out from its predicted path by a still more distant planet, and they indicated the region where search should be made for this disturbing body. It is worth emphasizing, at this point, that neither of these men had telescopes, so they communicated their predictions to other astronomers. As a result, *Neptune* was found fairly close to the place calculated, perhaps the most notable instance of discovery in the annals of mathematical astronomy.

Great as have been the prizes won by the discoveries of astronomy's earlier history, the present epoch is not only far more prolific, but intrinsically richer. In one sense, it is superfluous to ask how discoveries are made; they are simply the results of scientific work, which in its turn means merely the using of the tools of a science upon objects or facts hitherto unexamined or unexplained. The more powerful our tools, the faster will be our rate of work and discovery. If the attempt be made to define and to analyze the more important factors contributing to the present state of astronomical discovery, so rich in both quantity and quality, we shall find several contributing causes, interdependent, rather than separate in their effects. Though it will be of interest to segregate these, it will be seen at once that it is really possible to combine all in the one phrase,—better tools. These factors are:

1. The existence of many large observatories liberally supported by government appropriations or by benefactions, devoted almost exclusively to astronomical research. The number of investigators, and the available instrumental equipment, are immeasurably greater than they were half a century ago.

2. The great advances in mechanical processes which have enabled the instrument-maker to furnish more accurate instruments and larger lenses and mirrors; here we must include the work of the engineer in providing adequate mountings for giant instruments.

3. A tremendous development in the character and power

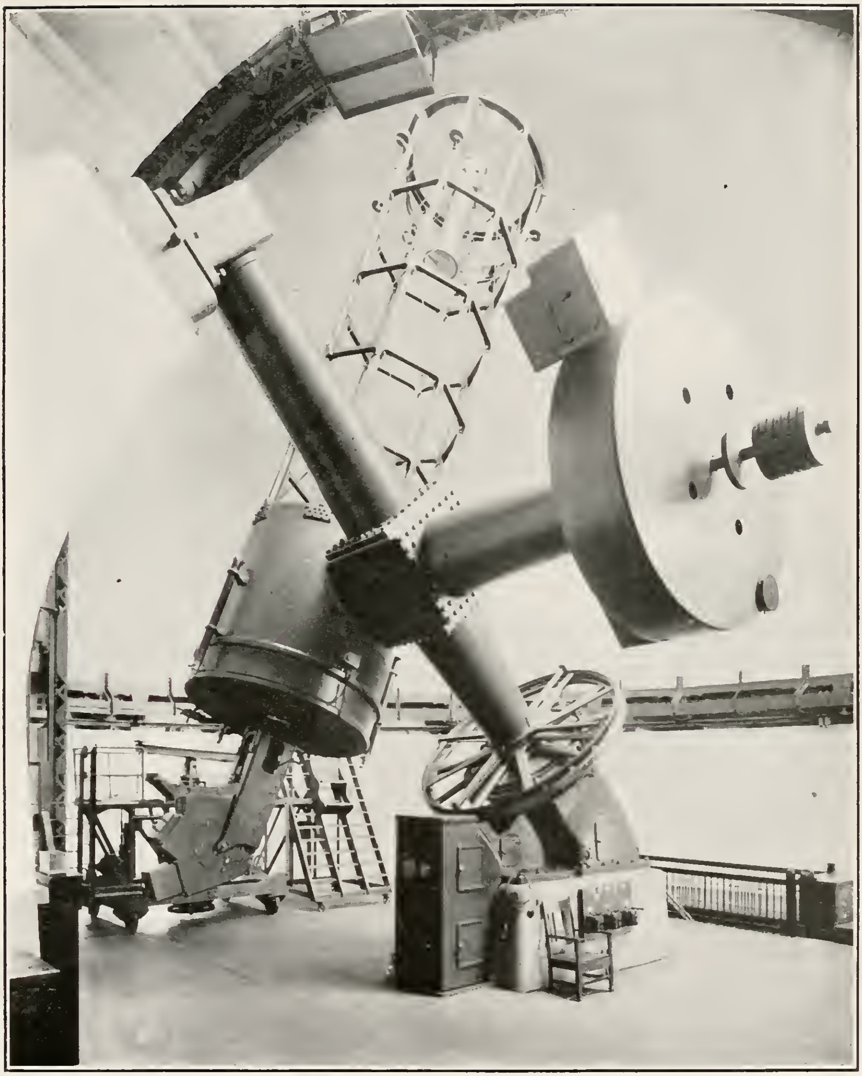


PLATE XXVII. The 72-Inch Reflecting Telescope of the Dominion Astrophysical Observatory.

of the methods employed, due in large part to the application and adaptation of processes perfected in the allied sciences of physics and chemistry.

4. Properly to be included under the preceding heading, but so important as to deserve separate mention,—the use of photography.

Of the above, it is photography, more particularly the perfection of the modern dry plate, which has most completely and radically changed the methods of astronomical discovery. Fully three-fourths of all modern astronomical observations are photographic, and it seems highly probable that the day may come when practically all astronomical research will depend upon photographic processes. A better conception of the manifold applications of photography in astronomy may be derived from the following short summary:

PHOTOGRAPHY IN OBSERVATIONAL ASTRONOMY

Fundamental Astronomy. The determination of the absolute positions of the Sun, the planets, and the stars is still mainly visual, though photography is invading this field.

The Sun. Fully 90% of modern observations are photographic.

The Moon. Mainly photographic, though for the study of minute details visual observation has some advantages.

The Planets. Photography as yet is used to but a small extent; visual observations are still best for the study of surface detail.

The Asteroids. Fully 80% is photographic, and about 100% in the work of discovering new asteroids.

The Comets. Comet *positions* are generally determined visually, but for studies of physical structure photography is supreme.

The Stars. For general charting and mapping purposes visual observation is fast being superseded by photography.

In the determination of stellar distances fully 75% is photographic, and the proportion is increasing.

For physical constitution, spectroscopic studies, radial velocities, etc., practically 100% photographic.

THE VARIABLE STARS. Possibly 50% photographic; visual observations still of great value; perhaps eventually entirely photographic or photo-electric.

THE DOUBLE STARS. Still nearly 100% visual; a field in which photography seems as yet to have little chance for successful competition.

THE NEBULAE. 100% photographic.

Illustrations of the power of the photographic method might be multiplied almost indefinitely, but such a course would far exceed the limits of a single lecture. A few instances must suffice.

Fig. 1, Plate XXVIII, shows a small section, about eight by ten degrees in size, of a chart of the *Bonner Durchmusterung*, a great star map which was made about the middle of the nineteenth century and is still an indispensable aid to the practical astronomer. The entire set of charts includes about 324,000 stars of magnitude 9.5 or brighter, in that part of the sky included between the north celestial pole and twenty-one degrees south declination; the positions were determined with a small telescope of about three inches aperture. The observations, and the preparation of these charts and the accompanying catalogue, meant a vast amount of patient work. At the center of the figure is seen a small dotted area, which indicates the position of one of the largest and brightest of the spiral nebulae, *Messier* 33, which is bright enough to be made out in the small telescope used for the survey. In Fig. 2 on the same plate, is shown the same region, on the same scale, as photographed with the Crocker Photographic telescope at Lick Observatory. It will be noticed that the nebula is not much more in evidence than on the star chart, but it would be difficult to say by how many times we must multiply the number of stars shown on the chart to obtain the total registered in the photograph. Moreover, the photographic plate was secured in a few hours, as against many nights of work in the case of the star map, and it is a permanent record, available for study and measurement as long as the photographic film shall endure. In the star chart, the human element has entered into every step of the process from the observation of the individual stars to

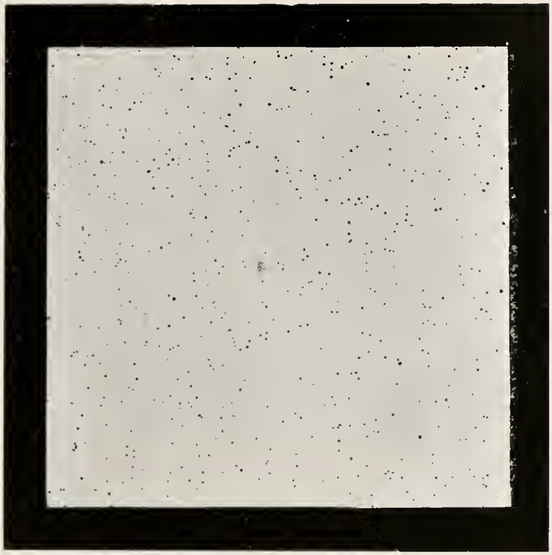


Fig. 1—B. D. Chart, M. 33 Central.

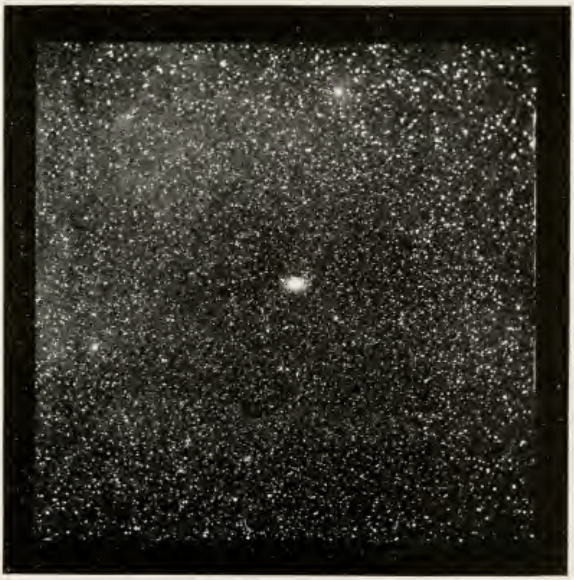


Fig. 2—Crocker telescope photograph, M. 33 Central.

PLATE XXVIII

the engraving of the map; at no time in the production of the second illustration has any manual dexterity or elaborate calculation entered *directly* into the final record of the relative position of an individual star. With a telescope of greater focal length we can secure a much larger-scale photograph of any desired small area of the region. Plate XXIX shows the central nebula, as photographed with the Crossley reflector.[3]

Great as has been the enrichment of the field of astronomical discovery caused by the introduction of the photographic method, that due to the spectroscope is even greater. Prior to the development of the spectrographic method, the story told by the ray of light from a distant star was a comparatively brief one. The ray of light told us little more than the precise position of the star, whether the star was variable, and whether the star was double; it gave us no information whatever as to *what* the star was. We know now that there lie buried within the inconceivably rapid vibration complex of the light ray whole volumes of information with regard to the temperature, physical condition, and chemical constitution of the star. The information may have been ten thousand or more years on the road, and we know nothing as yet of the wonderful medium through which the record of the light vibrations is transmitted to us, but we can analyze these vibrations and read a part of their message merely by passing the light through the prisms of a spectrograph. The spectrograph has changed the entire content of astronomical discovery from a record of position and movement to a record of composition and quality.

It has been stated earlier that the trend of the older field of astronomical research was toward the individual discovery, while that of the modern field is toward the class or group, the super-discovery based upon hundreds of individual advances. The discovery of the first asteroid, the first double star, the first spectroscopic binary, were events of great astronomical importance. Scores of these objects are now found yearly, and their utility depends less on their intrinsic values as separate facts

[3] At this point in the lecture, as delivered, many lantern slides were shown comparing the older drawings of sun-spots, comets, the Moon, and nebulae, with modern photographs. Slides were shown also illustrating the photographic discovery of asteroids and of the Ninth Satellite of Jupiter, and the photography of stellar spectra.

than upon the larger generalizations which may be drawn from the group.

Recent astronomical history is, however, not without many instances of brilliant individual discoveries. It has added to the older record:—two satellites of *Mars*, five of *Jupiter*, one of *Saturn*, hundreds of asteroids, hundreds of variable stars, thousands of visual and spectroscopic binaries, hundreds of thousands of nebulae, millions of stars, and a multitude of facts bearing on the physical constitution of the Sun, the stars, and the nebulae. It will be more representative of modern progress, however, to give a résumé of the results from a single method of research, rather than to limit ourselves to individual instances; the field which will be briefly treated is that involving the determination of stellar velocities by the Doppler-Fizeau shift of the spectral lines. The results of this method of attack have involved a host of minor discoveries, and have thrown a flood of light upon many of the problems which the origin and evolution of the universe present to the mind of man. These researches, moreover, are typical of modern progress in that they have involved the coöperation of many workers, and have necessitated years of observation before sufficient data could be secured to make possible the sifting out and elucidation of the basal principles.

We are all familiar with the fact that a musical note is said to have a certain pitch; that the reason why one note has a higher pitch of sound than another is because it is due to a greater number of air waves or vibrations per second. Similarly we may think of light as possessing something that is closely analogous to pitch in sound. Blue light, for instance, has about twice as many light-waves per second as red light (eight hundred trillion for blue, four hundred trillion for red light) so we may say, for the purposes of illustration, that blue light is about an "octave" higher in pitch than red light. Some of you may perhaps have been on a railroad train when another train was passing in the opposite direction, and sounding its whistle as it passed. On such an occasion it takes only a moderately keen ear to notice that the pitch of the passing locomotive's whistle is half a tone or so higher as it is approaching, and suffers a similar drop in pitch as it recedes. The speed

PLATE XXIX. M. 33 TRIANGULI.

Photographed by J. E. Keeler, Crossley Reflector, Sept. 12, 1899.

at which the trains are moving makes the pitch of the sound higher when they are approaching, and lower when they are receding from each other. Similarly, if a star is coming swiftly toward us, or moving swiftly away from us, this velocity changes the "pitch" of the light by a small amount. We can measure the amount of this shift in light-pitch or wave-length if we pass the light through the prisms of a spectrograph, using the light from some terrestrial, stationary source for comparison to give us our "zero point". We can thus determine the speed of the star *directly toward* or *directly away* from us, known as its radial velocity, in miles per second. This principle was, in itself, a notable discovery, but the discoveries which have followed as by-products of the application of this method to the determination of the radial velocities of many celestial objects form a very important part of recent astronomical progress.

First,—it was found that the stars in one part of space were, on the average, coming toward us at the rate of twelve and one-half miles per second, and apparently receding at the same speed in the opposite quarter. That is to say,—the Sun and all his system is really moving through space at the rate of about twelve and one-half miles per second. This had been known earlier qualitatively, but not quantitatively. With this came the knowledge that all the stars are in rapid motion, at average speeds of from eight to twenty-one miles per second, while some few stars are traveling at speeds of one hundred or more miles per second. The great extended nebulosities are almost at rest in space; the planetary nebulae are moving at average speeds of nearly fifty miles per second, while the spirals have the enormous average speed of nearly five hundred miles per second.

Further,—the gradual accumulation of radial velocities for many different stars showed that the stars of different spectral types were going at different average speeds, the stars which we think to be the younger moving more slowly, the older stars more rapidly. Just why this should be the case is not yet fully understood; some evidence is now being accumulated which may eventually show that these systematic differences in average speed are functions of the masses of the stars, rather than of their relative positions in the order of stellar age.

In the progress of these researches, many stars were found which are coming toward us at one epoch, and receding from us at another, this reversal of motion recurring at regular intervals of time. Such stars are revolving around a darker central star, which is generally too faint to leave any record of its spectrum. They are known as spectroscopic binaries; these are double stars discovered by the systematic variation in the pitch of the light they send to us, though they cannot be seen as double in the largest telescopes, because they are too distant. It has thus been found that about one in every three of the brighter stars, though apparently single under the highest magnifying powers, is a spectroscopic binary. This discovery has an important bearing on all theories of stellar evolution; perhaps relatively few suns have developed so as to have a retinue of comparatively small planets, as is the case in our solar system.

The same general method has been applied with great success to the study of the Sun and to the motions of the matter in and around the sun-spots, to *Saturn's* rings, where it was shown that these are in rotation, but not solid, and to many other fields of astronomy. Very recently it has been found, in the same way, that many of the planetary nebulae are in rapid rotation.

These revolutionary advances in astronomical theory are due to the application of the Doppler-Fizeau principle, with the aid of the spectrograph and the photographic plate, and are essentially all a product of the past quarter-century. How much work has it meant for astronomy to state these striking and important facts as discoveries? Many astronomers and many observatories have coöperated in collecting the necessary observations, but we shall consider only the work of the Lick Observatory in this field.

For more than twenty years about three-fourths of all the available time of the great refractor has been devoted assiduously to the securing of the spectrographic plates for this program, ranging in exposure times from a few minutes in the case of the brightest stars, to many hours for fainter objects.

Nearly eighteen thousand plates have been taken,—the largest collection of this class in existence. A branch observatory, that of the D. O. Mills Expedition at Santiago, Chile, was established to secure these plates for the stars in the southern skies, inaccessible from our northern latitude. In the course of this extended program some twenty people have taken part in the securing of these eighteen thousand spectrograms, or have made the measures and reductions which are necessary before the velocity of a star can be determined from the spectrographic negative. Last of all came the combination and the analysis of these thousands of radial velocities, which have given rise to those generalizations of wider scope resulting from the initial discovery of the Doppler-Fizeau principle.

It is with such extended researches and larger problems that modern astronomy is working, and the methods of astronomical discovery are simply the methods of astronomical work. In the larger theory, the greater truth of some super-discovery, there are frequently combined hundreds of individual discoveries of minor rank; for any fact, previously unknown, is a discovery.

There is abundant room for the development of new and brilliant methods of attacking such larger problems. In general, however, it appears probable that future advances will, in like manner, depend upon the accumulation of many discoveries concerning the units of a class of objects, and upon the careful and systematic analysis of these facts for the basic truths of stellar evolution.

Little has been said as to that element of personal inspiration or genius which enters into much of true discovery. It is by no means an indispensable ingredient, iconoclastic though such a statement may seen. There have been many instances where what we somewhat loosely term "genius" has appeared to be the determining factor. It would be equally easy to find instances of discovery made by observers of mediocre ability, in which the "divine fire" was replaced by mere plodding patience, or by the extraneous and adventitious aid of powerful equipment. The machine-like processes of photography and spectroscopy, the intervention of the hired plate-measurer and computer, have inevitably removed not a little of the more purely personal element from the modern field of astronomical discovery. Even so, the personal element is still a powerful, and in most work, an essential factor. These qualities have been well summarized by Jevons in his "Principles of Science":

> It would seem as if the mind of the great discoverer must combine contradictory attributes. He must be fertile in theories and hypotheses, and yet full of facts and precise results of experience. He must entertain the feeblest analogies and the merest guesses at truth, and yet he must hold them as worthless till they are verified by experiment. When there are any grounds of probability he must hold tenaciously to an old opinion, and yet he must be prepared at any moment to relinquish it when a clearly contradictory fact is encountered.

Though it seems somewhat paradoxical, there is a great deal of truth in the saying that any good theory brings with it more problems than it removes. In like manner, each great advance in modern astronomical theory has brought with it a host of new problems, and has opened up new fields of vast extent. We have seen our concepts of the size of the stellar universe steadily increase. Where once we doubtingly discussed distances of a few thousand light-years, we now confidently postulate distances of hundreds of thousands or millions of light-years. With the aid of the methods contributed by the allied sciences, our field of astronomical discovery has expanded in even greater ratio; like our subject-matter, it is infinite.

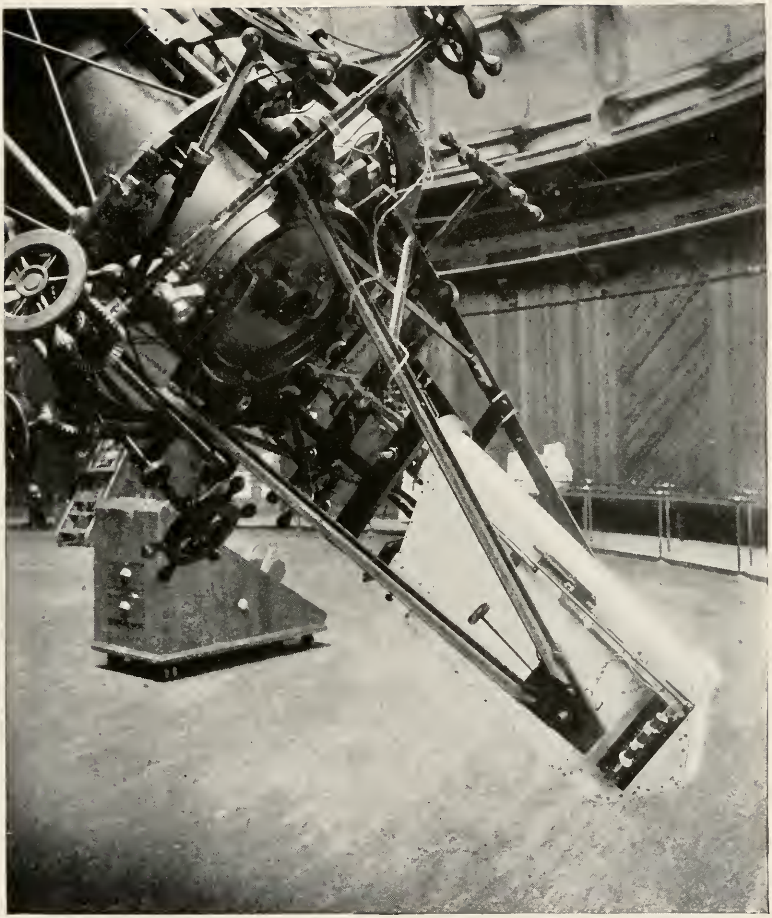


PLATE XXX. The Mills Spectrograph Attached to the 36-Inch Refractor.

IMPORTANT EPOCHS IN THE DEVELOPMENT OF ASTRONOMY[1]

By R. T. Crawford

When one stands in awe and admiration before the Woolworth building in New York, the Campanile of Venice, or that of the University of California at Berkeley, some massive bridge with its network of girders, the Milan Cathedral, or any other wonderful work of man, rarely does he consider the separate and distinct processes that contribute to its construction. It is the finished product that receives the words of praise and commendation. The foundations and other parts out of sight are almost completely neglected. The question "Who was the architect?" is nearly always asked; "Who was the engineer?" is seldom heard. It is quite right that we should praise and admire the designer, but we should give due meed of praise and admiration to the engineer who figures the stresses and strains of the various members of the edifice and designs the foundations and without whose genius the architect's conception could not come to realization. Nor should we stop here, but reserve some of our thoughts of glorification for those architects, engineers, physicists, chemists, and mathematicians who have gone before, who have contributed their bits to improve their arts and sciences, step by step, age after age, until now it has become possible to erect a Woolworth building; an impossibility a few short decades ago.

The completed edifice can not be set down at once for the world to admire. It must be built up patiently, stone by stone, and must rest upon a solid foundation. It is with this idea in mind that I address you this evening. In the first series of the Adolfo Stahl Lectures you were presented with some aspects of astronomy of the present time, the finished edifice, so to speak (although no astronomical work is ever finished). In this, the first of the second series of the Adolfo Stahl Lectures, an attempt will be made to show you the various stepping

[1] Delivered November 16, 1917.

stones that have been laid by the past masters of the science by which alone it has been possible to climb to the great heights attained by the astronomers of today.

In the brief time allotted for a single lecture it is impossible to tell the whole story, so I shall confine my remarks to the most important epochs in the development of astronomy, the oldest of the sciences.

In the earliest times the notions concerning the form of the Earth were as numerous and varied as were the peoples. About the 6th century B.C. Pythagoras and his followers taught that the Earth was spherical and a first advance seems to have been made. Many people have the erroneous idea that it was not known that the Earth is spherical until Magellan proved it by circumnavigating the globe.

The first determination of the distance from the Earth to the Sun was made by Aristarchus, 3d century B.C. This determination was highly ingenious, correct geometrically but yielding a very inaccurate result. This problem is so difficult, however, that no good determination was made until the time of Cassini in the 17th century; so, great credit is due Aristarchus for any determination at this early date.

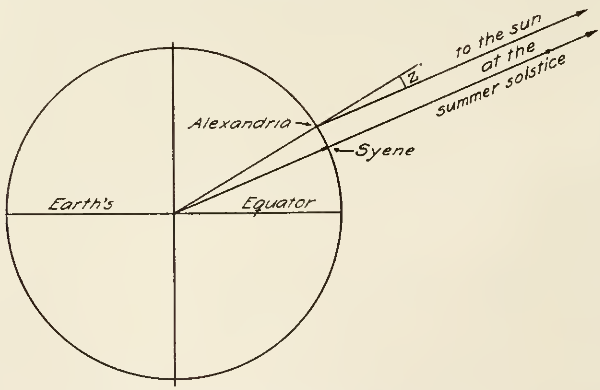


Fig. 9. Aristarchus's Method of Determining the Distance from the Earth to the Sun.

To Eratosthenes, 2d century B.C., is due the first measurement of the size of the Earth. At noonday, at the summer solstice, the sun shone vertically down a well at Syene, in Upper Egypt, while in Alexandria, at the same time, the

Fig. 1—The Well of Eratosthenes.

Fig. 2—Newton's Reflector.

PLATE XXXI.

angular distance of the Sun from the zenith was found to be approximately $\frac{1}{50}$th of a complete circumference, or about 7°. If Syene is assumed to be directly south of Alexandria, then it follows, from this observation, that the distance between them is $\frac{1}{50}$th of the circumference of the Earth.

The geometrical principle involved will be clear from Fig. 9. Since the distance to the Sun is very great compared to the distance from Alexandria to Syene, the lines from these stations to the Sun are practically parallel. Therefore the angle at the center of the Earth between radii drawn to the two stations is equal to the angle Z which Eratosthenes measured. Hence the arc AS is to the circumference of the Earth as 7° is to 360°. Eratosthenes' method is practically that used today. Our determinations are better only because we can make more accurate observations and measurements than he could.

The greatest astronomer of antiquity was undoubtedly Hipparchus, sometimes called the "Father of Astronomy," who flourished about the middle of the 2d century B.C. To him we credit, among other things, the invention of trigonometry, the first star catalogue of reasonable accuracy, the discovery of the precession of the equinoxes, and, above all else, the introduction of the truly scientific method of observation and investigation.

The first epoch in the development of astronomy may be said to have been brought to a close upon the appearance of Ptolemy's *Almagest,* the first great astronomical classic. Ptolemy lived in the 2d century A.D. He does not seem to have contributed much original work to the science, but he rendered an inestimable service by bringing together in his monumental work, and thus preserving for us, nearly all that had been done by those who had preceded him.

The *Almagest* is noted principally for Ptolemy's exposition of the geocentric theory of the solar system, the theory that the Earth is the center of the system and that all of the other bodies, including the Sun, revolve about it in a system of circles or epicycles. He sets forth the arguments pro and con in the controversy between the geocentric and the heliocentric theories, and then, perhaps influenced by the great weight of Aristotle's opinion, rejects the heliocentric theory and adopts the geocentric.

Following the time of Ptolemy learning seems to have gone into nearly total eclipse during that period of about fourteen centuries known as the Dark Ages. Many reasons have been assigned for the decline of learning in this period, but one of the principal causes is often overlooked. This is the powerful influence of the authority of Aristotle. Great as Aristotle may have been as a philosopher, as a scientist he was a failure. This is due to the fact that the tenets he set forth rested wholly upon thought analysis and were untested by actual experiment, a wholly unscientific method of procedure.

During this period it was considered that Aristotle had done all of the world's thinking, so that there was no further need of thinking. His influence was so great that no one dared to question any of his dicta. If one, perchance, was so hardy as to attempt it he was probably immediately silenced by some caustic question such as "Do you think you know more than Aristotle?" No one seems to have dared to think. No wonder the people were in the Dark Ages! It has been well said that Aristotle did more to retard the progress of the world, at least of the scientific world, than any other one man. How the Dark Ages came to an end will be related presently. In the meantime we come to the next important epoch in the development of astronomy.

At the end of the 15th century came Copernicus, who gave us the second great astronomical classic, the *De Revolutionibus Orbium Celestium*. In this Copernicus discussed the pros and cons of the two theories of the arrangement of the solar system as Ptolemy did, but came to a different conclusion. Copernicus held the heliocentric theory to be the true one, that is, that the Sun is the center of the solar system and that all of the planets, of which the Earth is one, revolve about the Sun.

As can readily be imagined this doctrine did not find ready acceptance. For many centuries the old geocentric idea had held sway and it was not to be overthrown easily. It was about half a century later that the observations and teachings of Galileo gave the final push to the tottering geocentric theory and it fell.

From the middle of the 16th century to the middle of the 17th we find three epoch-making names in astronomy, Tycho

Brahé, Kepler, and Galileo. The latter two were contemporaries following immediately after Tycho.

Beginning at this time we find a revival in observational work. This was carried on partly in Cassel, where we find the first observatory built with a revolving dome and the first use of a clock to record time observations. But the principal observational work then was done by Tycho at Hveen. He recognized the need of more accurate positions of the Sun, Moon, planets and stars than were available. Tycho, therefore, erected an elaborate observatory and equipped it with as fine instruments as were then possible. While he made no startling discovery, he amassed a store of very accurate observations, especially of the planets, which were destined soon to play a very important rôle in the development of astronomy.

Tycho's valuable observations fortunately fell into the hands of Kepler, who mined through them with remarkable patience and perseverance. Up to this time the positions of the planets had been predicted on the assumption that they moved in circles or combinations of circles. But Kepler was soon able to show from Tycho's accurate observations that they could not move in such a way. He then set about to discover the true paths. After much trying and guessing he at last found that their motion could be represented accurately by ascribing the ellipse as the true path, with the Sun situated at one focus of the ellipse. We have here the first departure from the old idea of motion in a circle.

Then Kepler reasoned, that as a planet is at varying distances from the Sun on account of moving in an ellipse, it probably would move with a variable velocity. Again he started his trying and guessing and finally hit upon his second wonderful law, namely, that a planet moves in such a way that the line joining the Sun and the planet describes equal areas in equal intervals of time.

Once more his active brain got to work and he began to consider the fact that as the various planets are at different distances from the Sun there is probably some relation between the distances and the time of revolution of the various planets about the Sun. If one planet is twice as far from the Sun as another, will it take twice as long to go once completely around the Sun? He soon saw that no such simple relation held true. So again he started his trying and guessing and finally arrived at his wonderful Harmonic Law, which states that the squares of the periods (expressed in years) are equal to the cubes of the mean distances from the Sun (the Earth's distance being taken as unity).

You have probably gathered from all this that Kepler was the world's champion guesser, and he probably was. Even so, he could not have arrived at these three wonderful laws had he not had his material systematically arranged. We are told that he chose his second wife after investigations most methodical. He put down on cards the points of merit of each one of nearly a dozen maidens, and after studying them carefully, made his choice. Kepler was probably the founder of our present elaborate card index system.

This epoch marked by Kepler and Galileo is certainly a noted one in the development of astronomy. While Kepler was discovering his beautiful laws of planetary motion, Galileo in Italy was doing work which in itself was epochal. When he applied the telescope to the skies for the first time a vast new field of investigation was started. This is so evident that we shall not dwell upon it further. In addition to this, however, he made several other contributions to science which would have made him famous, an account of which would require several lectures. We shall dwell upon only two. One of these is his support of the Copernican heliocentric theory, which he upheld in his famous work entitled *The Dialogue of the Two Systems*. It was this support of Galileo that undoubtedly hastened its general acceptance.

I wish to dwell upon the second of these contributions more at length, as it marks one of the greatest epochs in the development, not only of astronomy, but in the whole realm of thought. It concerns that movement at the end of the Dark Ages known as the Revival of Learning, or Renaissance. This probably began in the 15th century, but, in my opinion, the rapid revival (so rapid, indeed, as to make it practically the Revival itself) began with Galileo.

As mentioned before, the dicta of Aristotle had held sway over the world's thought for some fifteen centuries. Among

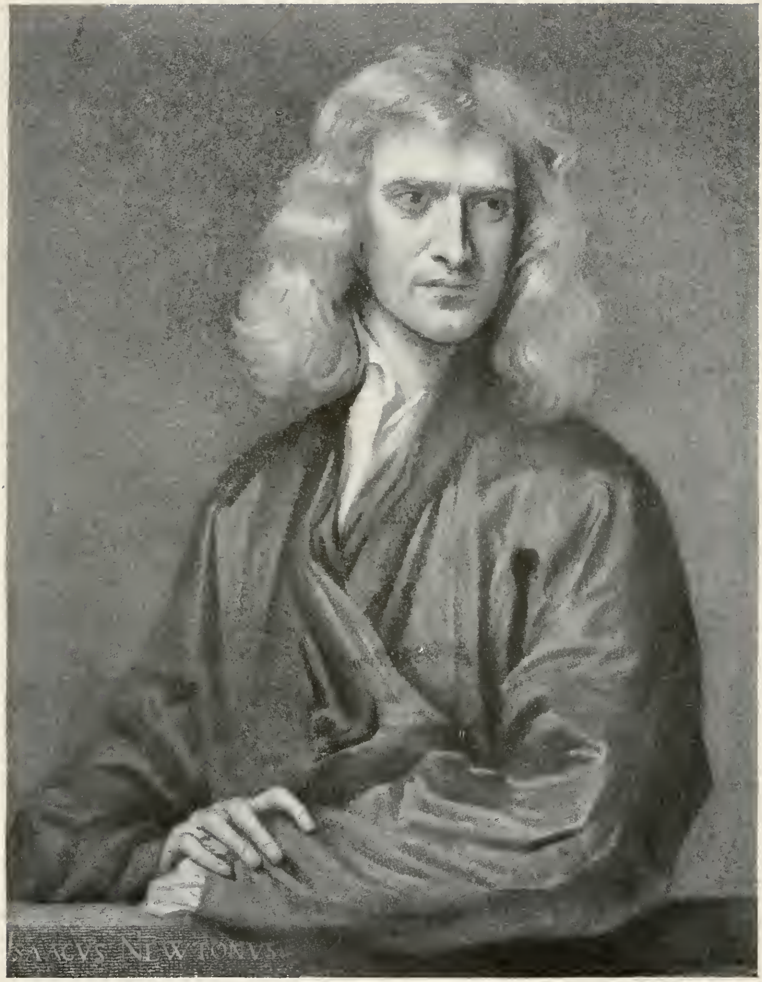


PLATE XXXII. Sir Isaac Newton, 1642-1727.

other things he had said that a large heavy body would fall faster than a small light body. Galileo, true scientist as he was, would not take the word of anyone, even Aristotle, for a thing when it was in his power to prove or disprove the statement. So, mounting to the top of the Leaning Tower of Pisa, before a large gathering of interested people, he let fall from this height simultaneously two bodies, one large and heavy, the other small and light. According to Aristotle the heavy body ought to have reached the ground much sooner than the light one. But the astonished people saw the two falling side by side, and landing at the base of the tower at practically the same instant. This was one of the most dramatic experiments the world has known. With the fall of those bodies fell the influence of Aristotle in matters scientific. You can easily imagine that, with the disproving of one of his dicta, the others immediately came into question. Investigators in all lines of thought soon began to appear, and the rapid revival of learning was on.

Galileo died in 1642, and Newton was born in 1643. The interval between Galileo's death and the epoch marked by Newton's activities was one of steady progress. Instruments were improved somewhat, and came into more general use; the micrometer was invented; accurate measurements of lengths of arcs in different latitudes were made from which it was found that the Earth is not a perfect sphere, but an oblate spheroid. Observational work was carried on most assiduously, especially at the Paris Observatory. In addition to the discovery of the true form of the Earth, the most important developments at this time were the discovery of the finite velocity of light by Römer working under Cassini at the Paris Observatory, and Cassini's evaluation of the distance from the Sun to the Earth. He deduced the value 9.5″ for the parallax of the Sun, which corresponds to a distance of 78,000,000 miles. This is the first fairly good approximation to that all-important distance.

The next great epoch in the development of astronomy is that connected with the name of Sir Isaac Newton, who lived from 1643 to 1727. The work of this man, whose name is undoubtedly the greatest in astronomy, is so wonderful both in quantity and quality that it is difficult to know what to say about it in the few minutes available.

The name of Newton suggests immediately his law of Universal Gravitation, viz.: that every particle in the universe attracts every other particle in the universe with a force that is proportional to the product of the masses of the two particles and inversely proportional to the square of the distance between them. It would unfortunately take too much time to tell how he came to arrive at this law. This is the law upon which all work in theoretical astronomy and celestial mechanics is based. Newton is properly called the "Father of Gravitational Astronomy".

Kepler had shown in his three laws the *manner* in which the planets move, but he had not the slightest idea of *why* they move in this way. For some time a vague idea was prevalent that there was some such thing as a gravitational force residing in the Sun, but it remained for Newton to formulate it and prove it. Starting with his law Newton, with his mathematical genius, was able to prove Kepler's Laws and to show that, acting under the gravitational influence of the Sun in this way, they *must* move as described by Kepler. To do this and to prove other problems in theoretical astronomy the necessary mathematics were not available in Newton's time, so he had first of all to bring his marvelous mathematical talents into play. As a result of this he invented the all-powerful mathematical tool known as calculus.[2]

With these and other mathematical tools which his sagacity gave us he was now able to explain many things which were awaiting explanation, among which may be mentioned the precession of the equinoxes, discovered by Hipparchus nearly twenty centuries previously; certain inequalities in the motion of the Moon; perturbations in general, and the tides. Another field of investigation was thus opened up which was quite as vast as that started by Galileo.

In addition to founding gravitational astronomy Newton may also be credited with the founding of modern astronomy or astrophysics when he discovered the composite character of white light, the phenomenon by which white light, when passed through a prism, is broken up into its constituent parts and

[2] The honor of inventing calculus has to be shared perhaps with the German mathematician, Leibnitz.

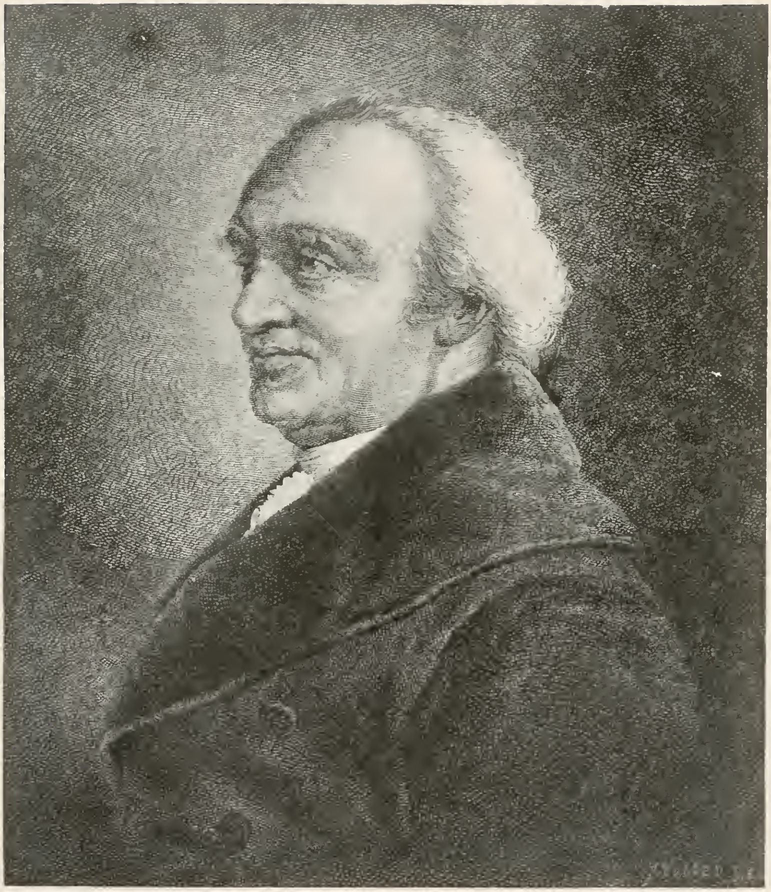


PLATE XXXIII. Sir William Herschel, 1738-1822.

spread out into a band of color which we call the spectrum. Although spectrum analysis did not begin to develop until the middle of the 19th century, its foundation was laid by Newton.

With this discovery of the composite character of light Newton was enabled to give the correct explanation of the phenomenon known as chromatic aberration, that trouble which the astronomers of that time were having with the fringe of color around an image which affected the sharpness of the image. Here Newton made a mistake in his scientific work, for he decided that this trouble could not be overcome. We now know how to eliminate chromatic aberration almost completely by making the object glass not of a single lens, but of two or more lenses of different density. But this discovery was made half a century after the time of Newton. We should be very thankful, however, that he made this mistake, for it led him to the invention of the reflecting telescope. Whereas the amount of bending of a ray of light upon passing through a prism or lens depends upon its color, all rays, no matter what the color, obey the same law of reflection, viz.: that the angle of incidence is equal to the angle of reflection. Newton, therefore, saw that if the rays were brought to a focus on the principle of reflection, the image would be freed from chromatic aberration, as all of the rays, regardless of color, would be brought to the same focus, and a white object would yield a white image with no halo of colors to bother. Acting upon this idea he constructed the first reflecting telescope, a modest affair with a one-inch mirror made of a combination of copper and tin and highly polished. This instrument of such historical interest is still to be seen as one of the priceless exhibits in the library of the Royal Society in London. Although small and inefficient this little instrument is the forerunner of the increasingly large and valuable reflectors culminating in our own time in the 72-inch reflector of the Dominion Astrophysical Observatory and the monster 100-inch reflector about to be put into operation at the Mount Wilson Solar Observatory.

The results of most of the work of Sir Isaac Newton were given to the world in the publication of his *Principia,* issued in three large volumes.

Beginning with the time of Newton we find astronomy developing so rapidly that its progress must now be traced, not as a whole, but along its various branches.

Just before the time of Newton the principal observational work had been done by the continental astronomers. One would naturally expect the next advances in the observational line to be developed by them and the theoretical branch to be explored by the English, following Newton. But, curiously, the converse was the case.

During the 18th century the principal observational advances were made by the English. Toward the close of the 17th century Flamsteed, the first Astronomer Royal, founded the observatory at Greenwich. On account of the lack of funds his instrumental equipment was very meager and he did little beyond making a star catalogue. The next two Astronomers Royal, Halley and Bradley, however, did much to advance the science.

Halley was a great admirer of Newton. Following some of the lines of Newton's work he computed the paths of some twenty-four comets. Noting that three of these were traveling in practically the same path, separated from each other at nearly equal intervals of 75 or 76 years, Halley ventured the idea that these were not three separate comets but were three appearances of one and the same comet at about 75-year intervals. He predicted the return of the comet. He did not live until the predicted year, but the comet appeared on schedule. This is the first instance of the kind in history, and the comet is named, as you know, Halley's comet, in honor of the man who first predicted its return. The return which he announced took place in 1759. It has returned again twice since then, in 1835 and in 1910. This marked another advance in astronomy in that it added other moving bodies to the solar system, and showed the people that comets were no longer to be feared, that they were merely members of the solar system, moving under the attraction of the Sun, and that their motions and positions could be computed in accordance with Newton's and Kepler's Laws just the same as in the case of the planets.

Among other things done by Halley of a largely developing character may be mentioned his discovery of the proper motions of the stars; and his scheme for determining the solar parallax,

PLATE XXXIV. Sir William Huggins, 1824-1910.

and hence the distance from the Sun to the Earth, by observations of the transit of *Venus*.

Bradley, the successor of Halley, discovered aberration and nutation. All of the objects in the sky are displaced somewhat, due to the facts that the Earth is moving and that the velocity of light is not infinite. This displacement is known as aberration. It was discovered by Bradley quite by accident in seeking to find a displacement of the stars due to parallax.

We must credit Bradley also with improving the accuracy of observational work. Not only was he a keen observer, but he had his instruments constructed by the most skillful mechanics and mounted in the best possible manner. Further, he was one of the first to take into account possible errors arising from defects of his instruments.

Contrary to natural expectation we find but little done in the 18th century in England along the lines of Gravitational Astronomy. This country does not seem to have possessed minds of a caliber to follow the lead of the immortal Newton. His work was principally geometrical and for this reason difficult to master. On the continent, however, there appeared a group of mathematical astronomers who founded and developed what is called the method of *analysis*, that is, a development following the lines of algebra. With this they were enabled to develop the planetary and lunar theories of celestial mechanics to a very high state. The leaders in this work were Euler, a Swiss, Clairaut, D'Alembert, Lagrange, and Laplace of the French school. Lack of time prevents a detailed statement of what they accomplished. A comprehensive discussion of the state of the developments at this time is published in the monumental work of Laplace entitled the *Mécanique Céleste*. Among the interesting and important things done by Laplace may be mentioned his proof of the stability of the solar system, and of the fact that *Saturn's* rings could not be solid. The physical proof of the latter was not accomplished until near the end of the 19th century, when it was beautifully demonstrated by Keeler.

Laplace also set forth in a beautiful work, the *Système du Monde,* the Nebular Hypothesis that goes under his name. This theory of the formation of the solar system held sway for more than a century; and while we are now obliged to reject it in the precise formulation given by Laplace, the fundamental idea in it, that of the evolution of the solar system from a primal nebula, is still accepted by astronomers.

During the latter part of the 18th century and the first part of the 19th observational astronomy was carried to great heights by Sir William Herschel, working with his devoted sister Caroline at Slough, England. His remarkable work was made possible by the large instruments, reflectors, that he made, culminating in his 40-foot telescope.

He added the knowledge of the existence of the planet *Uranus* by discovering it accidentally in 1781. He made many other observational discoveries, but his most important development work was his discovery of binary star systems and his general survey of the sky for nebulae and the distribution of the stars. These led him to speculate on the form of the sidereal universe and mark the beginning of that wonderful work that is the principal problem of the 20th century astronomers. His investigations led him to set forth his so-called "grindstone theory," that is, that the universe is shaped like a grindstone, having the greatest depth in the plane of the Milky Way.

The developments in the 19th century were so numerous as to become almost bewildering when one tries to narrate them. We can at best mention here but few. Gravitational astronomy has been improved and developed along the lines laid down by the five famous mathematicians of the 18th century, in large part by Pontécoulant, Delaunay, Leverrier, Poincaré, Gauss, Hansen, Gyldén, Adams, and our own Newcomb and Hill. Time does not permit of the enumeration of the individual contributions of these and yet others. But I will pause to mention two things. The first is the discovery of *Neptune* in 1846, which resulted from the computational work of Adams, of England, and Leverrier, of France. The other is that the best lunar theory we have is that given us by the famous American, G. W. Hill, to whom the Bruce Medal of the Astronomical Society of the Pacific was awarded shortly before his death a few years ago.

Observational astronomy progressed with rapid strides in the last century, due to the improvements in the size, number, and quality of instruments, and in the mathematical methods deduced for handling observational material. The latter are

PLATE XXXV. Simon Newcomb, 1835-1909.

due principally to Gauss and Bessel. We owe to Bessel also the first detection of the parallax of a star. Instruments were made much larger and better, principally here in America, culminating toward the end of the century in the great refractors of the Lick and the Yerkes Observatories.

Toward the end of the century two important discoveries were made which must be mentioned. The first is the discovery of the variation of latitude by Küstner at Bonn; the other is the discovery made by Keeler at the Lick Observatory that the spiral nebula is the rule and not the exception among the nebulae. The latter gave the final blow to the nebular hypothesis as formulated by Laplace and started astronomers again to speculating upon the structure of the universe.

Finally, in this hurried review, we come to note the development of modern astronomy or astrophysics. This was started, as was related, when Sir Isaac Newton discovered the composite character of light. Early in the 19th century Fraunhofer had noted and mapped certain dark lines running across the spectrum of the Sun, the lines which are named after him. The true explanation of these was given about the middle of the century by Kirchhoff, and the new science of astrophysics was well started. Here again was opened up a new field of investigation quite as large as that started by Galileo with his telescope.

In this, the 20th century, the reflecting telescope is outstripping the refractor. We have ever larger and larger reflectors, culminating, as has been told, in the 100-inch reflector at Mount Wilson. Hand in hand with this goes the development of spectroscopes and minor apparatus, and the perfection of photographic processes. Keeler's discovery concerning the nebular forms, and the development of astrophysics mark an epoch which starts the 20th century well on its way to master the great unsolved problem of astronomy, the structure of the universe.

I am only too well aware of how inadequate this sketch is; many more things perhaps should have been said. I hope, however, that, incomplete as it is, this account has given you some idea of the various foundation stones upon which the beautiful astronomical superstructure has been erected.

OUR NEAREST STAR, THE SUN[1]

By Charles E. St. John

If the Sun were removed to eight times the distance of its nearest stellar neighbor, it would appear among the fainter stars, just fairly visible to the unaided eye. Like the other stars, it is self-luminous, but among them it is conspicuous only because of its relative nearness, as there are many other stars that surpass it in size and greatly excel it in luminosity. The blazing *Sirius,* the brightest star in all the sky, has 3.4 times the mass of the Sun and sends out 48 times the light, but even it is far surpassed in absolute luminosity by other giant stars.

Nevertheless the importance of the Sun to us is typified by its apparent prominence in the heavens, for, in a very real sense, we are children of the Sun. The Earth is held in her path by the invisible attraction of the Sun, a pull greater than could be exerted by a bond of steel hundreds of miles in diameter; or, as Young puts it, it would be necessary to cover the whole Earth with wires as large as telegraph wires and only about half an inch apart in order to get a metallic connection that would stand the strain. Not only is the motion of the Earth in space controlled by the masterful Sun, but what is more directly evident, the Sun is the source of practically all our light and heat, without which life, as we know it, could not exist upon the Earth. Some one has said that if the Earth were cut off from all solar radiation for a single month, all life would be extinguished and the world become a frozen waste.

It is not so evident, but as clearly true, that the energy stored in wood, coal, oil and gas has come to us from the Sun. Under the influence of sunlight, particularly of the red and blue components, the carbon dioxide of the atmosphere is taken in by the leaves of trees and plants and acted upon to form the complex constituents of plant growth, mainly compounds of carbon with hydrogen, oxygen and nitrogen. Their chemical transformation requires the absorption of energy

[1] Delivered December 14, 1918.

which is accumulated and stored in these compounds, to be released and again transformed when they are burned rapidly in ordinary combustion, or slowly in our own bodies. Every heart beat, every breath we take, every thought, and every act performed draws its working power from the accumulated solar energy stored up in plant and animal growth. The transformation of solar energy in plant growth takes place in the leaves under the action of sunlight upon the green coloring matter, the chlorophyll. As heat engines plants cannot be considered efficient, transforming as they do only one or two per cent of the solar energy falling upon their leaves, but the energy supplied, as will appear later, is enormous; plants work continually during growth and store up energy in permanent form; these are favorable conditions and result in tremendous advantages for man. The energy of coal has waited for his touch many millions of years and what, if any, escapes his wasteful use will endure uncounted millions yet without loss of its potential energy. The energy of the Sun is stored in the water lifted into the atmosphere by the Sun's power and carried by wind-driven clouds to higher regions, whence it falls as rain or snow, ever renewing the reservoirs and so rendering them a practically exhaustless source of power.

The study of the Sun is of interest not only for its immediate importance to us, but because the Sun is the only star near enough to us to allow of intensive and detailed study. For a proper orientation it may be well to consider some of the tremendous magnitude relations of the Sun.

The diameter of the Sun	863,000 miles
The distance from the Earth	93,000,000 miles
The mass of the Sun	332,000 $\times$ Earth
The mass of the Earth	6.58×10^{19} tons
The mass of the Sun	2.19×10^{27} tons
Distance to nearest star	25×10^{12} miles

It is impossible for us to conceive the meaning of such colossal numbers, but they serve to indicate relations; and they make it less surprising that we know so little than amazing that we have learned so much concerning bodies at such inconceivable distances, and that the human mind has been able to bridge such vast spaces and bring to our knowledge more and more the secrets of the universe.

The advancement of our knowledge of the Sun and stars depends in great measure upon the analysis of light by the spectroscope, an instrument by which the white light of the Sun is stretched out into a spectrum, that is, a narrow band of colors extending from red through yellow, green and blue, to violet, crossed at right angles by a vast number of narrow dark lines. It is to these dark lines, the Fraunhofer lines, that the solar investigator gives his attention rather than to the brilliantly colored band. From the changes in the relative positions, intensities, and other characteristics of these dark lines, he determines the substances in the Sun, the pressure and motions in the atmosphere, the law of its rotation, the temperature and magnetic effects in sun-spots, and endeavors to find answers to the many as yet unsolved problems. The spectrum is to most people a kind of unknown language. The interpretation of its message from the Sun and the far more distant stars is the special work of the astronomer. He finds the key to it in the physical laboratory, which forms an essential part of a modern solar observatory. When in the laboratory a substance like iron, for example, is turned to vapor at a very high temperature, the iron vapor becomes luminous and emits a characteristic light. This light when analyzed by a spectroscope yields, not a band of colors, but a series of narrow bright lines scattered through the red, yellow, green, blue and violet. Each element when in the form of vapor may be made to yield a line spectrum which distinguishes it from every other element and furnishes the means for its positive identification. Moreover, incandescent vapors absorb from white light passing through them precisely the rays which they by themselves emit, so that under suitable conditions of temperature and emission, the spectrum of the transmitted white light shows dark (absorption) lines in the exact positions of the bright lines that characterize the spectrum of the vapor, and these dark lines serve equally well for its identification.

These principles are used in the identification of substances in the atmosphere of the Sun and stars. The vapors and

Fig. 1—Coincidence of bright lines (a) from iron vapor with dark lines (b) in the Sun's spectrum, violet region, λ4200.

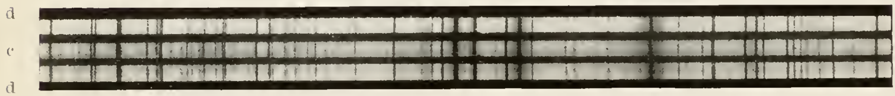


Fig. 2—Displacement of the lines at the east (c) and west (d) limbs of the Sun, green region, λ5167.

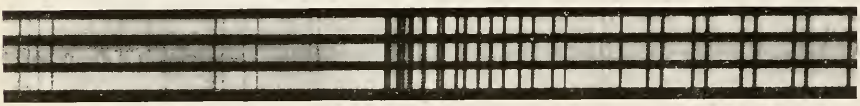


Fig. 3—Lines of B group due to oxygen in the Earth's atmosphere undisplaced by Sun's rotation, red region, λ6867.

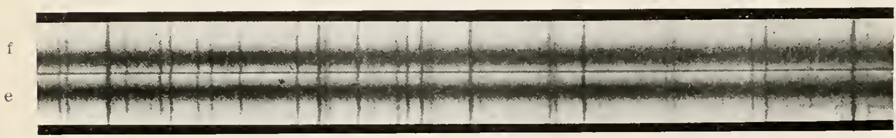


Fig. 4—Displacement of the lines on the near (e) and far (f) sides of a sun-spot showing outflow, blue region, λ4765.

PLATE XXXVI.

gases in these atmospheres, though at temperatures of thousands of degrees, are cooler than the source of the white light originating lower down and, as this passes through them on its way to us, it impresses upon its own spectrum their characteristic absorption lines. A portion of the violet region in the spectra of the Sun and of the glowing vapor of iron is reproduced in Fig. 1, Plate XXXVI. The coincidence between the bright lines of the iron spectrum and dark lines in the Sun's spectrum is complete and shows therefore the presence of incandescent iron vapor in the solar atmosphere.

Of the 92 elements indicated by the periodic system all except five or six have been found upon the Earth, some in minute amounts only. The number of elements identified with certainty in the Sun is 38 and includes the common metals—iron, nickel, copper, zinc, lead, tin. Of most of the heavy metals, such as gold, platinum, iridium, and uranium, there is no positive evidence. If they are represented at all in the solar spectrum it is only by the faintest lines. The absence of definite evidence of the presence of these heavy elements in the Sun may be due in part to their actual rarity. If the 92 possible chemical elements be arranged in the order of increasing atomic numbers, it is found, as Professor Harkins points out, that the comparatively light elements occurring in the first third of the series supply 99 per cent of the substances in the Earth's accessible crust and in meteorites: i. e., two-thirds of the elements, the heavier ones, furnish only a fraction of one per cent of the Earth's crust and of the cosmic material represented by the meteoric visitors from interstellar space. If the proportions between the light and heavy elements and their distribution in the Sun are comparable, as seems probable, with the proportions and distribution in terrestrial sources, there can be at most only traces of them in the lower levels of the solar atmosphere and it is not surprising that we have not yet detected them with certainty. The groups of non-metallic elements, such as chlorine and bromine, oxygen and sulphur, nitrogen and phosphorus, are not represented in the solar spectrum by their characteristic lines, except possibly oxygen and nitrogen. The suggested explanation is found in the observation that the presence of metallic vapors tends to suppress the spectra of the non-metals when the two classes of substances occur in the same mixture.

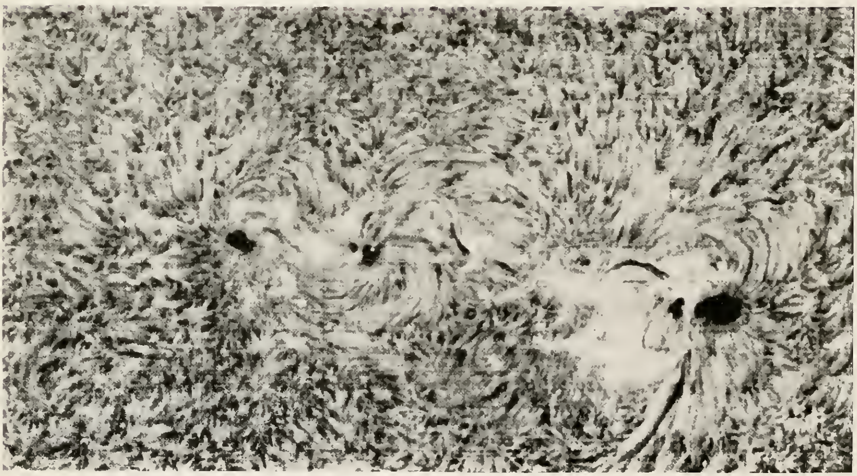
As a locomotive whistle is higher in pitch when the train is approaching than when receding from the observer, so light coming from a rapidly approaching source is bluer, and from a receding source is redder, than when the source is at rest; this manifests itself in the spectrum by a slight displacement of the lines toward the violet or toward the red according as the source is approaching or receding. This is known as the Doppler effect. In Fig. 2, Plate XXXVI, are shown narrow spectra taken from the east and west edges of the Sun on the line of the equator, the two outer from the west and the central one from the east edge. When carefully examined, it is seen that the lines are slightly displaced, the lines of the central strip are to the left, that is, to the violet, of those in the outer strips. From a microscropical measurement of the displacement $\Delta\lambda$ in terms of the wave-length λ and the observed velocity V of light, the velocity with which the east edge of the Sun is approaching and the west edge receding is found from the formula $v = \frac{\Delta\lambda}{\lambda} V$ to be approximately 2 km. per second, or nearly 4500 miles per hour. It follows that the equatorial region of the Sun turns on its axis once in 24.5 days. The rotation is slower for higher latitudes, and from this it is evident that the Sun does not rotate as a solid. As these differences in rotation are probably vestiges from the past, a complete knowledge of the Sun's rotation is important in the development of solar theory.

Some of the lines in the solar spectrum are due to selective absorption in the Earth's atmosphere, but in this case the absorbing matter is at rest relative to the observer and the lines of terrestrial origin remain undisplaced in spectra from the east and west edges of the Sun. This furnishes a means of distinguishing between solar and terrestrial lines. Fig. 3, Plate XXXVI, reproduces such a spectrum, showing the great B group due to oxygen in the Earth's atmosphere, the systematically spaced lines occurring in the deep red. These are undisplaced while the weaker lines of solar origin are all distinctly shifted. This is seen especially well in the group of four faint solar lines to the right of the middle of the portion

a

(a) Spots and granulations of the photosphere. Direct photograph.

b



(b) Vortical streaming of the hydrogen in the same region. Spectroheliogram.

PLATE XXXVII.

Solar Observatory Photographs.

of the spectrum reproduced. Here also the central strip is from the east edge of the Sun's disk and the lines of solar origin are displaced to the left, that is, toward the violet.

Another application of the Doppler effect is the study of the currents in the solar atmosphere around sun-spots. It is found that in the lower levels of the Sun's atmosphere the flow from spots is outward along the Sun's surface, and inward for the higher-lying vapors which are rushing into spots with tremendous cyclonic whirls. Since the Sun is a globe, the flow outward from a spot near the Sun's limb is toward the observer on the near, and from the observer on the far, side of the spot.

In Fig. 4, Plate XXXVI, the spectra from the two sides of a spot are shown juxtaposed. Along the line of juxtaposition the lines in the spectrum from the near side are displaced to the violet and those from the far side are displaced to the red, indicating in both cases a flow outward. The displacements are largest for the faintest or low-level lines. They become smaller and smaller as stronger and stronger lines are observed until for the strongest lines in the Sun's spectrum, the H and K lines of calcium, the hydrogen lines and the strongest lines of sodium, magnesium and iron, the displacements are in the opposite direction, indicating an inflow for the high-level vapors. From the amount of displacement it is possible to determine the relative distribution of the constituents of the Sun's atmosphere. In this way it is found that the vapors of the heavy and rare elements occur only at the lower levels, and that the lighter and more abundant substances are distributed over a far wider range of altitude, some of them forming the indefinite boundary of the Sun.

The surface of the Sun, the photosphere, ordinarily appears to the unaided eye as a brilliant disk without markings of any kind, but when photographed or observed with the telescope the surface appears distinctly granular, with bright mottlings upon a darker background. The bright patches, three hundred to four hundred miles in diameter, are thought to be the tops of rising columns of hot vapors. Often spots many thousands of miles across are seen, each with a dark center, the umbra, surrounded by a shaded area, the penumbra.

The umbra is only dark, however, in comparison with the brilliant photosphere, as its temperature, though lower than that of its surroundings, is comparable with the highest terrestrial temperatures. These features may be recognized in the reproductions of Plate XXXVII; (a) is from a direct photograph and shows granulations and spots; (b) shows the same region photographed with light from the hydrogen in the upper solar atmosphere. In this the streaming, whirling movement of the hydrogen gas is distinctly seen and represents a cyclonic storm of vast extent.

The umbra of a sun-spot is, as Hale discovered, a powerful magnetic field. This is shown by comparing the behavior of the spectrum lines in spots with their behavior when the radiating vapor is in a strong magnetic field. In the laboratory, under such conditions, many lines are separated into components with characteristic properties, the Zeeman effect. That the lines behave in the same way in the spectra of spots furnishes positive evidence that a magnetic field exists in the umbra of a sun-spot. The doubling of the lines when light is produced in a magnetic field is shown in (a) Plate XXXVIII, and in (b) the doubling in the umbra of a sun-spot.

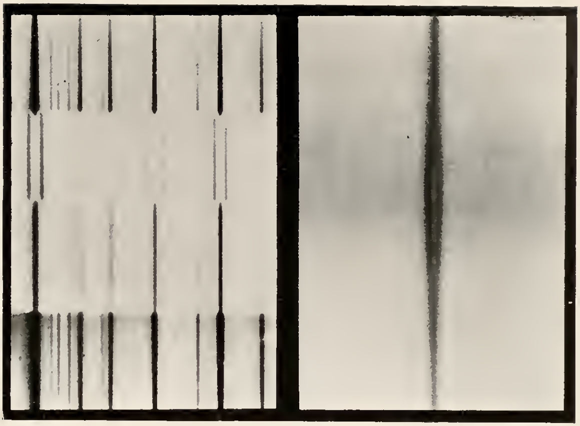
During a total eclipse of the Sun great red-colored prominences are often seen extending many thousands of miles beyond the limb. These are mainly clouds of hydrogen and calcium vapor and take their color from the strong red light emitted by glowing hydrogen. These are now recorded daily by covering the Sun's image with a circular disk, thus producing an artificial eclipse, and photographing them by the spectroheliograph, an instrument by which the surface of the Sun and its surroundings can be photographed in the light of a selected spectral line. In (c) and (d), Plate XXXVIII, a prominence is shown photographed in this way by Ellerman, with a long exposure to get the detail beyond the limb and with a shorter exposure for the detail of the portion of the prominence projected on the disk. The two photographs show that certain dark markings on the Sun's disk brought out only by the spectroheliograph are prominences in projection; that is, intervening masses of cooler vapor high above the visible surface of the Sun. These absorb from the transmitted photospheric light more light of their own rate of vibration than they send towards the Earth, so that in light of this particular color or wave-length they appear dark against the hotter and hence brighter background of the disk. It is the characteristic property of the spectroheliograph to "see" the Sun photographically in the light of any selected wave-length. The illustrations in Plate XXXVIII, (c) and (d), colored the proper shade of red, that of the red light of hydrogen, would represent the Sun as seen by an eye sensitive to this particular color and blind to all others.

A combination of two photographs obtained by the spectroheliograph is reproduced in Plate XXXIX. One shows the Sun's disk taken by the light from calcium vapor and gives the distribution of this particular substance in the solar atmosphere at that time, the other records the accompanying prominences then projecting beyond the Sun's visible edge. These are the bright red protuberances which form the most striking feature when the Sun is covered by the Moon during a total eclipse. On the disk, bands of bright flocculi are shown in the two sun-spot belts, one on each side of the Sun's equator. These areas change in number, size, and configuration, following variations in solar activity, and are always conspicuous in the neighborhood of sun-spots. The Sun is by no means in a quiescent state. Variation in its activity is indicated not only by the increase or decrease in the size and number of spots, faculae, prominences, and flocculi, the recording of which is now a matter of daily routine at a solar observatory, but also by the movements, sometimes on a tremendous scale, in its enveloping atmosphere. The ordinary speed of outflow of low-lying vapors from spot centers along the solar surface is fifty to a hundred miles per second, velocities of an order of magnitude not approached in the Earth's atmosphere.

A striking illustration of the rapidity of movement in the upper regions of the solar atmosphere is shown in Plate XL. A dark, that is, a relatively cool, cloud of hydrogen had been observed for some days projected against the glowing photosphere. It was apparently motionless, but one day a series of nine hydrogen spectroheliograms was made in quick succession upon a single photographic plate. It happened that just then the cloud was caught in the current and was rapidly drawn into a neighboring spot or pair of spots. It attained a velocity of nearly a hundred miles a second and when, after development of the plate, another trial was made all trace of it had disappeared. The real importance of the observation is that it showed the direction of movement along the arms of the spiral structure that occurs around sun-spots upon hydrogen spectroheliograms (Plate XXXVII), a question upon which evidence at that time was not conclusive. Later developments in methods of observation, applying the Doppler principle, though less spectacular, enable one to make the observation for any spot when it is near the Sun's visible edge.

As it is possible by working with the slit of the spectrograph close to the edge of a large image of the Sun to see and to photograph in full sunlight the "flash" spectrum, the bright lines given by the Sun's gaseous atmosphere when the white disk is just covered by the Moon at a total eclipse, there remains but one of the recognized solar phenomena that requires for its observation the conditions obtaining only at a total solar eclipse, namely, the corona, an extensive halo of greenish pearly light so faintly luminous that the sunlight diffused in the Earth's atmosphere renders it invisible except when that light is cut off by the Moon at a total eclipse. The coronal light is thought to arise partly from sunlight by a kind of dust-fog around the Sun, and partly from a hypothetical element, coronium, giving the characteristic green ray that corresponds to nothing known in the Sun or upon the Earth. This lends the corona a peculiar interest and together with the uncertainties concerning its nature and relationship to the Sun must for a long time give it prominence in the program of eclipse observations.

Numerous efforts have been made to discover connections between changes in the Sun and terrestrial phenomena. Sunspots, faculae, and prominences increase together to a maximum number, decrease to a minimum, then rise again to a maximum in regular sequence, that is, they show a definite periodicity. The question may be raised, Are there phenomena on the Earth that run the same periodic courses? If terrestrial changes manifest the same orderly sequence over a long period of years we would be justified in assuming a connection between the solar and such terrestrial phenomena.



a b

(a) Doubling of lines in the magnetic field.
(b) Doubling of line in the umbra of a sun-spot.

c

d

(c) Detail of prominence beyond the limb.
(d) Detail of its projection in the disk.

Photographs by F. Ellerman.

PLATE XXXVIII.

Sun-spots have been observed for a hundred and fifty years. When the spot numbers are plotted for the different years the resulting curve shows that they occur in cycles and that the average period of the cycle from maximum to maximum is 11.1 years. The magnetic elements of the Earth show, aside from the secular and regular daily variations, irregular fluctuations in intensity; the so-called magnetic storms are examples of extremely vigorous disturbances of this character. When the sun-spot and magnetic-variation curves are compared, they are found to be identical in period and the peculiarities in one are matched by similar peculiarities in the other. No one questions their intimate connection, but when

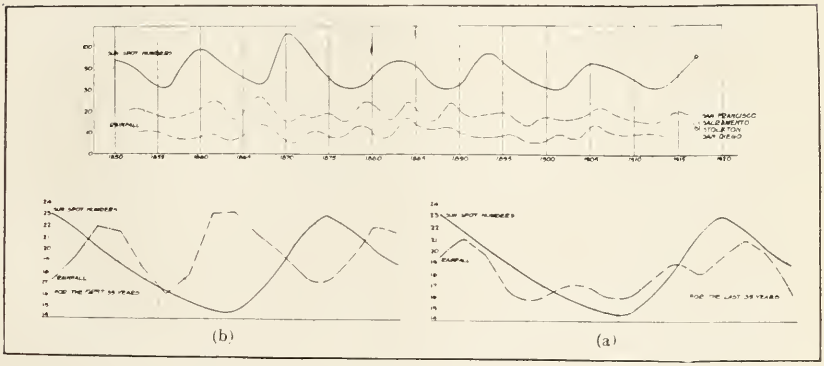


Fig. 10. Comparison of Rainfall with Sun-Spots.

an effort is made to correlate the weather, the rainfall for example, with sun-spots it has not as yet been possible to establish any well defined relation. It may be interesting to compare the rainfall in California with the sun-spot curve. Records at San Francisco, Stockton, and Sacramento are available for nearly seventy years. Such a comparison is shown in the curves in Fig. 10. At once it is seen that the years of maximum rainfall coincide with neither the maximum nor the minimum of the sun-spot curve. The danger of basing a conclusion upon too limited data is illustrated in the two short curves in Fig. 10. Curve (a), a composite for the last 35 years, shows an approximation to similarity with the spot curve, while curve (b), for the first 35 years, shows complete dissimilarity. No one has been able to suggest any valid ground for expecting a direct connection between sun-spots and local rainfall; but when it is found by observations that there are changes in the amount of heat sent to us from the Sun's abounding store, we would seem to be justified in expecting to find a direct relation between terrestrial temperatures and variations in solar radiation, as the Earth's temperature is a function of the Sun's heat emission. We would expect to find a general rise in temperature with increased solar radiation, but even here the matter is not so simple. During a sun-spot maximum the Sun sends us three or four per cent more heat than during the minimum. The spots are not directly concerned in this increased radiation, they are only symptoms of the greater activity of the Sun. The solar gases are in a more turbulent state and bring more heat from the hot interior to the surface during the periods of increased activity. This change of three or four per cent is distributed over a space of five or six years and hence is slow in producing its effect, but fluctuations of five or six per cent that run their course in a week or ten days are shown by the Smithsonian observations. The temperatures at fifty stations well distributed over the Earth have been correlated by Dr. Clayton with the indicated short-period fluctuations in the solar radiation. The results are surprising. In the equatorial regions the temperatures rise with increased solar radiation, but in the Earth's temperate zones the temperatures fall. At Pilar, Argentina, increase of temperature followed increase of solar radiation and reached the maximum effect in one or two days, while at San Diego, California, decrease of temperature followed increase of solar radiation, and the maximum effect occurred after three or four days. Manifestly secondary causes are set in motion which in part mask the direct solar action in the temperate zones. The Sun being more nearly overhead in the equatorial regions, the influence of increased radiation is there more quickly felt, the temperature of the atmosphere is increased and the abnormally heated air rises and overflows the temperate zones, producing conditions that disturb, in a way unknown as yet, the blanketing effect of the atmosphere. A similar paradoxical result appears in the lower temperatures of the world in

PLATE XXXIX.

Combined Photographs of Prominences and Flocculi.

Solar Observatory Photographs.

general at sun-spot maximum than at minimum, though the solar radiation is greater at sun-spot maximum. The observed lowering in temperature is about one degree Fahrenheit while the increased radiation of the Sun indicates, according to Abbot, a rise of some three or four degrees. The variations in the amount of heat given out by the Sun that run their course in a few days and are followed by observable changes in temperature over definite regions of the Earth suggest the possibility of being able in the near future to forecast related terrestrial conditions over extended regions days in advance of their occurrence.

The measurement of the solar constant, the total intensity of solar radiation outside the Earth's atmosphere at the Earth's mean distance from the Sun, as made by the observers of the Smithsonian Institution at the Washington, Mount Wilson and Mount Whitney stations, is 1.95 calories per square centimeter per minute and it is thought that future investigation will make no considerable change in this value. The amount of energy represented by this radiation is difficult of conception. Assuming, as we have reason to do, that the Sun radiates equally in all directions, we can easily calculate the total emission, as it is 1.95 calories per minute on each square centimeter of a sphere whose radius is the mean distance of the Earth from the Sun, that is, 93,000,000 miles, or 15×10^{12} centimeters.

Total emission $= 1.95 \times 4 \, (15 \times 10^{21})^2$ calories per minute. This is sufficient, as Abbot calculates, to melt a layer of ice 426 feet thick in a year. A layer 426 feet thick over the cross-section of the Earth is equivalent to a layer 106.5 feet over its surface, so that we can say that the heat received by the Earth in a year is sufficient to melt a surrounding shell of ice 106.5 feet thick. Abbot further calculates that the melting in a year of a shell of ice 426 feet thick surrounding the Sun at the Earth's mean distance would represent as many heat units as the burning of 4×10^{23} tons of anthracite coal, or a mass of coal 60 times the mass of the Earth.

The great terrestrial sources of heat are combustion, the transformation into heat of electrical energy obtained from water power, the disintegration of radio-active elements, and the Earth's internal store. If we try to account for the Sun's heat by combustion we reach an absurdly small result for the life of the sun. We have just seen that the yearly output of heat is equivalent to that from the burning of 4×10^{23} tons of coal. If the Sun were composed of pure coal its combustion would supply the heat loss only for

$$\frac{2.19 \times 10^{27}}{4 \times 10^{23}} = 5{,}500 \text{ years},$$

a moment only in the life history of the Sun-Earth system.

It has been suggested that the maintenance of the solar radiation is due to the continued fall of meteoric matter into the Sun. A mass coming from an infinite distance would acquire a velocity of 610 kilometers or 385 miles per second at the surface of the Sun and when brought to rest would disengage 6,000 times as much heat as would be produced if it were coal burning in oxygen. To compensate for the loss of radiation would require that 22 pounds of matter fall upon each square yard of the Sun's surface per hour. This would increase the diameter of the Sun so slowly that 35,000,000 years must elapse before the increase would attain one second of arc. It would, however, increase the mass of the Sun to such an extent that the effect could not escape detection. Bosler calculates that in the last 2,000 years the accumulation would have been sufficient to change the orbital motion of the Earth by one-eighth of a year, a change, needless to say, that has not occurred. Moreover, few meteors coming from interstellar space would fall into the Sun, as most of them would circulate around it as comets do.

A source of heat that has been very generally admitted since its suggestion by Helmholtz, is the gravitational attraction of the Sun upon its own material, as a gradual falling of the Sun's substance toward the center would transform the potential energy of gravitation into heat. The estimates of the energy available in the past from this source are based upon the contraction of the Sun to its present size from a diameter exceeding that of the orbit of *Neptune*, the outermost known member of the solar system. The energy supplied by this contraction would have sustained the present rate of radiation for approximately 25,000,000 years. According to Newcomb the Sun will have shrunk to half its present diameter in 7,000,000 years and will be unable to furnish heat sufficient to support life as we know it for more than 15,000,000 years.

Though the gravitational contraction of the Sun is regarded as a real source of energy, it is generally admitted that it alone is not sufficient to account for radiation through the enormous periods of time required for the geological transformation of the Earth. In the effort to meet this recognized difficulty the suggestion has been made that the solar radiation was less intense during past ages than at present, the deficit being supplied by the inherent heat of the Earth or by receiving heat from a large solid angle subtended by a greatly extended nebular Sun. And since the discovery of the liberation of energy by the breaking up of radioactive substances, much attention has been given to the suggestion that the presence of such substances in the Sun would assist in maintaining the solar radiation and give it sufficient duration to meet the requirements of geological transformation. Direct proof of their presence in the Sun is lacking, though the occurrence of helium and lead in the Sun, products of the disintegration of radium, may be taken as indicative of their possible presence. That the lines of radioactive elements do not occur in the solar spectrum is not surprising in view of their high atomic weights. If radium and its parent element, uranium, do exist in the Sun, they are probably at a very low level in the solar atmosphere and their lines would consequently be extremely faint or absent. The whole question is one of extreme difficulty and has not as yet received a satisfactory solution.

The outer portions of the Sun are certainly gaseous. This is shown by the presence of lines in its spectrum, since gases only can give a line spectrum. The photosphere forms the visible disk of the Sun and is the source of the continuous spectrum. Upon the constitution of the photosphere astronomers are not in agreement. Some consider it a cloudy layer similar to clouds in our own atmosphere, but while the terrestrial clouds consist of minute water droplets suspended in the air, the solar clouds are supposed to be the condensed vapors of unknown substances floating in the atmosphere of incondensable vapors. According to the investigation of Abbot the temperature of the photosphere can not be lower than 10,500° F., and probably not less than 11,500° F. Moissan found that all known elements volatilize at a temperature of 3,500° C. or 6,300° F. In view of these observational results it is thought by other solar physicists that clouds can not exist in the Sun's atmosphere and that the continuous spectrum originates in the lower and denser layers under conditions in which gases would give a continuous spectrum.

As to the state of matter in the interior of the Sun we know nothing by observation, and here again the astronomers have different opinions. All agree that the temperatures in the Sun's interior are vastly higher than the surface temperature, reaching many millions of degrees, and that the pressures due to the Sun's gravitation are also tremendous near the core. As we know nothing experimentally of the behavior of matter under such extremes of temperature and pressure, the field is open for individual opinion. In view of the low average density of the Sun, one-fourth that of the Earth or 1.4 times that of water, it is clear that very far down below the surface the Sun must still be gaseous. Those who consider that the Sun may have a solid or liquid core deduce their conclusions from the enormous pressure existing there. Those who believe that the whole interior is gaseous look at the question more from the point of view of temperature. Though air, hydrogen, and helium, the most refractory of the elements, can be liquefied under pressures available in the laboratory, they must at the same time be below certain critical temperatures before any pressure, however great, can liquefy them. As the temperature in every part of the Sun is above the critical temperature of every known substance, the prevalent opinion is that the whole interior of the Sun is gaseous.

When the Sun is considered among a universe of stars, it is only one among hundreds of millions. The distance from its nearest known neighbor is so great that it transcends the imagination. In terms of the velocity of light its distance is about 4.4 light-years, that is, the distance traversed by light in 4.4 years with a velocity of 186,000 miles a second. There are

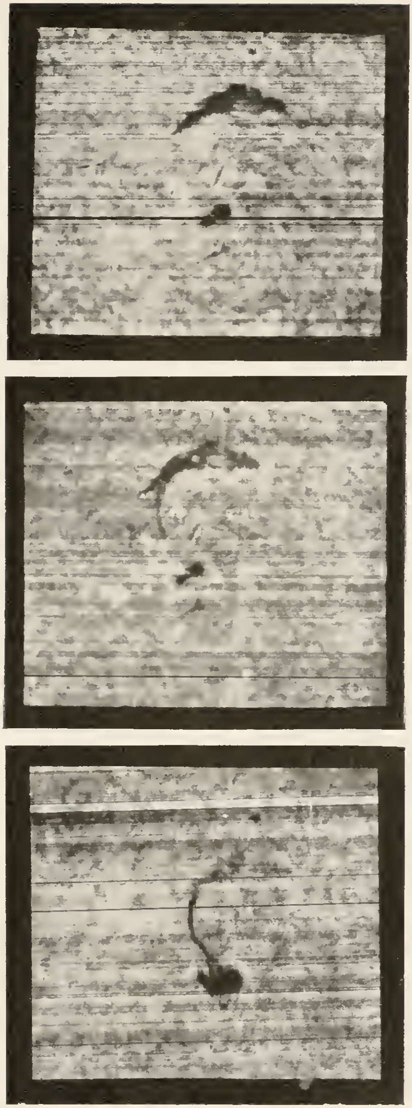


PLATE XL.

HYDROGEN FLOCCULUS DRAWN INTO SUN-SPOT.

Solar Observatory Photographs.

perhaps thirty or forty stars within a radius of four times this distance. It is evident that in a sense we are quite alone in space even with a hundred million other Suns. We speak of the fixed stars, but this is a misnomer, as they are all in rapid motion, but, because of their great distance, movement can only be detected by measurements of the highest precision. Our Sun is no exception, as it is sweeping through space with a velocity of twelve and a half miles per second, a speed that carries the Sun and its attendant train of planets over a million miles a day, so that when the Earth has made a complete revolution around the Sun, it is still 385,000,000 miles from where it was the year before. With all this speed it would require 70,000 years to reach the nearest star, even if we were traveling in that direction.

The question of very great interest is, How did our solar system come into existence and what will be its future? The evolution of the Sun takes place so slowly that no change has been noted in historical times. We cannot hope to solve its past nor to foretell its future evolution from observations on the Sun alone; but the Sun is one among the other stars and these apparently represent a series of types in a progression from a nebular stage to a dead or dying Sun. When from a knowledge gained from the study of their spectra and other characteristics the various stages in stellar evolution are found, it will be possible from its spectrum to locate the Sun in the series of evolving stars, and both its future and its past may be determined. The story is written in the ether of space and must be learned from the interpretation of the records made by the spectroscope. This is why the modern astronomer speaks and writes so continually of the spectrum and its teachings, and the layman who wishes to know the basis and not merely the results of the astronomer's conclusions will find it of great assistance to familiarize himself with the principles of spectrum analysis.

The immediate province of a solar observatory is to solve as far as possible the problems relating to our Sun. To take this citadel of the sky three lines of attack are open to us, all converging upon the central objective. First, the direct attack upon the Sun itself. This offers great opportunities and the hope of immediate gains; moreover, as it is our nearest star, the minuter details of stellar character can be studied with great advantage through the Sun. Second, the Sun is only one among a universe of similar suns, so that the broader question of the relation to the sidereal system and the evolutionary history of the Sun are most hopefully approached through a study of the distant stars. Third, the student of the Sun must ever have his feet upon the solid Earth, his observations must be checked and interpreted and often directed by investigations in the physical laboratory, which therefore forms an essential adjunct to the observatory. Through the coördination of these three modes of approach and the harmonious interaction between them, the great advances of the immediate past have been made and far greater gains of the future may be confidently hoped for, and the dream of the savage and the civilized man as pictured by Wells in *The World Set Free* may yet be fulfilled. He says of the savage:

> Man began to think. There were times when he was full, when his lusts and his fears were all appeased. He watched the streaming river and wondered from what bountiful breast this incessant water came; he blinked at the Sun and dreamt that perhaps he might snare it and spear it as it went down to its resting place amidst the distant hills.

Of the twentieth-century boy who has just had his imagination fired by a lecture on the wonders of radium, he writes:

> He made his way to the top of Arthur's Seat and there he sat for a long time in the golden evening sunshine, still, except that ever and again he whispered to himself some precious phrase that stuck in his mind. "If," he whispered, "if only we could pick that lock." He seemed to wake up at last out of his entrancement and the red Sun was before his eyes. Into his mind came a strange echo of that ancestral fancy, that fancy of a Stone Age, dead and scattered bones among the drift two thousand years ago. "Ye auld thing," he said, and his eyes were glistening and he made a kind of grabbing gesture with his hand, "Ye auld red thing. . . . We'll have ye *yet*."

PLATE XLI. The Great Nebula in Orion.

Photographed by J. E. Keeler, Crossley Reflector, Nov. 16, 1898.

NEWS FROM THE STARS[1]

By Robert G. Aitken

Like the Athenians in the days of St. Paul, we all delight to tell or hear of some new thing. "What's the news?" is a standard form of greeting and few of us can pass a bulletin board or a newsboy shouting "extra" without stopping to get the news. And marvelous indeed is the organization that makes it possible for us to learn each day the more important items of news from every part of the civilized world. Whether it is that Steffanson has reached Fort Yukon after his long stay in the Arctic regions, that Guatemala has been visited by a disastrous earthquake, or that General Allenby has entered Jerusalem on foot, the agents of the Associated Press have noted the fact almost before the event and we read of it next morning in our daily paper.

At the present time, of course, the news we are all most eager to hear is the news from "over there," and in this the astronomer is as keen as the most "practical" man of business. I am well aware that the latter sometimes regards the astronomer with a certain air of good-humored tolerance, as a man who walks with his head in the clouds and his eyes fixed upon the stars, oblivious of the ordinary, or even the extraordinary, affairs of our common daily lives. And it would indeed seem that if any were to be unaffected by the present war it might well be a little company of men dwelling upon a more or less isolated mountain top, engaged in the purely scientific study of the stars.

But let me bear witness that we are united with you in one brotherhood in our love of country and of righteousness, and that we are striving even as you to do our part toward making justice and right prevail upon the Earth. Every man, woman, and child, even to the month-old baby, in our little community

[1] Delivered January 11, 1918.

on Mount Hamilton is a member of the American Red Cross; every girl and woman is giving every possible minute to knitting and sewing for the Red Cross; every employee of the Lick Observatory holds at least one Liberty Bond, every household is intelligently and conscientiously conserving food and fuel; our little community has "gone over the top" in every "drive" for funds, beginning with the appeals for relief long before the first Red Cross drive last spring. And that is the least of it. Practically every family has near relatives at the front, and four of our boys, sons of the three astronomers who have boys old enough to serve, are volunteers in the active military service of their country. Two are in France at this moment, Lieutenants in the Engineer Corps and in the Aviation Service; one is on board a man-of-war, and the fourth is in the Marine Corps. Yes, I think I may say that the astronomers on Mount Hamilton are interested in the news—*all the news*—bearing in any way upon the war.[2]

It is our personal duty, meanwhile, quietly to continue getting the news from the stars and making it known to those who may be interested. In this work we cannot rival our friends of the Associated Press in promptness. However alert we may be, however quick to seize and decipher the messages flashed to us with the speed of light from "the marches and strongholds of space," our news lags far behind the event. You were doubtless reminded of that fact if you read an article that appeared in one of the San Francisco papers one morning in December. The headlines ran:

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[2] Although this paragraph has no definite relation to the subject of "News from the Stars," it is allowed to stand as an expression of the attitude of the Lick Observatory community to the war. In reading it, the date (January 11, 1918) must be held in mind. Later on the Marine mentioned crossed to France and saw hard service in the front line; and two other boys, sons of astronomers in the Observatory, entered upon active military service as volunteers. One of the two went to Italy and rendered valiant service in the ambulance corps; the other was commissioned Second Lieutenant of Infantry and detailed as instructor to a Training Camp in this country. Indeed *every male graduate of the little grammar school on Mount Hamilton volunteered for war work.*

The responses of the community to the later Liberty Bond, Red Cross and other "drives" were as prompt and generous as those to the earlier ones. In every instance the amount asked for was oversubscribed—sometimes four to eight-fold—on the opening day of the drive. For a more complete statement see a note by Dr. W. W. Campbell in the *Publ. Astron. Soc. Pac.*, **30**, 353, 1918.

THIS NEWS IS LATE, BUT HERE IT IS AT LAST

Extra! Extra! All About Big Disasters of 20,000,000 Years Ago

THREE SUNS BLOWN UP

Information Reaches Earth Finally as Tiny Specks on Photographic Plate.

The article was based upon a Lick Observatory Bulletin announcing the discovery by Dr. Curtis of three novae, new stars, in spiral nebulae, and barring the statement of the "blowing up" of three suns and of a few other details was accurate enough and certainly very interesting reading. A cipher or two might perhaps be dropped from the number of years given in the headlines quoted, but, at best, the news was a very long time indeed in reaching us, measured by the standards of our human experience. I shall tell you more about this item of news a little later on, but just now I want to ask you to fix your attention on the stars which shine upon us in the early hours of these winter evenings when we face the south and look up into the sky.

There are few regions of the starry heavens more attractive to the unaided eye than the one now spread before you. High in the sky, near the zenith, is the little group of the *Pleiades*; south and to the east from them stand the *Hyades*, with ruddy *Aldebaran* for their leader; still farther southeast is *Orion*; and towards the southeastern horizon, *Sirius*, the brightest star in the sky. East and a little north from the red star *Betelgeux, Alpha Orionis*, shines *Procyon*, and north and slightly east of *Procyon* the twin stars, *Castor* and *Pollux*. The great planet *Jupiter*, between the *Pleiades* and *Aldebaran*, and *Saturn*, low in the eastern sky, are added attractions during the present winter.

Beautiful as it is to the unaided eye, every increase in optical power as we apply the telescope to the various parts of this section of the sky brings out new wonders. Not only is the apparent number of stars increased beyond our power to count, but many of them are found to be double or multiple; others, to be surrounded by those cloud-like masses of light which we call nebulae. *Theta Orionis,* the middle star in the sword of *Orion*, for example, which, indeed, is hazy to the eye alone, is now seen to be a nebulous mass entwined about a little group of stars. This object, commonly known as the Great Nebula in *Orion,* is in fact one of the most remarkable in the whole heavens and it is one about which we have recently been finding out some new facts which I am sure will be of interest to you.

To realize their significance it will be necessary to glance briefly at the history of this nebula as revealed by the telescope. As long ago as 1656 Huyghens, the great Dutch astronomer who first solved the problem of *Saturn's* puzzling aspect as viewed through early telescopes, saw three of the stars in the little group of the now familiar *Trapezium*; the fourth was certainly known in Herschel's time, and, later, fainter companion stars were added to two of the four. One or two excessively faint stars within the *Trapezium* were discovered by Alvan Clark and by Barnard with our 36-inch refractor; and Frost and Adams, at the Yerkes Observatory, found the brightest star of the *Trapezium* to be a spectroscopic binary system. Merely as a star group, then, *Theta Orionis* is a wonderful object; a group of suns forming a single physical system of a size so vast that our solar system, in comparison, shrinks to insignificance. But far more wonderful is the cloud-like mass of greenish-white light enveloping these stars. Just visible to the naked eye as a hazy patch, the brighter part is readily seen with a pair of opera glasses; but to get an adequate idea of its beauty, its extent, and the bewildering complexity of its details it is necessary to view it with a powerful telescope, or to study a photograph taken with a large modern reflector. It is hopeless to attempt description, just as many able astronomers have found it hopeless to try to portray all of its features by even the most careful drawings.

I have called it a nebula, but that term is applied to at least three different classes of objects, the spirals, the planetaries, and the irregular gaseous nebulae. Our object belongs to the third category, for the spectroscope long ago showed that it

PLATE XLII. Vacant Lanes and Nebula in Taurus.

Photographed by E. E. Barnard with the 10-inch Bruce telescope, Jan. 9, 1907, 5½ hours' exposure.

consists of gases shining by inherent light, but whether this light is due to intense heat or to some other cause it has until recently been quite impossible to say. Even now we are not prepared to assert that the question has been definitely settled. The great difficulty about believing it to be due to heat is the almost incredible extent and tenuity of the nebula. On the photographs taken with the Crossley reflector both the north and south, and the east and west diameters exceed 40 minutes of arc. To translate this value into linear measure, miles or kilometers, it is necessary to know how far away the object is. This we do not know, but it is possible to set a *minimum value* for the distance. The parallax is certainly less than 0.01 second of arc; that is, a line 93,000,000 miles long (the distance from the Earth to the Sun), drawn upon the surface of the nebula would to our eyes subtend an angle less than a hundredth of a second of arc. The diameters of the nebula are therefore certainly more than 240,000 ($40 \times 60 \times 100$) times 93,000,000 (22,320,000,000,000) miles and may be more than ten times as great. Some one has computed that if the material were only 1/1,000,000 as dense as ordinary atmospheric air at sea-level, the mass of the nebula would be so great as to compel all of the stars in that region of space to travel toward it. As a matter of fact no such motion is observed and the tenuity must be even less than the almost incredible limit named. That such a mass of matter can be hot enough to be incandescent is hard to believe, but recent investigations indicate that this is the case.

Every effort has been made to determine whether there are any changes in the position of the nebula as a whole or in any of its parts, but without positive results. This does not, of course, mean that the nebula is absolutely stationary in space but only that whatever motion there may be across the line of sight is too small to become apparent to us in the time during which accurate measures have been made. In this interval there may have been, for all that we can say, a motion of translation amounting to some hundreds of millions of miles, but, if so, the resulting angular displacement has been so small that we have not been able to detect it. The spectroscope, however, permits us to make accurate measures of the motion of a celestial body *in the line of sight* no matter how far away the body may be. Its testimony is to the effect that the Sun and the nebula as a whole are moving away from each other with a velocity of about 18 kilometers a second; but by far the greater part of this relative velocity is due to the Sun's own motion through space and only a small fraction to the actual motion of the nebula. In fact, this nebula, like other diffuse gaseous nebulae, seems to be almost stationary when compared to the motion of the average star.

The materials of the nebula, however, are far from being in a quiescent state. Three or four years ago MM. Buison, Fabry and Bourget, at Marseilles, applied an interferometer attached to a 24-inch reflecting telescope to its study. In effect this apparatus resembled a spectrograph in that it permitted the observers to make accurate measures of the radial velocity of the portion of the nebula examined, and it had the advantage over the ordinary slit-spectrograph of permitting such measures to be made over every part of a field some four minutes of arc in diameter on a single photograph. These investigators found that different parts of the nebula were moving with different velocities. The interferometer has the further advantage of giving, under certain conditions, a theoretical value of the atomic weight and of the temperature of the gas whose radiation is measured and, in the present instance, the authors were led to conclude that the atomic weights of the unknown gases in the nebula were intermediate between that of hydrogen and that of helium, and that *the temperature might be as high as 15,000° Centigrade*. Conclusions of such fundamental importance to our theories of stellar evolution will, of course, be most carefully verified before they are finally adopted, but the ability of the investigators and the scrupulous care they took to check their work at every stage lend great weight to their results.

Recent spectrographic measures at the Lick Observatory and elsewhere have fully confirmed these results so far as the internal motions are concerned. A detailed study of the *Orion* Nebula has formed part of the program of work with the Mills Spectrograph during the past few years and accurate measures of the radial velocities of the gases in many different parts have been made. It is found that in some parts they are receding relatively, in other parts approaching, the relative velocities occasionally exceeding 10 kilometers per second. The whole mass, therefore, must be conceived of as being in seething and well-nigh chaotic turmoil.

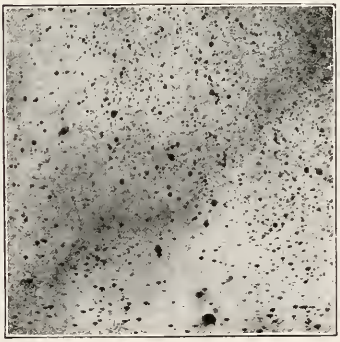
Now this is one of the latest items of news we have received from the Great Nebula in *Orion* and it illustrates very well the impossibility of having our astronomical news even approximately contemporaneous with the event. The motions which were recorded by the spectrograph were those indicated by the light waves which entered the slit, but those light waves left the nebula certainly more than 300 years ago!

Let me give you another illustration. Somewhat east of the region we are considering there is a star known as *Epsilon* of the constellation *Hydra*. Long ago Struve found that this was a double star, one component being decidedly fainter than the other. In 1888, Schiaparelli noted that the brighter component was itself a very close double, the two components again being quite unequal in brightness. Now I followed the motions in this close pair by measuring the relative positions of the two components with the 36-inch telescope for 15 years, during which time the fainter star seemed to make a complete revolution about the brighter one, and from these measures I computed the elements of the orbit. At the same time measures made with the spectrograph showed that the motion of the brighter star in the line of sight was variable and an independent determination of some of the elements of the orbit was thus made possible. Moreover, from the two determinations it was possible to calculate with considerable accuracy how far away the system was. It proved to be about 135 light-years distant. Therefore the revolution of the two stars which I witnessed was not the one actually taking place during those 15 years, but the one which took place 135 years earlier, or during the days of our own Revolutionary War! Since then the small star has traveled about the brighter one (more precisely, the two stars have traveled in their orbits about their common center of gravity) fully nine times and during the next 135 years the light waves telling us of those motions will reach the Earth. It is literally true that the student of stellar motions is a student of ancient history and is an eye-witness of events which happened centuries ago.

Let us return to the constellation of *Orion.* The drawing and photograph reproduced on Plate XLIII show that the so-called Great Nebula is really only a very small part of the nebulosity which winds about the entire constellation. This vast faint nebulosity is best photographed with quite small telescopes, which at first thought may seem very strange. The explanation is found chiefly in the fact that our large telescopes cover only a small sky area at any one time, whereas a small telescope of reasonably short focal length includes a large area. A small portion of the outer *Orion* nebulosity was seen by Sir William Herschel with his great reflector more than a century ago, but in more recent years its existence was doubted because certain photographic telescopes, of great power for many classes of work, failed to show it. In 1889, however, Professor W. H. Pickering, in the course of his tests of atmospheric conditions on Mount Wilson, now the site of the Solar Observatory, photographed this remarkable object with a portrait lens of 2.6 inches aperture and 8.6 inches equivalent focus. In 1894, Professor Barnard was experimenting at the Lick Observatory with a little lens taken from a cheap (oil) projecting lantern. The lens was but 1.6 inches in diameter and had an equivalent focus of 6.3 inches. Unaware of Pickering's work, he photographed the constellation of *Orion* and fully verified the existence of this great enveloping nebula. In gathering news from the stars, then, we use visual and photographic telescopes ranging in aperture from a single inch to the 100 inches of the great reflector on Mount Wilson, and we attach to these our spectrographs, photometers and other apparatus for special investigations.

There are other constellations which contain similar diffused and faint nebulae. One, the most interesting of these, surrounds the little group of the *Pleiades*, in the constellation *Taurus*, a group of stars that is, perhaps, the most familiar of any in the sky. The average eye sees six stars in this little group; keener eyes, especially in the clear air of mountain regions, distinguish seven or eight or even more. A small telescope greatly increases the number, but, unlike some glob-

A. Drawing from two lantern-lens photographs (Oct. 3 and 24, 1894).



B. Photograph, with Willard lens, of region enclosed in the square in the drawing above (Oct. 17, 1893), 3 hours' exposure.

PLATE XLIII. The Great Curved Nebula in Orion, by E. E. Barnard.

ular clusters, the number can not be increased indefinitely by photographing the region with telescopes of ever greater power. The entire group, as I have said, is involved in nebulosity similar to that which encircles *Orion.* This was first noted by Professor Barnard but has since been photographed by a number of different astronomers. Attention in recent years has been concentrated upon other features of the *Pleiades* group, particularly upon the brighter stars and upon certain remarkable nebulae associated with them.

The most recent study of the stars in the cluster is that just completed by Dr. Trümpler, at the Allegheny Observatory. He finds that the cluster includes from 80 to 90 stars as bright as 9.0 magnitude (bright enough, that is, to be just visible in a telescope of one-inch aperture), with probably 55 more stars between magnitudes 9.0 and 9.5. Doubtless, stars still fainter belong to the cluster but a large percentage of the faint stars of the region certainly form part of the stellar background upon which we see the cluster projected. We can distinguish between the two classes of stars by the fact that the cluster stars are moving together through space. And it also appears that the stars thus moving together resemble each other in the character of their spectra. These two qualities, community of motion and resemblance of spectrum, lead us to conclude that the stars in the cluster had a common nebulous origin, and it is not at all improbable that in the nebulosity surrounding the group we see the remnant of the material out of which the stars were formed.

In addition to the apparent association of the stars and nebulosity, there are several arguments in favor of this view. For example, long-exposure photographs, like those taken with the Crossley reflector, show that some of the brightest stars in the group are immersed in nebulosity and the spectrograph testifies that they have extensive gaseous atmospheres with relatively small cores of denser matter. In other words, they are probably still in the earliest stages of their development as stars. Again, Slipher has shown that the light of the nebula associated with *Merope,* one of the bright stars of the *Pleiades,* has precisely the same quality as the light of the star. He finds the same to be true of the star *Maia* and its nebula, and, more recently, he, and Pease at the Solar Observatory, have found two other instances of star and nebula which possess light of identical quality. Slipher has argued that this indicates that the nebula is shining not by its inherent light but by light reflected from the star or stars, and Hertzsprung's photometric measures in the case of the *Merope* nebula bring confirmatory evidence. Whether we accept or reject the explanation, the observations show the close connection of the two classes of objects.

It is a most interesting fact that *Merope* and *Maia* and the other two stars which have so far been found to be attended by nebulae radiating light of the same quality, are "helium stars," that is, stars in whose spectrum the lines of helium are strongly marked. For the stars in general have been classified according to the character of the spectrum they exhibit and it has been found that the blue-white helium stars stand at one end of a continuous series running through white, yellow, orange and red to deep red stars. On what may be called the classical theory of stellar evolution this order represents the successive stages of stellar development from infancy to old age. In recent years the classical theory has been strongly challenged and a substitute theory offered according to which the youngest stars as well as the oldest are red and the blue-white stars occupy a middle position. This is not the place to present the forceful arguments brought to the support of each of these hypotheses, or to discuss their relative merits. I have mentioned them merely to point out that one of the greatest difficulties in the way of the acceptance of the two-branched evolutionary theory is the close association of the helium stars with diffuse nebulosity such as exists in the constellation of *Orion* and in the *Pleiades*. There is no correlation whatever between such nebulae and red stars.

This is perhaps as good a place as any to insist upon the necessity of discriminating between the facts of observation and the theories which may be based upon those facts. Though elementary, the distinction is frequently lost sight of and astronomy, or rather the reputation of the astronomer. suffers. It is a *fact* that the companion star in the system of *Epsilon Hydrae* changes its position continuously with respect

PLATE XLIV. The Pleiades.

From a photograph by Sir Isaac Roberts, Dec. 8, 1888, exposure 4 hours.

to the brighter star in such a manner that after 15 years it returns to its apparent starting point. The *theory* is that the change is due to the motion of the two bodies in elliptic orbits about a common center of gravity under the law of gravitation. In this case the evidence from numerous double stars is so overwhelmingly strong that the theory has as much weight as the observed facts. In other instances, as for example, the identity in the quality of the light of star and nebula or the arrangement of stellar spectra, the facts are beyond question but they may perhaps be subject to more than one interpretation. We are quite willing to abandon any theory, however cherished, whenever the facts fail to support it.

Let us again return to the constellation of *Orion* in order to consider a photograph taken by Dr. Curtis with the Crossley reflector only a week ago (Plate XLV). The photograph shows the region just south of *Zeta Orionis*, the eastern star of the three in the "Belt." Passing over other features, I want to call your attention to the sharply marked dark blotch, like an ink-blot, just above the center of the picture. At first sight it might be taken for a defect of some kind in the film. That it is not a defect was demonstrated by the fact that it reappeared in identically the same position on a different plate of the region taken on the following night. The reality of the marking being thus established, the question arises whether it represents a non-luminous substance which obstructs the passage of light from the luminous area into which it projects or whether it is a vacant region in space, a "tunnel" bored through the fabric of the constellation. This particular marking has not, so far as I am aware, been photographed before; the picture before you gives one of the latest items of news received from the stars; but "black holes" have long been known in certain regions of the Milky Way and are beautifully pictured in many of Barnard's photographs as well as in those taken by other observers.

Twenty years ago it was thought not impossible that these markings might really represent vacant regions of space, but further investigation of them with modern photographic telescopes, an investigation in which Professor Barnard has been especially prominent, has led to the abandonment of this hypothesis by most astronomers. The edges of the markings are usually far too sharp, the forms are frequently too strikingly similar to those of bright nebulae, and too many of the dark patches are found in regions where it is impossible, on any reasonable theory of stellar distribution, to account for the sudden absence of faint stars.

It is of course conceivable that a compact cluster of stars rushing through space might clear a path for itself and leave a vacant lane; but in the cases known to us there is no evidence of the existence of such a cluster in any position where it might be assumed to be after making such a lane. Hence if any one of these "holes" had such an origin the cluster must have passed many million years ago. But in this event we would not have the sharply cut outlines, for the stars are all in motion and, as Dr. Campbell has pointed out, these motions would in such a time interval have carried many stars into the vacant region, obliterating the clear-cut edges and possibly the "hole" itself.

On the other hand, Bessel long ago remarked that luminosity is not a necessary property of cosmical bodies. "The visibility of countless stars is no argument against the invisibility of countless others." If this may be true of stars there is no apparent reason why it may not be true also of nebulae. As a matter of fact we have quite definite evidence of the existence of dark objects of both classes and some of the strongest of this evidence is furnished by the novae, or new stars, such as are the subject of the newspaper article to which I referred a little while ago. By a nova is meant a star which suddenly appears in a spot where no star was previously known to exist.[3] In recent years a number of such new stars have been discovered, especially by photography, and in every case they have exhibited quite similar phenomena. The brightness increases enormously in a very short period of time; maximum

[3] In a few instances a nova has been identified with a very faint star known for years before its sudden outburst. Perhaps the best example is the brilliant nova which appeared in the constellation *Aquila* on June 8, 1918, and on the following night rivaled *Sirius* in brightness. The astronomers at the Harvard College Observatory photograph the entire sky on a systematic plan many times each year, and the plates thus secured form an invaluable photographic reference library. An examination of the appropriate plates enabled Professor E. C. Pickering to state at once that the nova had been visible as a faint star (11th magnitude) at least as long ago as May 22, 1888, for it was photographed on that date.

FIG. 1—In Orion (5^h 36.0^m;—2° 27′).

FIG. 2—In Sagittarius (17^h 56.6^m;—27° 50′).

PLATE XLV. DARK NEBULAE.

Photographs by H. D. Curtis, Crossley Reflector.

brightness lasts for a few days or hours only and is followed by a more or less gradual decline which often proceeds to the point of absolute invisibility; and the various stages of its light curve are synchronal with well defined changes in the spectrum. Various explanations of these phenomena have been offered. Certainly a nova is the result of a celestial catastrophe of some kind, but no completely satisfactory explanation of the nature of the catastrophe has so far been found. The most plausible theory (though one not entirely free from objections) is that the outer strata of a dark or nearly dark star rushing through a region of space filled with more or less dense nebulosity are heated to incandescence, the depth of the incandescent strata and the intensity of the consequent luminosity depending upon the degree of resistance encountered by the star. In at least one instance, *Nova Persei* of 1901, we know that the new star was attended by nebulosity which, in appearance, was expanding in all directions from the star. Now this nebulosity was not known before the star's outburst. Possibly it was entirely dark, like the nebula south of *Zeta Orionis,* but not dense enough to manifest itself by contrast, as the latter does; possibly it was feebly luminous and might have been detected had the region been photographed with a suitable telescope and a sufficiently long exposure. But though unknown we are reasonably certain that it existed independently of the star and was not a product of the latter's outburst, for the observed angular velocity, when converted into miles per second on the basis of the minimum possible distance separating us from the star, was so enormous that we cannot believe we were witnessing the actual translation of material particles. Far more reasonable is the hypothesis, first suggested by Kapteyn, that the apparent motion was due to the great wave of light sent out from the star. As this wave reached successive portions of the nebula these

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Several hundred plates of the region taken on later dates show a relatively slight variation in its brightness (about half a magnitude), but it was still approximately of the 11th magnitude on June 3, 1918. Clouds prevented photographs on the next three nights, but on a plate taken on June 7th the star was very much brighter, being of the 6th (photographic) magnitude. Light waves from the sudden great outburst, then, began to reach the Earth sometime between the 3d and 6th of June, so that we know positively that less than six days were required for a 100,000-fold increase in the star's brilliancy (12½ stellar magnitudes). This is the brightest nova known since Kepler's star in *Ophiuchus* which appeared in 1604.

became visible to us, shining by reflected starlight as the Moon shines by reflected sunlight. After the wave passed, each part in succession again became invisible and the effect was that of nebular material moving radially from the star with the velocity of light. *Nova Persei* increased in light fully 60,000-fold (12 magnitudes) in less than five days, and quite rapidly lost a large portion of its light after reaching its maximum; and calculation has shown that when it was at maximum brightness its light was intense enough to affect our photographic plates if reflected from nebulous matter at the distances where this was actually observed. Slipher's recent work, to which I have already referred, affords strong collateral evidence in support of this theory, inasmuch as it gives us instances of other nebulae which are quite probably shining in whole or in part by light reflected from the stars with which they are associated.

The novae are exceedingly interesting objects and might well be made the subject of an independent lecture. Here I can only take time to tell you one or two of the latest news items we have regarding them. Up to July, 1917, 32 novae had become known, the majority of them in comparatively recent years and largely through the comparison of photographic plates. With but three exceptions all of these new stars were situated in the Milky Way; of the exceptional cases one (T *Coronae*) was not a typical nova and the other two appeared in spiral nebulae. Since July, seventeen additional novae have been announced, *fifteen of them in spiral nebulae.*[4]

Now this distribution is a very remarkable one, especially when we recall the fact that several different lines of investigation are leading astronomers to regard with increasing favor the theory that the spirals are not members of our own stellar system but are independent systems, "island universes." That the new stars are actually in the spirals and not between us

[4] The figures for the number of novae have been changed in this paragraph and those following to correspond to the state of our knowledge early in December, 1918. Two novae—*Nova Monocerotis* and *Nova Aquila* No. 3 (see footnote 3)—have been discovered in the Milky Way since the lecture was delivered, and seven in spiral nebulae. It is a remarkable fact that eleven of the seventeen novae now known to have appeared in spiral nebulae have been found in the Great Nebula of *Andromeda,* eight of them appearing in the short interval between July, 1917, and November, 1918.

and the nebulae is beyond question. A single nova might perhaps appear projected upon a nebula to which it did not belong; that seventeen should appear in the line of sight toward some spiral nebula is, as Curtis has remarked, "manifestly beyond the bounds of probability".

These recent discoveries are one result of the intensive study of the spirals which has been in progress at several different observatories in the last few years. It was Ritchey, at the Solar Observatory, who found the first one. A photograph of the spiral known as N. G. C. 6946,* which he secured on July 19, 1917, with the 60-inch reflector, showed a star of 14.6 magnitude that did not exist on plates of the nebula taken in 1910, 1912, 1915 and 1916, some of which showed stars as faint as the 21st magnitude. By August 16th the star had lost more than half of its light and may now be once more too faint to be photographed.

Ritchey's discovery at once set astronomers at work comparing all available photographs of spirals. Curtis at the Lick Observatory promptly added three more novae by his study of the Crossley reflector plates, and Ritchey, Pease, Shapley, Duncan and Sanford at the Solar Observatory have increased the number to fifteen. The apparition period of a nova may be limited to a few months or even to a few weeks and it is easy to see that many novae may have appeared in spirals at times when no photographs were taken. Now that attention has been directed to their relatively frequent occurrence in these objects we may expect the number of such discoveries to increase more rapidly.

It is interesting to note that the new series of novae are all very faint objects as seen from the Earth. On the average they have only reached the 14th magnitude at maximum brightness and at minimum light have certainly fallen below the 21st magnitude in nearly every instance. The Milky Way novae discovered during the last 25 years have attained, at maximum, magnitudes ranging from about —1.4 to +11, the average being about +6, or eight magnitudes brighter than the average for the novae in spirals.

* From its number in Dreyer's *New General Catalogue of Nebulae and Clusters of Stars.*

Let us assume that, on the average, the new stars in the two sets attain the same absolute luminosity at maximum light; then it follows that, on the average, the novae in spirals are at least 40 times as distant as those in our Milky Way. If we take 20,000 light-years as the probable distance for the latter, the former are 800,000 light-years distant. It is obvious from such an argument that the discovery of novae in spirals has a definite bearing upon the theory that the spirals are independent or "island universes".[5] The theory may not be correct, the argument may be fallacious; but it is just such hypotheses and deductions that the astronomer must make. For while it is his first duty, like that of the reporter for the daily press, to gather the facts and describe them accurately, his ultimate purpose, since he is a scientific investigator, is to correlate the newly observed facts with those already known and thus finally discover the natural laws of whose operation the phenomena are the manifestation. Even a false hypothesis may help him toward the truth provided he preserves an open mind and is willing to discard it or to modify it as additional facts may require.

It has been my endeavor in this hour's talk to bring before you a very few of the latest items of news from the stars and by means of them to illustrate the nature of the work upon which the astronomer is engaged. I have had another purpose also, and that is to take your thoughts away, for a short time, from the cares and anxieties of our every-day life. It is with deliberate purpose, too, that I have included in my items several which relate to the stars now visible in our early evening sky, for I hope that you may be led, from time to time, to look up thoughtfully at these stars. If you will do so, I think you will find that, as a recent English writer says, "the stars have a balm for us if we will but be silent," for the "huge and thoughtful night speaks a language simple, august, universal."

"It is one of the minor consolations of the war," continues this writer, who is personally doing his utmost to support his government in the prosecution of the war, "that it has given us in London a chance of hearing that language. The lamps of

[5] See also the notes by Curtis and by Shapley in the *Publ. Astron. Soc. Pac.*, 29, 180, 213, 1917.

PLATE XLVI.

The Great Nebula in Andromeda and the locations of ten Novae discovered at the Solar Observatory. Nova No. 2 is visible on the photograph.

the streets are blotted out, and the lamps above are visible—the great procession of the stars is the most astonishing spectacle offered to men. Emerson said that if we only saw it once in a hundred years we should spend years in preparing for the vision. It is hung out for us every night, and we barely give it a glance. And yet it is well worth glancing at. It is the best corrective for this agitated little mad-house in which we dwell and quarrel and fight and die. It gives us a new scale of measurement and a new order of ideas. Even the war seems only a local affair of some ill-governed asylum in the presence of this ordered march of illimitable worlds."

RECENT PROGRESS IN THE STUDY OF MOTIONS OF BODIES IN THE SOLAR SYSTEM[1]

By Armin O. Leuschner

Introductory Remarks

During the past ten days astronomers all over the world have been startled by the announcement of the discovery of a mysterious object of starlike appearance moving over a degree a day in a northeasterly direction. If the discovery represents a minor planet, of which nearly one thousand are known at the present time, the object would nevertheless be of great importance astronomically because its observed angular motion around the Sun exceeds that of the Earth.

According to Kepler's Harmonic Law the angular motion of bodies moving around the Sun diminishes more rapidly than the distance increases. Minor planets are generally discovered when the Earth is somewhere between them and the Sun, so that the distance of the planet from the Sun is greater than the distance from the Earth. As seen from the Earth, the planet would then in general *appear* to move in the opposite direction, or westward. This motion, known as retrograde motion, is the usual motion of planets when discovered near opposition.

The fact that this object, as seen from the Earth, is moving in an easterly direction nearly a degree a day indicates that its angular motion around the Sun is greater than that of the Earth. This apparently contradicts the Harmonic Law of Kepler, but this law applies merely to the average motion which is uniform in the orbit when the orbit is nearly circular, but if the orbit is very eccentric then the angular motion of a minor planet near perihelion is far greater than near aphelion. Hence if a minor planet moving in a very eccentric orbit is discovered near perihelion a situation such as is presented by the mysterious object recently discovered might exist.

[1] Delivered February 15, 1918.

The observed position and motion of the object therefore at once lead to the conclusion that it is moving in a highly eccentric orbit. The possibility of the object being a tiny moon revolving around the Earth is excluded by the fact that its motion then would have to be approximately in a great circle of the celestial sphere, but this is contradicted by the observations. The choice therefore lies between a minor planet moving in an unusually eccentric orbit and discovered near perihelion, and a comet of a very unusual appearance. Comets usually move in highly eccentric ellipses, but even if they have a starlike appearance, the larger telescopes readily identify them as comets by the nebulosity which surrounds them. The discoverer evidently was not able to commit himself as to the nature of the object and it has therefore been announced under the general designation "Object Wolf".

It is not the first time, however, that a comet has been discovered with a distinctly stellar appearance. In 1913 such a comet was discovered by Neujmin in Russia, and was designated for some time as an "object" until the discovery with larger telescopes of nebulosity surrounding it, and the calculation of the orbit definitely placed it in the class of comets.

The first telegram announcing the discovery of the Wolf object was received in America a week ago (February 7, 1918). The original telegram contained two approximate photographic positions obtained on February 3 and 4. On Monday, February 11, another cable was received giving the third and accurate position of the object. As the first observations are generally secured in haste, so as to make sure that sufficient data shall be available for the necessary calculations, errors in observation occur frequently. These errors naturally are a source of unnecessary labor and annoyance to the investigator of the orbit.

Since the first two European observations were only approximate, giving the position merely to the nearest minute of arc, some hesitancy was felt in attacking the problem. But the second telegram contained further announcement of such a character that the object became even of greater interest, for it stated that revolving about the object was another considerably fainter object at a distance of 340 seconds of arc as seen from the Earth, and revolving about it at the rate of 13 degrees an hour, so that the complete revolution would be made by the satellite in about 36 hours. In spite of the meager data an attempt was therefore made to learn something about the general character of the orbit. The computation was undertaken by Professor R. T. Crawford and Mr. H. M. Jeffers. They soon found that the problem did not admit of a solution. In other words, no object could exist moving in the manner in which the observations indicated. The only other alternative would be that one of the observations was seriously in error.

While an attempt was under way to locate a possible error, a telegram was received from Director Campbell informing us that Dr. H. D. Curtis had photographed the object with the Crossley reflector, and had accurately measured its position. Tabulation of the now available four positions (the European positions being taken on February 3, 4 and 5, and the Mount Hamilton position on February 11) enabled us to suspect that the first European right ascension might be in error. Mr. Jeffers made a new solution on the basis of numerical data which I readily estimated from the observations. Such a solution may be made in two ways—either with or without previous assumption regarding the nature of the orbit. Since comets usually move in highly eccentric orbits which are not very different from parabolas, it is customary to assume the orbit to be parabolic. Mr. Jeffers made an approximate general solution and found that the object moved in a pronounced hyperbola, but astronomical experience teaches us that there is no object in existence which moves in a pronounced hyperbola. Again we seemed to be confronted with something impossible, but Mr. Jeffers, who was performing the calculation, correctly concluded that the hyperbola was merely a result of the uncertainty of solution. Such uncertainty may be removed by making a conditioned solution assuming the orbit to be a parabola. The resulting orbit fitted all four available observations with the exception of the first European right ascension which had been suspected to be in error.

An American astronomer reported that on a photograph the object appeared to be surrounded by a slight nebulosity. The approximate orbit and the reported nebulosity point to the possibility that the object may be a comet. But there still exists the possibility that the parabolic orbit is merely an approximation to a highly eccentric ellipse, which can be derived only on the basis of more accurate observations to be secured within the next few days.

In the meantime we must await developments. These recent experiences illustrate the first stages of an orbit investigation and serve to show how much the investigator of the orbit depends upon accurate observations for a satisfactory result of his work.[2]

LECTURE[3]

The study of motions of bodies of the solar system, like the object just referred to, is based on Newton's law of gravitation. This law states that every particle of matter in the universe attracts every other particle of matter with a force which is proportional to the product of their masses, and inversely proportional to the square of their distance. This means that if two bodies, each as massive as the Sun, and at a distance apart which equals the distance of the Earth from the Sun, attract each other with a certain force, then two similar bodies at twice the distance attract each other with one-fourth the force; at three times the distance with one-ninth the force. Further, if one of the bodies be replaced by a body one-half as massive as the Sun, then the force is one-half; if one body is one-third as massive and the other one-fourth, then the force will be one-twelfth. This law of gravitation, together with three axioms or laws of motion announced by Newton in 1686, which we need not consider here, have served for the interpretation of the motions of bodies to the present day, not only in the solar system but in the universe at large. It may therefore be called the law of universal gravitation.

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[2] Later observations did not confirm the existence of nebulosity, nor of the satellite, and one of the observations which produced a parabola was found to be defective. The object has turned out to be a minor planet moving in an elliptic orbit of greater eccentricity than that of any other known planet.

[3] Delivered in substance also at the University of California, March 23, 1915, as the Faculty Research Lecture for the year 1914-15.

The law of gravitation is probably not the ultimate statement of force operating in the universe, but merely an aspect of the same. The ultimate statement must include other phenomena, such as the pressure of light established in physics and supposed to be effective on the minute particles of a comet's tail, and electro-magnetic phenomena. We are not concerned with these phenomena in the study of the motions of planets, satellites and the nuclei of comets in our solar system. And yet there exist certain apparently unexplained discrepancies of motion of massive bodies which have cast doubt on the absolute correctness of Newton's law. It may be said with certainty that in spite of all that has been written to the contrary, these discrepancies present no evidence that Newton's law of gravitation requires correction, for the discrepancies referred to are constantly being diminished by a more rigid and comprehensive mathematical translation of the law into motion and by more perfect numerical methods. Such improvements as have been made in recent years by Newcomb and Brown in the interpretation of the motion of the Moon, inspire us with confidence that ultimately all remaining discrepancies will be conquered on the basis of Newton's law.

At any rate until every possible mathematical device in the application of Newton's law has been exhausted, we must accept its formulation as sufficient for the complete explanation of the motion of massive bodies.

The process of translating the law of gravitation into motion has challenged and is still challenging the highest mathematical ingenuity. The translation, as far as it has been accomplished, teaches us that the apparently irregular motions of the bodies as seen from the Earth are controlled by beautiful and harmonious laws, and these laws enable us to determine the past and future motion of individual bodies and thus to interpret the solar system as a whole.

As stated before, according to Newton's law, every particle of matter attracts every other particle of matter with a force determined by their masses and mutual distances. Let us take the case of only two masses; and, in order to simplify our consideration still further, let us consider a comet or a minor planet (asteroid) moving about the Sun as a primary, or a satellite (moon) moving about a planet as its primary. The mass of the comet, asteroid, or satellite is negligible, and we are concerned only with the mass of the primary. These are the simplest cases of the so-called problem of two bodies. The translation of Newton's law into motion for the two-body problem has been fully accomplished by Newton and has resulted in the mathematical demonstration of certain laws, which had previously been stated in a somewhat imperfect form by Kepler, who had evaluated them as the result of a lifetime of guesses.

These results of the translation of Newton's law into motion tell us that each planet, comet, or satellite moving solely under the attraction of its primary, moves in its own plane, from which it never can depart; that this plane passes through the center of the primary; that each describes about the primary a curve known in mathematics as a conic section, which may be a circle, or an ellipse, or a parabola, or an hyperbola; that whatever may be the conic, the line (radius vector) joining body and primary describes equal areas in equal times; finally, that the time (period) of revolution about the Sun in the circle or ellipse depends solely on the semi-major axis of the conic, in such a way that the square of the period expressed in years is numerically equal to the cube of the distance expressed in astronomical units of length, which unit is the distance of the Earth from the Sun. When, therefore, the semi-major axis of an ellipse or the radius of the circle is given, the period in years becomes known at once. If we divide the circumference of 360° by the number of days in the period we obtain the average angle described about the Sun in one day, which is called the mean daily motion μ, usually expressed in seconds of arc.

These are the harmonious and orderly laws that reveal themselves from the translation of Newton's law into motion in the simple case of the problem of two bodies. Mathematicians have not as yet accomplished the complete translation into motion and the discovery of all of the corresponding harmonious laws in the case of three or more bodies mutually attracting one another.

Interpreted in another way, the translation of Newton's law into motion in the case of two bodies reveals the fact that the path of a body is fully described by what may be termed distinct and independent earmarks, which are called elements, and these earmarks or elements, six in number, depend on certain initial conditions. If we assume as initial conditions that at a given instant a body is in a certain position with respect to the Sun and that it is projected in a given direction with a given speed, then these initial conditions, namely, position and velocity, will fully determine the numerical values of the six earmarks or elements of the orbit. A position is mathematically expressed by three numbers, or coördinates,

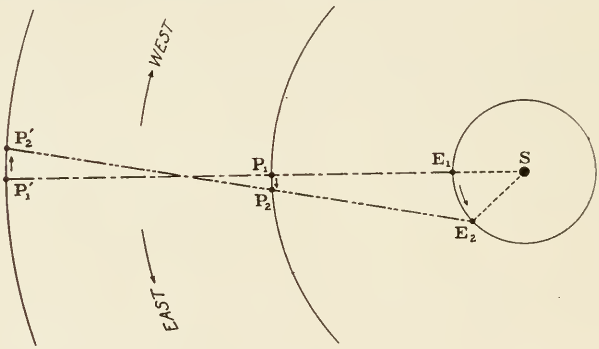

FIG. 11. THE APPARENT RETROGRADE MOTION OF A MINOR PLANET NEAR OPPOSITION.

and the magnitude and direction of velocity are expressed by three other numbers. These six initial numbers determine the numerical values of the six earmarks or elements which result from the translation of Newton's law into motion. Thus we see that six known numbers or conditions lead us to the six elements or earmarks, and when these initial conditions, whatever they may be, are accurately given, then the orbit of the body as described by its elements becomes very accurately known, and we are enabled to trace the past and future motion of the body, and thus the past and future of the system as a whole, provided that for the present we restrict ourselves to the two-body problem. These matters will appear a little clearer from the diagrams and tables which we shall now discuss.

Figure 11 shows the Earth and a minor planet in two corresponding positions E_1, P_1 and E_2, P_2 in their respective orbits with reference to the Sun S. Both move in an easterly direction approximately in circles. For each of these two bodies the cube of the distance from the Sun expressed in astronomical units is equal to the square of its period of revolution expressed in years. The easterly or direct motion of the planet around the Sun is therefore less rapid than that of the Earth. In the first position planet and Sun are on opposite sides of the Earth and the planet is said to be in opposition. P_1 is seen from E_1 in the position P_1' on the celestial sphere. P_2 is seen from E_2 at P_2', which is west of P_1'. As seen from the Earth a planet near opposition moving in a nearly circular orbit appears to be moving westward or in a retrograde direction.

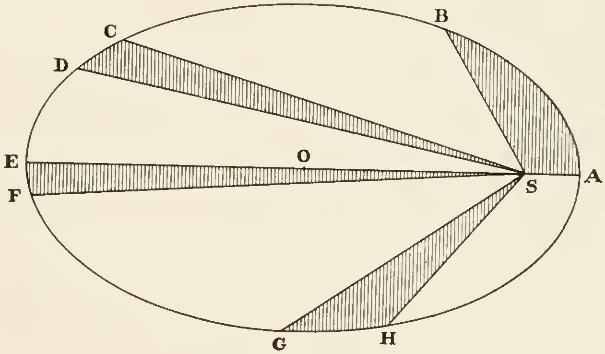

FIG. 12. THE LAW OF EQUAL AREAS IN ELLIPTIC MOTION.

Figure 12 shows an ellipse. The shaded sectors illustrate the law that equal sector areas are described in equal times. The shaded areas are supposed to be equal. It takes the body just as long to move in its curve from A to B as from C to D, from E to F, and from G to H. At A when it is near to the Sun at perihelion its angular motion around the Sun S is therefore much more rapid than when it is far away from the Sun at aphelion. The areas of two successive sectors of the conic are proportional to the times which it takes to describe them. But the ratios of the areas of triangles contained between three successive radii vectores, which form an important part in our discussion, are approximately proportional to the intervals only if these intervals are comparatively small. The distance from S to A is called the perihelion distance (q), because at A the body passes around the Sun. The distance from the center to either vertex is called the semi-major axis. The Sun is at the focus S of the ellipse. The distance of S from the center O divided by the semi-major axis is called the eccentricity, or the amount that the Sun is out of center. The size of the ellipse depends upon the major

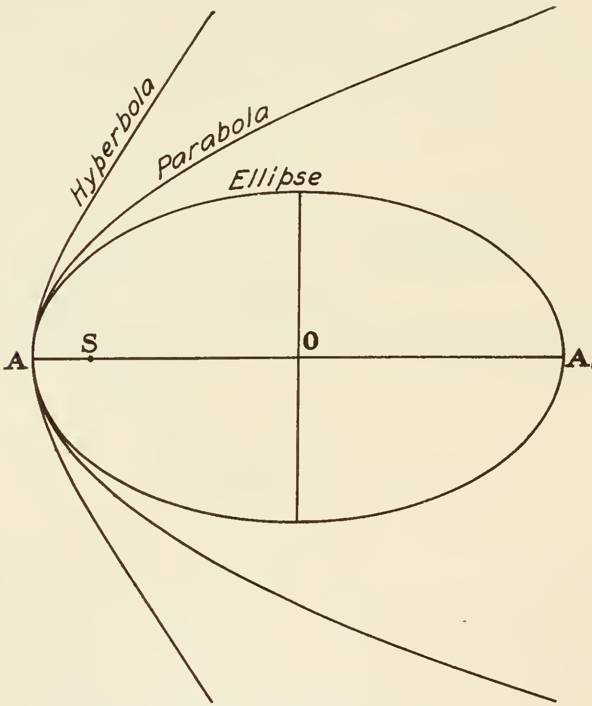

FIG. 13. ELLIPSE, PARABOLA AND HYPERBOLA.

axis, but its shape, whether circular or flat, depends upon the eccentricity. The semi-major axis and the eccentricity form two of the earmarks or elements of the orbit. For the ellipse the eccentricity is less, for the hyperbola greater than unity, for the circle it is zero and for the parabola exactly unity.

Figure 13 shows an ellipse, a parabola, and an hyperbola. The ellipse, as we saw before, is closed. The parabola is a limiting ellipse, which is closed at infinity. The period of a revolution of a body moving in a parabola is infinite, and therefore such a body after visiting the Sun will return only after an infinite time, or not at all. The hyperbola also is a curve which passes off to infinity, so that a body moving in it will never return. It is clear at once that bodies moving in parabolas or hyperbolas might be considered as visitors from outer space, which after revolving around the Sun again disappear into space. Whether a body will describe an ellipse or a parabola or a hyperbola depends upon the initial conditions referred to before, namely, on its position and velocity at a given time.

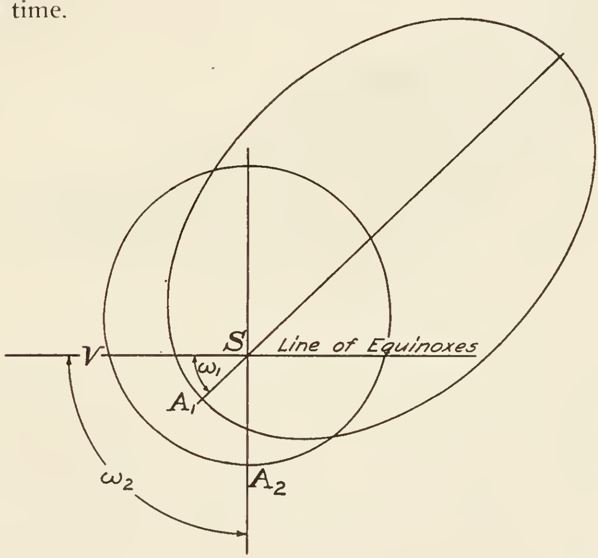

Fig. 14. Two Ellipses, Showing How the Angle ω Defines the Position of an Orbit in Its Own Plane.

Figure 14 exhibits two ellipses. The axes lie in different directions with reference to the horizontal line. The angle between a fixed reference line and the axis is another earmark of the orbit. It tells us how the orbit lies in its own plane. The fourth earmark is given by the date of perihelion passage. These earmarks are expressed by symbols in astronomy as follows: the semi-major axis by the letter a; the eccentricity by the letter e; the angle which the semi-major axis makes with the reference line, usually the line of nodes, to be defined presently, by the Greek letter ω; the time of perihelion passage by T. With these four earmarks and with the aid of Kepler's improved laws it is possible to determine the position of the body in its orbit at any given time. In place of a we may choose the period P or the mean motion μ as the first element. For a parabola the perihelion distance q is chosen as element in place of the infinite semi-major axis. It remains to determine the position of the body in space.

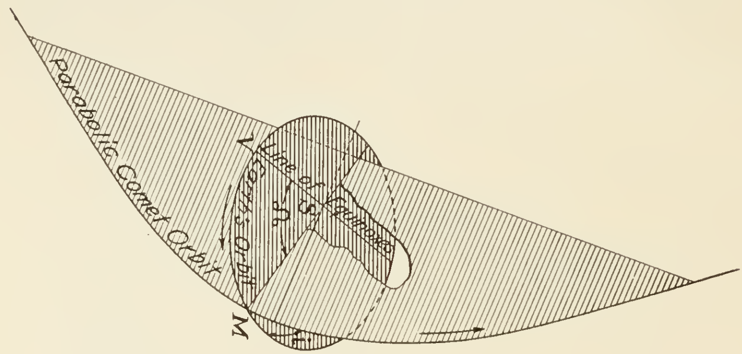

FIG. 15. THE ORBIT OF THE EARTH AND OF A COMET.

In Figure 15 we see the Earth's orbit. Its plane may be taken as a reference plane. Then we see the plane of the orbit of a comet which in this case is a parabola. The orbit planes intersect in a straight line called the line of nodes and at a given angle. The point where the comet crosses the ecliptic from south to north is called the ascending node. The angular distance of the node from some fixed point in the Earth's orbit, generally the Vernal Equinox, V, is designated by the Greek letter Ω, while the angle of inclination is designated by the letter i. These six elements or earmarks are the numerical characteristics or constants which distinguish the orbits of different bodies, according to Kepler's and Newton's laws.

The accuracy with which the numerical values of the elements can be calculated depends not only on the accuracy of the given initial conditions, but also on a number of other factors. What are these given conditions, in practice? They were stated before in terms of the position and velocity of the body with reference to the Sun at a given time, but these initial conditions cannot be known at first hand.

When a new object is discovered, it is observed from the Earth, which itself is in motion around the Sun. At a particular instant it is seen projected on the sky in a certain direction. Nothing is known about its distance either from the Earth or from the Sun. Its position on the celestial sphere is defined exactly as a point is defined on the Earth in geography. On the Earth we locate a point by its geographical longitude and latitude. Two similar arcs or angles (spherical coördinates) are used to locate the point at which the body is seen on the celestial sphere. Referred to the celestial equator they are called right ascension (α) and declination (δ) instead of longitude and latitude. Every observation of direction thus gives us two angles, an α and a δ, or in our former language, two initial conditions. Our translation of the law of gravitation into motion has shown us that we need six of these conditions. Therefore the body must be observed at least at three different times to furnish the necessary initial conditions for the determination of the elements.

The process of transforming observed positions (α, δ) into elements is called an orbit method.

In the problem of two bodies, we are dealing with two distinct aspects of the study of motion. The one is the symbolic mathematical translation of Newton, demonstrating Kepler's laws without numerical calculation, which reveals the general laws of motion and the geometrical nature of the elements. The other is the derivation of orbit methods and the numerical calculation of the elements of the orbit. In the case of the two-body problem the mathematical derivation of the general laws from the law of gravitation is comparatively easy, but the derivation of the elements of an orbit from observed conditions, such as right ascensions and declinations, involves enormous mathematical intricacies.

The foregoing statement brings us to state the subject of our present discourse. We shall be concerned this evening with some considerations regarding improvements accomplished in the methods of orbit determination and we shall illustrate our methods by the results of recent applications at the Students' Observatory of the University of California.

The significant fact about all of the methods so far in general use is that they are indirect. Since the distances of the observed object from the Earth or the Sun are unknown at the outset, an assumption regarding them is made in the older methods. A further assumption consists in considering the ratios of the triangular areas referred to above proportional to the corresponding intervals. With these assumptions elements are determined numerically. As a check the positions are then computed from the elements for the dates of observation. If the computed do not check with the observed positions, new assumptions are made and the approximations are kept up until the problem is satisfactorily solved. Therein consists the indirectness of the methods.

Following certain principles originated by Laplace, certain direct methods have now been devised which are practically free from assumptions and which admit of the determination of the distances by direct computation, and thus also lead directly to the desired results. It is, of course, impossible to go into the details of the principles of these methods, but we may briefly summarize what they accomplish as follows:

We can perform a very simple general solution without the previously customary assumption regarding the nature of the conic or regarding the nature of the object, whether in doubtful cases it is a comet or a planet or a satellite. When any kind of an assumption is made the solution is called a conditioned solution. But if warranted we may follow the traditional method of assuming the orbit to be a parabola or a circle or an ellipse of assumed period, and we may then test the feasibility of the assumption in the course of the solution. The distance of the body from the Earth is found by direct computation. In a conditioned solution a simple geometrical device furnishes this geocentric distance, and in a general solution its accurate value is taken from a table. The moment the distance is known the solution for the elements becomes comparatively simple. New mathematical expressions make the solution possible in many cases where the older methods fail. The numerical accuracy of the results may be determined in advance. When a number of mathematical solutions arise it is now possible to discriminate the orbit in which the body actually moves. The new formulae admit of the transition from a general to a conditioned solution without much extra labor, while in the older methods a change of assumption regarding the nature of the conic requires an entirely new process of computation. The effects of displacement of the observed body as seen from different points on the Earth (parallax) is readily overcome. Immediate account may be taken of the attractions of other bodies besides the Sun.

The earlier orbit methods for the two-body motion are based on Newton's previous translation of his law into motion, resulting in the perfection of Kepler's laws, with the consequent definition of the elements. This analytical solution was thereafter applied without due consideration of the conditions of individual cases. Prejudiced by the fact that in the two-body problem the analytical solution preceded the derivation of orbit methods, astronomers have held that it would not be possible to accomplish a direct solution of the orbit of a body moving simultaneously under the attraction of more than one mass, as of *Jupiter* and the Sun, such as is the case with the 6th, 7th, 8th and 9th satellites of *Jupiter* discovered within recent years, until the translation of Newton's laws into motion should have been accomplished for three or more bodies moving under their mutual attractions. The orbit computations made elsewhere on the 6th, 7th and 8th satellites of *Jupiter,* and on the 9th satellite of *Saturn,* were based on a very large number of observations extending over several months, and involved months of extraordinary labor. Even then the investigators stated that inasmuch as no method existed for the solution of cases of this sort, the determination of the orbits was almost impossible. It was accomplished finally only by varying assumptions regarding one or more of the elements and making the others fit the observations.

Without attempting to go into the history of the derivation of the new methods of handling these cases, it may suffice to state that in order to determine the orbit of a body moving under the attraction of a major planet and of the Sun, it is not necessary to wait for the mathematical translation of

Newton's law into motion for three or more bodies which has not as yet been accomplished. On the contrary it has been possible to derive a method whereby accurate results may be obtained with comparatively little trouble from only three or perhaps five observations taken at limited intervals of a few days. It is thereby possible to preserve a discovery on the basis of scant observational material before the body may disappear. These advances will be illustrated by means of results obtained at Berkeley in recent years.

Immediately following the discovery of a new object, it is of prime importance to predict its motion for the immediate future from the first three available observations, generally secured in different parts of the world and transmitted by telegraph. For this purpose preliminary elements are calculated first from the observed α and δ, and then positions (α, δ) are computed from the elements at equidistant dates following the observation. The tabulated values of the positions (α, δ) form an ephemeris, which together with the elements is distributed by telegraph all over the world so that observers may locate and observe the body. The accuracy of the predicted ephemeris depends on the accuracy of the elements from which it is computed. The constant aim of theoretical astronomers is to devise and employ orbit methods which yield the most accurate results from observations made in quick succession, even less than a day apart, with the least expenditure of time in calculation. In any orbit method the accuracy of the elements increases of course with the length of time that the body has been under observation and with the accuracy of the observations. If one orbit method yields from a short arc elements and an ephemeris comparable in accuracy with results requiring a longer arc in another method, then the former method becomes more satisfactory than the latter. Comparisons of many orbits computed at Berkeley with those derived by older methods elsewhere lead inevitably to the conclusion that the Berkeley results are more satisfactory. A typical case is exhibited in Table 1. In this table the differences ΔT, $\Delta\omega$, etc., of the elements T, ω, etc., of Comet *d* 1907 (Daniel), from the best available elements, in this case by Kritzinger from an arc of 74 days, are given, to show how

TABLE 1.—COMET *d* 1907 (DANIEL)

THE ORBIT OF REFERENCE IS THAT OF KRITZINGER FROM A 74-DAY ARC. *A. N.* **176** 15.

No.	ΔT	Δω	ΔΩ	Δ*i*	Δ log. *q*	Arc	Computer	Reference
I	+ 1.97 d	+52° 23′	— 0° 39′	+ 2° 43′	—0.4047	3 days	STRÖMGREN	*A. N.* **175** 155
II	+ **0.18**	+ **0 25**	**0 0**	— **0 11**	+**0.0052**	**6 days**	**Crawford Einarsson Glancy**	*L. O. B.* **No. 119**
III	— 5.43	+14 59	— 0 22	+ 1 4	—0.1574	8 days	STRÖMGREN	*A. N.* **175** 191
IV	— 0.29	+ 0 32	0 0	+ 0 2	—0.0062	19 days	KRITZINGER	*A. N.* **175** 259
V	— 0.04	+ 0 7	+ 0 2	+ 0 1	—0.0016	27 days	DYBECK	*A. N.* **175** 307

Orbit (II) computed at Berkeley from a 6-day arc is considerably better than orbit (III) from an 8-day arc and slightly better than (IV) from a 19-day arc. Improvement is found in orbit (V) from a 27-day arc. Another orbit, not given here, by Millosevich from a 67-day arc is practically the same as the orbit of reference.

close various preliminary orbits computed from short arcs, observations taken a few days apart, approach the best orbit finally available for reference.

In another case, Comet *e* 1909 (Daniel), a European astronomer, employing the older orbit methods, required an arc of 37 days to obtain as accurate an ellipse as that obtained by Messrs. S. Einarsson and R. K. Young at Berkeley from a 7-day arc, while other investigators were still satisfied with a parabola from a similar arc. In still another case a European astronomer, after computing several orbits for Comet *b* 1910 (Metcalf) from arcs of increasing length, finally, by the use of an arc of 37 days, reproduced the Berkeley results obtained by Mr. Young from a 2-day arc.

A very interesting case is that of Comet *e* 1910 (Cerulli-Faye). This comet was discovered by Cerulli in Italy, and first observed November 9 at Rome. In addition two other observations at 2-day intervals were available. The usual direct solution for a parabola by Mr. W. F. Meyer and Miss Sophia H. Levy at Berkeley gave elements which showed some similarity to those of Comet Faye, which had been considered lost. At the time of the discovery of the Cerulli comet the lost comet Faye was an object of intense interest to the astronomical world for the reason that astronomers failed to find it in its predicted place in 1903. The comet was originally discovered by Faye in 1843, and was observed in seven successive returns, until 1896, its period of revolution being about seven and a half years. A very accurate orbit had been derived on the basis of the observations of its first four appearances up to 1866, by taking into account the disturbing attractions of the major planets of the solar system. It had been found later, at every return following 1866 up to 1896, by bringing forward the earlier calculations, but without taking account of the disturbing action of the major planets. Between 1896 and 1903, when it was again due, it passed close to *Jupiter* and suffered considerable change of motion. Predictions for 1903 placed it in an unfavorable position for observation. In spite of exhaustive search on the part of many astronomers it could not be located. The fate of this comet aroused considerable interest. It was thought that it might have suffered the fate of Biela's comet, which is supposed to have disintegrated into a swarm of meteors. Its fate was all the more puzzling because it had been observed at eight different returns, and the numerous observations taken at these appearances ought to have led to a very accurate determination of the orbit and an exact prediction of its position if the disturbing actions of the major planets were carefully taken into account. A calculation of these predictions, however, is an enormous task and may require years of labor.

The importance of the question prompted the Royal Academy of Sciences of Denmark in 1906 to announce to the astronomical world the competitive problem, "To study in detail the orbit of the periodic comet Faye on the strict basis of the observations taken between 1873 and 1896". A prize of four hundred crowns was to be awarded to the investigator whose calculations should lead to the rediscovery of the comet which again was due in 1910. This was the situation when it was recognized at Berkeley that the parabolic elements of Cerulli's comet bore such a close resemblance to those of the lost comet that the identity seemed probable. Since the original parabolic solution could be at once modified into a general solution without hypothesis as to the eccentricity of the orbit, and since our methods enable us to form a fairly reliable opinion as to the accuracy of a general solution, this general solution was undertaken by Mr. Meyer and Miss Levy, and resulted in elements which were so nearly identical with those of the lost Faye comet that announcement could be made without hesitation that the new comet discovered by Cerulli was identical with the supposedly lost Comet Faye. The solution of the competitive problem will be unnecessary for the time being.

The adoption of the periodic orbit in this case, based on a general solution from a very short arc, was justified by the important innovation of determining the possible limits of the period from the observations.

In September, 1913, the Russian astronomer Neujmin announced the discovery of a starlike object which had the appearance of a minor planet. Later, after careful observation with large telescopes, the object was found to be a comet. The starlike appearance of this comet gives rise to the suspicion that some of the objects which have been announced as asteroids and for which orbits have been computed on the elliptic hypothesis with very uncertain results, may after all be comets moving in nearly parabolic orbits, which would account for the fact that they have never been observed again. It will be an interesting problem to run down these cases which have given rise to much theoretical speculation, and thereby to solve many a mystery existing in regard to the motion of these bodies. Comet Neujmin being of a starlike appearance admitted of a high degree of accuracy in the observed positions. When, therefore, on the basis of the usual parabolic hypothesis, we found so slight a discrepancy as 13″ in the representation of one of the observations, we felt confident that this discrepancy, however slight, could be accounted for only by the fact that the object was moving in a decidedly elliptic orbit. A transition was then made by Messrs. Einarsson and Nicholson to a general solution, which resulted in the first orbit seen in Table 2. Later, on the basis of a longer arc extending from September 9 to October 17, or 38 days, a more exact orbit could be determined, which was found to be in remarkable agreement with our first results from 1-day intervals.

Table 2.—Comet *c* 1913 (Object Neujmin).

Sept. 6, 7, 8.				Sept. 9, 22, Oct. 17.			
ω	348°	53.8′		ω	346°	13′	16.8″
Ω	347	57.5		Ω	347	53	55.5
i	15	6.3		i	14	50	45.2
Φ	50	22.4		Φ	50	53	41.1
μ	203.40″			μ	199.001″		

The announcement of a periodic orbit from 1-day intervals created considerable doubt as to the correctness of our conclusions. This is the first time in the history of astronomy that such a result has been obtained from so short an arc. It has been the custom, and it is still customary as a rule in astronomical circles, to adhere to the hypothetical parabola until the disagreement between observations and predictions becomes so striking that astronomers are forced to depart from the parabola. The preliminary daily motion of 203″ differed only by 4″ from the final value, 199″. European astronomers published results as follows: From the same dates, a parabola which was accepted in preference to our ellipse; from September 6, 8, 11, or a 5-day arc, another astronomer derived a mean motion of 390″; from September 6, 8, 12, or a 6-day arc, another astronomer a mean motion of 376″; and finally another astronomer, by extending the observations from September 6 to October 9, or 33 days, obtained the result of 195″, which was comparable in accuracy with that obtained at Berkeley from the first three observations.

Comet *a* 1910, discovered January 16, 1910, in South Africa, created intense interest by its great brilliancy, rivaling that of Halley's Comet. Owing to its brightness orbits were computed by many astronomers, but the results differed so enormously as to attract profound attention in the astronomical world. At Berkeley, unfortunately, the usual plan of calculating a preliminary orbit could not be adhered to, because it had been arranged with the Lick Observatory that the attention of the astronomers there should be given to spectroscopic observations, since it was thought that on account of its brightness the comet would be so frequently observed elsewhere that abundant observations would be telegraphed. But none were received, and at Berkeley the comet was hidden from the range of the instruments by trees surrounding the observatory. When the widely discrepant orbit computations became known, Dr. Curtis secured three photographic positions for us at the Lick Observatory, which yielded the correct orbit without difficulty, the calculations being made by Mr. Meyer and Miss Levy.

Professor Tscherny of Warsaw, Russian Poland, the city about which much has been heard during the war, recognized that there was some system in the discrepancies of the orbits in that they could be arranged into three groups in which the individual orbits were fairly consistent. He at once suspected the reoccurrence of a phenomenon noted only once before in the history of astronomy, namely, that the mathematical solution of the orbit might give three distinct parabolas, different computers having obtained one or another of the three possibilities. Theoretically, the possibility of a triple parabolic solution had been previously established by the astronomer Oppolzer, but no method of deciding in which of the three orbits the body actually moved was available. It was supposed that this question could be settled only on the basis of continued observation. At the time of discovery of this comet we had in press a simple method of ascertaining whether a single or triple parabolic solution was possible in a given case with a test whereby without further observations it could be decided which of the three orbits was the true one. If this paper had been off the press at the time of the discovery of Comet *a* 1910, astronomers might have been saved much trouble. Hereafter, in a case of triple parabolic solution the correct physical solution may readily be ascertained.

The method of eliminating the two purely mathematical solutions in the case of a triple solution is so simple that I cannot refrain from stating it briefly. It can be shown that when the body is supposed to move in a parabola there can be either one or three, but not two, parabolic solutions for the geocentric distance of the comet. If one of the mathematical parabolic solutions is the correct physical solution, within the limits of accuracy attainable for the orbit, that particular parabola should also reveal itself by making a general solution without parabolic assumption. It can be shown that there can be one or two, but not three, general solutions for the geocentric distance. Hence only one of the parabolic solutions can agree with the general solution within the accuracy of the calculation. All the computer has to do then is to get the three approximate parabolic geocentric distances, which is done by an easy geometrical device, to compare the same with the two general solutions to be taken from a special table of geocentric distances, and to select that parabolic geocentric distance which is consistent with a geocentric distance from the general solution. If none of the parabolic solutions is consistent with a general solution, then all three must be rejected and a general solution must be adopted as in the case of Faye's comet. This process is exhibited in Table 3 for Comet *a* 1910 from computations by Miss Levy.

Table 3.—Multiple Orbit Solutions for the Geocentric Distance of Comet *a* 1910.

(In astronomical units.)

Parabolic Solutions

(1) 1.02 (2) 0.86 (3) 0.63

Tabular General Solutions.

(1) 1.09 (2) 0.88

With regard to the uncertainty of the solutions, there is agreement only between the second parabolic solution, for which the geocentric distance = 0.86, and the second general solution, for which the geocentric distance = 0.88. The difference 0.02 is comparable with the computed uncertainty of the general solution. Both of the other parabolic solutions are therefore to be discarded.

It is now possible to determine the correct periodic orbit in a variety of ways, while adherence to the older methods might result in an erroneous parabolic orbit. In Table 4 we have a case for which, on the basis of an intermediate orbit so chosen from a previous approximate knowledge of the orbit as to actually represent the second observed position, the discrepancies or residuals, $\Delta\alpha$, $\Delta\delta$, between the observed (O) and computed (C) positions are distributed over the first and third observed places. By a process of differential correction the intermediate orbit may be improved so as to produce a perfect agreement between observed and calculated positions. In making this improvement we may make a conditioned solution on the basis of a parabolic hypothesis, or we may make a general solution. When a conditioned solution is made the computation can be arranged in such a way that if the parabola is not the true orbit this fact shall reveal itself by an exorbitant disagreement in one of the coördinates, as for instance the first declination. In the table it is shown that the parabolic hypothesis leaves an intolerable discrepancy of more than 11′ in the first declination, so that this hypothesis must be rejected. The solution was then completed by Professor Crawford and Mr. A. J. Champreux without hypothesis and resulted in an ellipse with a period of 6⅔ years, which satisfied observations exactly.

Table 4.—Differential Correction of Orbit of Comet *e* 1906 (Kopff).
Dates of Observation.
(I) August 24, (II) September 5, (III) September 15.

Residuals of Intermediate Orbit.

		I.	III.
(O—C)	$\Delta\alpha$	— 4′ 23.5″	+0′ 20.0″
	$\Delta\delta$	— 5 54.1	—3 40.7

Residuals After Differential Correction on Parabolic Hypothesis.

		I.	III.
(O—C)	$\Delta\alpha$	— 0′ 39.3″	+0′ 4.1″
	$\Delta\delta$	—11 49.7	—0 30.7

For the general solution, eccentricity = 0.52, period = 6⅔ years.

A preliminary orbit of Comet *b* 1912, discovered by Schaumasse, was calculated by Fayet at Nice before the observations necessary for a computation had reached Berkeley. Fayet announced a similarity of the parabolic elements with those of Tuttle's comet, which had appeared 13½ years previously. A new process, in the nature of a conditioned solution, was then applied by us. The interval between the perihelion passages of the two comets which are suspected to be identical is assumed to be a multiple of the period. In order to test this new principle, a general solution without hypothesis, such as was made for the Neujmin comet, was also applied. A remarkable condition was found to exist. The first three observations made on October 21, 22 and 23 could be satisfied by any kind of an orbit from a circle to a parabola. If the new principle had the practical value that the theory showed it to possess, then a conditioned solution of the orbit of Schaumasse's comet, on the basis of the actual period of 13.7 years of Tuttle's comet, should bring the new elements into close agreement with those of Tuttle's. This was actually found to be the case, while neither a parabolic nor a general solution could have confirmed the identity of the two comets from so short an arc. The introduction of this principle was all the more important for this comet because an attempt to reproduce the position of the new comet from the orbit of Tuttle's comet resulted in a discrepancy of 80° in the position. This discrepancy was due partly to perturbations which Tuttle's comet had suffered in the meantime, and partly to the relative positions of Sun, comet and Earth, which aggravated any displacement with reference to the Sun when viewed from the Earth. The interval between the dates of periheleon passage in 1899 and 1912 corresponded to an average mean motion of 263″. Later Fayet calculated the effect of pertubations on the original mean motion of 269.6″, and found this effect to change it to 264″, in close agreement with the value we had obtained by our principle of identification without performing the computation of the perturbations. The computations in this case were made by Miss A. E. Glancy and Miss Levy.

A similar case is that of Comet *d* 1913 (Delavan). The identity of this comet with Comet 1852 IV (Westphal) was suspected by the discoverer. It was at once confirmed by our calculations, and an exact period determined. Comet Westphal was observed for nearly six months after July 4, 1852, and Hnatek of Vienna made a very careful study of the orbit from all available observations. He found that the period of revolution could not be determined with great accuracy, and therefore made predictions for the return on the assumption of different periods. His latest prediction was confined to periods between 61.0 and 61.3 years. These predictions were made to aid in the search for the comet in 1913. The comet, however, was not discovered from the predictions, but it was identified with their aid. The area of the sky in which the comet might be looked for toward the end of September of the year of discovery, according to the assumed periods, extended nearly 90° by 115°. Even the difference of period between 61.1 and 61.2 years placed the comet anywhere within an area of 15° by 40°. The new comet was discovered within that area. and therefore was suspected to be identical with the Westphal comet. From the position and motion given by the first two observations and with the aid of Hnatek's ephemerides Mr. S. B. Nicholson and Miss Anna Kidder established the period to be 61.121 years. With this adopted period the new principle of conditioned solution, on the basis of an adopted period, was applied as in the case of Comet Schaumasse-Tuttle, with results which left no doubt as to the identity of the Westphal and Delavan comets.

Table 6 shows the close agreement of the orbit of Comet Delavan computed from observations made on September 27 and 30 and October 4 with the elements of Comet Westphal.

Table 6.—Orbits of Comets Delavan and Westphal.
1913, September 27, 30, October 4.

	Comet Westphal.		Comet Delavan.	
T	1852 Oct. 12. 4731 Gr. M. T.		1913 Nov. 26. 1067 Gr. M. T.	
ω	57° 02′ 13″	1913.0	56° 31′ 36″	1913.0
Ω	347 01 40		346 47 45	
i	40 57 24		42 33 07	
e	0.919990		0.918644	

Adopted period 61.121 years.
Resulting period 61.118 years.

A parabolic orbit was computed by Miss Kidder and Mrs. S. B. Nicholson for Comet *e* 1913 (Zinner) from the first three observations at one-day intervals, the parabola coming within the range of possible solutions. This orbit is seen in the second column of Table 7. The editor of the *Astronomische Nachrichten* cabled that from an orbit computed in Europe he suspected the identity of the comet with a comet observed in 1900 and discovered by Giacobini. The best known period of the latter comet was 6.87 years, and for that period a conditioned solution was undertaken, given in the last column. This brings the elements into closer agreement with those of Giacobini, and confirms the identification. The characteristic then of this principle of identification is that if the suspected identity is correct a conditioned solution under assumption of the proper period will bring the elements of the new comet into closer agreement with those of the comet to be identified than would a parabolic or even a general solution.

Table 7.—Orbits of Comets Zinner and Giacobini.
1913, October 23, 24, 25.

	—Giacobini, 1900 III—		—1913 *e* (Zinner)—	
	Period 6.87 years.		Parabola.	Assum'd Per. 6.87 yrs.
T	1900 Nov. 28.17	T	1913 Nov. 2.48	1913 Nov. 2.10
ω	171° 29′	ω	171° 37.3′	171° 29.1′
Ω	196 32	Ω	191 36.9	195 27.3
i	29 52	i	33 14.6	31 01.1
q	0.9342	q	0.99894	0.97787
e	0.74168	e	1.0	0.72968

Table 8 furnishes an illustration of the enormous amount of labor that may be saved by the application of convenient methods of solution. Professor Kreutz of the University of Kiel, a noted orbit expert, attempted as usual to pass a parabola through the first three available observations, taken on November 9, 13 and 17, or at 4-day intervals, of a comet discovered in 1892 and known as Holmes's comet. In defining the elements of an orbit, earlier in the evening I called attention to the fact that the older methods involve a process of guesses. The first four orbits in the table were obtained by Professor Kreutz in this way with an enormous amount of labor. None of these parabolas would represent the observations from which they were calculated, and thus finally he was led to attempt a general solution which gave him a fifth and a correct orbit, the period being about seven years, which accounted for the fact that a parabola could not be made to represent the observations.

Such a laborious process is absolutely unnecessary at the present time; it is not necessary to proceed as far as the computation of a single parabola, for by testing whether the parabola lies within the range of possible solutions, it could be eliminated at the start. As this appeared to be a test case, Mr. Shane of the University of California and other students of the class in theoretical astronomy repeated the solution of this orbit. The very first and direct solution, without applying corrections so as to get the best possible result, yielded an orbit which agrees very closely with the true orbit, for which we may take the one by Hind, the last in the table, as it is based on a long arc. When some outstanding residuals in Mr. Shane's orbit are removed the results will be as satisfactory as those of Mr. Kreutz after five orbit computations.

Table 8.—Elements of the Comet 1892 III (Holmes).
Nov. 9, 13, 17.

	ω	Ω	*i*	*q*	*e*	μ	*P* (yrs.)
Kreutz I	340.4	329.4	24.9	1.90	1.00	....	....
Kreutz II	339.2	332.1	24.9	1.83	1.00	....	....
Kreutz III	334.8	339.6	24.9	1.62	1.00	....	....
Kreutz IV	328.3	346.4	25.1	1.41	1.00	....	....
Kreutz V	13.6	331.5	20.9	2.14	0.42	500″	7.09
Shane	28.0	329.5	21.2	2.25	0.36	536″	6.62
Hind	14.7	331.6	20.8	2.14	0.41	513″	6.90

Last orbit from Nov. 9, Dec. 7, 1892, and Jan. 5, 1893.

Professor W. H. Pickering of the Harvard College Observatory has drawn attention to the fact that the parabolic elements of a comet observed for a few days in 1907 and known as Comet 1907 III bear a remarkable resemblance to those of a comet observed in 1858 and known as 1858 III. For this latter comet Schulhof has published elliptic orbits, with periods ranging from 5.8 to 7.5 years, with a most probable period of 6.6 years. Pickering adopted a period of seven years, and substituted this for the infinite period of the parabola of Comet 1907 III, without changing the other elements of the parabola. This has been the customary procedure. He then made predictions from this combination of elements, which failed to lead to the rediscovery of the comet. This is but natural, because it can be shown that when one element, in this case the period, is changed, all the other elements must also be recomputed, to represent the given observations. This may be accomplished by a conditioned solution with assumed period.

Such a conditioned solution, made by Miss Young on the basis of a 7-year period, brings the orbits of the two comets into striking resemblance. The identity of the comets, suspected by Pickering, therefore becomes exceedingly probable.

Aethra is an asteroid, or minor planet, discovered in June, 1873, by Watson at Ann Arbor, and observed for twenty-two days at Ann Arbor and at Marseilles, France. Two orbits were computed by Watson, one resulting in a daily motion of 980″ and the other in a daily motion of 846″. This difference represents such an uncertainty of the orbit as to make it practically out of the question that the planet could ever be located again except by the introduction of methods which would remove the uncertainty of the resulting orbit. It actually failed of rediscovery at its next opposition. Luther later computed several orbits, after an elaborate investigation. For many of the returns Luther made extensive predictions and at these returns an exhaustive search was made visually, and later also photographically, at many observatories. A large area of the sky was covered photographically in the hope that the object might be found, but it has remained lost to the present day. Dr. D. Alter, of the University of California, has undertaken the computation of a new orbit from the original observations, by our own methods, excluding, however, from consideration all of Watson's observations, to avoid systematic corrections for different observers. Watson's second orbit was based on his own observations, to the exclusion of the Marseilles observations, while Luther's results were based on all of the observations. Dr. Alter's first results, based on entirely different observations, agree almost exactly with the second orbit of Watson. Up to the present time forty-two years have elapsed since the loss of this object. The difference in the mean daily motion, according to Luther on the one hand

and Watson and Alter on the other hand, assuming both orbits to be of equal value, is 60″ per day. In a year this would amount to 365′, or roughly 6°, and in 42 years to 252°, which would displace the object to such an extent as to make a search absolutely unavailing. Dr. Alter has thus shown that there is nothing remarkable about the loss of this object. Further investigation on his part has brought out the fact that the observations permit of so large a range of solutions that a definite orbit determination is not possible and that its rediscovery must be left to chance.

The explanation of the loss of this planet as now accomplished is all the more important because the mean daily motion according to Luther was 904″, or approximately three times that of *Jupiter*. If the mean motions of the small planets are tabulated in comparison with that of *Jupiter*, it is found that there is none with so nearly three times *Jupiter's* mean motion. The fact that, according to Luther, at one time a planet did exist under those circumstances and has since been lost has given rise to much astronomical speculation as to the stability of such an orbit; that is, as to whether a body could continue to exist in our solar system under such conditions. Dr. Alter's preliminary results show that the important question raised by the loss of *Aethra* has no significance, because it was based on uncertain elements. Furthermore, there is absolutely no reason why, under the law of gravitation, planets should not exist at this and similar gaps. In recent years the long existing gap at 600″, which is twice the mean motion of *Jupiter*, has been filled by the discovery of four minor planets. This is a striking example of how inaccurate numerical results in astronomy which have been accepted as standard may lead to considerable and exhaustive mathematical investigation of theoretical questions, which become irrelevant on the basis of more accurate numerical data.

There is some justification in expressing considerable doubt regarding the accuracy of the accepted orbits of many comets and asteroids. Since the majority of the comet orbits have been computed on the parabolic hypothesis, and since no test has been made as to whether they might be elliptic, except in a few instances, a revision of the published elements by new computations would probably reveal a somewhat different picture of the character and distribution of comet orbits, and similarly of asteroid orbits. This would require a revision of the theoretical results deduced on the basis of the accepted orbits. The more accurately and the longer a comet is observed, the more accurately will its orbit become known by any method. In 1907 I ventured to assert that the supposition that as a rule comets move in parabolas was erroneous. This gave rise to considerable discussion. This conclusion, previously suggested on the basis of theoretical considerations, was contradicted by the accepted orbit statistics, but is now universally accepted. It can be shown that even the available orbit statistics prove that comet orbits as a rule are elliptic, and parabolic only within the range or uncertainty of solution, and that therefore many accepted parabolas may on revision be found to be ellipses. In Table 9 the comets are classified according to the years in which they were discovered and observed. In Table 10 they are tabulated according to the length of time expressed in days during which they have been under observation. Table 9 shows that as instruments became more accurate in successive periods the percentage of parabolas rapidly diminished. Table 10 shows that with the increased number of days of observation the percentage of parabolas diminishes even more rapidly. There can be no doubt that every comet observed with sufficient accuracy and for a sufficient length of time will be found to be moving in an elliptic orbit. The average eccentricity of these elliptic orbits is very high. The explanation of high eccentricities lies in the nature of things. Long-period comets cannot be seen from the Earth unless their orbits are so highly eccentric that they come within the range of visibility near perihelion. A large number of comets are probably moving fairly close to the Sun, say within four or five times the distance of the Earth from the Sun, but they can not be discovered unless their orbits are sufficiently eccentric to bring them close to the Sun at perihelion and therefore within the range of vision. While this treatment of orbit statistics practically eliminates the possibility of parabolic orbits there remain in the list of accepted orbits a number of hyperbolas. Recently Thraen, Fayet, Fabry and Strömgren have investigated these by tracing them back in order to ascertain whether at some previous time these comets came sufficiently close to a large planet to have the original elliptic orbit changed into an hyperbola. Their calculations have led to a positive result in this direction in every case. As a rule, therefore, we may safely assume that comets have been forever members of our solar system, and that the number of comets that may visit us from outside space is insignificant. If such comets do visit us, they should move in hyperbolic orbits.

Eccentricity of Comet Orbits.

Table 9.

Discovery Dates.	Parabolas.
Before 1755	99 per cent
1756-1845	74 per cent
1846-1895	54 per cent

Table 10.

Duration of Visibility.	Parabolas.
1-99 days	68 per cent
100-239 days	55 per cent
240-511 days	13 per cent

The latest application of a method of determining the motion of a body moving under the attraction of both *Jupiter* and the Sun has been made by Mr. Nicholson of the University of California for the Ninth Satellite of *Jupiter,* discovered by him at the Lick Observatory in July, 1914. There was some doubt whether the object was a new moon close to *Jupiter* or a minor planet seen in the direction of *Jupiter.* A characteristic feature of the method is that it permits of a general solution without previous assumption regarding any of the elements, and without assumption as to which is the primary in case more than one attracting body is involved. The method gives all possible mathematical solutions simultaneously, and the physical solution is readily established. The fundamental mathematical expression admits of 28 different mathematical solutions of the geocentric distance of a body, but by a simple geometrical process, in the derivation of which Mr. B. A. Bernstein of the University has been of great assistance, the number of solutions to come under consideration is readily reduced to three.

Figure 16 shows a somewhat complex curve and a straight-line intersection of the same in five points. These intersections correspond to the mathematical solutions of the geocentric distance of the object. The actual values of these distances may be read off from the horizontal axis at the top of the figure. By drawing perpendiculars from the five intersections to the axis we thus find the following five possible geocentric distances in astronomical units, in order from left to right:

—1.90; ±0.00; +3.91; +4.23; +6.85.

In the curve the left-hand branch is due to the attraction of the Sun, the right-hand branch to that of *Jupiter*. The negative and the zero distances have no significance for our purposes. Orbits were computed by Mr. Nicholson corresponding to the three positive distances. The first of these was found to be elliptic, the other two, corresponding to the larger distances,

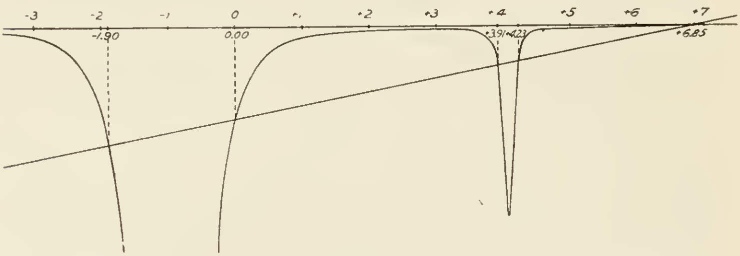

FIG. 16. DIAGRAM FOR THE GRAPHIC DETERMINATION OF THE GEOCENTRIC DISTANCE OF A CELESTIAL BODY.

turned out to be hyperbolic and on that account might have been rejected as improbable. As a final test on the validity of the ellipse all three orbits were compared with a later observation, with the result that the ellipse was definitely established and the object thereby identified as a new satellite of *Jupiter*.

The whole problem was solved from three observations on an arc of nine days. A prediction was made and the body was found in the predicted place a month later. The observations were continued by Mr. Nicholson over two months, until September. The results of his computations are exhibited in Table 11, three different orbits of Satellite IX being given. The first line gives the preliminary solution resulting from the diagram (Figure 16), the second gives its improvement by taking into account later observations, and the last resulted from the adjustment of the orbit on the basis of all available observations and of the perturbations due to the Sun. According to this solution the Ninth Moon of *Jupiter* has a period of revolution of 2.18 years. For comparison, the elements of the previously known Eighth Satellite are also given. Its period is 2.16 years. This agreement of periods is very remarkable, as is also the similarity of some of the other elements.

Table 11.—Orbits of Jupiter's Eighth and Ninth Satellites.

	Arc	ω	Ω	*i*	*e*	μ	*P* Years
IX Prelim. orbit.........	9 days	71.2°	309.4°	157.8°	0.16	1134″	3.12
IX Improved orbit .	2 months	353.7	310.6	156.9	0.12	1678″	2.12
IX Perturbations applied.......	2 months	359.9	310.5	157.0	0.11	1626″	2.18
VIII	....	67.8	240.0	144.8	0.35	1646″	2.16

One of the most remarkable cases was that of an object, an asteroid, known as 1911 MT. This object was discovered by Palisa, in Vienna, in October, 1911. As stated before, such an object in opposition ought to be moving westward, but this object was moving rapidly eastward. This unprecedented observation was telegraphed to European observatories, but on account of some omission did not reach America. Owing to its peculiar motion the object was lost so that only three observations in all, taken in two nights, were available. European astronomers attempted solutions on every available hypothesis. Extended photographic search was made at many observatories, but the object remained lost. The peculiar motion of the body was due to the fact that its orbit is highly eccentric and that it was near perihelion and very close to the Earth. Although further away from the Sun than the Earth, it moved relatively faster in angular motion around the Sun, so that its motion as seen from the Earth was direct and not retrograde. But this motion was complicated by the fact that owing to its nearness to the Earth it was seen in different directions from different observatories, on account of parallax. Such complications had never arisen before, and no method existed for taking account of this displacement.

At the 1911 meeting of the Astronomical and Astrophysical Society of America it was announced as a great astronomical calamity that this object had been lost. I suggested to a class of graduate students that a satisfactory orbit might be computed without much difficulty. Two students, Messrs. E. S. Haynes and J. H. Pitman, volunteered to undertake the solution under my direction, and Mr. Haynes later made this problem one of special investigation. He obtained an orbit from the very meager material, which was published in April, 1912, with the request that on the basis of the new predictions astronomers search their photographic plates. Promptly after our published results reached England a cable came announcing that the object had been found in the predicted place on three plates taken at the Greenwich Observatory.

Many other investigations of a similar kind are constantly under way in California and elsewhere. Among the Berkeley investigations might be mentioned Professor Crawford's and Mr. Meyer's work on the Eighth Satellite of *Jupiter;* Dr. Einarsson's work in determining orbits of the so-called Trojan Group of asteroids, which have a mean motion very nearly the same as that of *Jupiter;* and the investigation of the perturbations of the Watson asteroids by the speaker under the auspices of the National Academy of Sciences. It is natural for an investigator to select those cases for investigation which have given considerable difficulty, or which hitherto have been found impossible of solution.

You will have noted that many persons have been concerned in the theoretical work conducted at Berkeley. The University has been fortunate in the past, and I trust will be equally fortunate in the future, in counting among the younger members of the astronomical staff and among the student body many capable and enthusiastic workers, women as well as men, without whose assistance little could be accomplished in our orbit work. Although the most expeditious and accurate methods of solution are employed, problems of the kind we have discussed require intense and constant application on account of the precision demanded and of the intricacies of the calculations. Yet there is a certain excitement and thrill involved in the expectation of a satisfactory result as the calculations approach their conclusion, so that not infrequently the computations are continued throughout the night when the end of the work is anticipated for the following day.

At some institutions astronomers are in position to devote all their time to investigation. In universities as a rule only such time can be given to investigation as can be spared by the staff of the department from their duties of instruction and by the students from their regular studies. If we were so fortunate at Berkeley as to command the help of one or two regular research assistants many additional problems of importance could be attacked. Perhaps the most fortunate circumstance for us at Berkeley is our close relationship to the Lick Astronomical Department of the University, through which we are able to receive without the slightest delay observations of the highest precision to serve as the basis for the solution of urgent problems.

I have made no attempt to emphasize the intellectual and material service rendered to the civilized world by theoretical and other astronomical researches, but it may be of interest to know that in the present war astronomers and their knowledge have been found to be of the greatest service. The Berkeley Astronomical Department takes pride in the fact that since our entrance into the war every member of our staff to the number of ten has gone into service either directly under the colors or in a civilian capacity and is meeting every expectation in our country's fight for liberty.

THE BRIGHTNESS OF THE STARS, THEIR DISTRIBUTION, COLORS, AND MOTIONS[1]

By Frederick H. Seares

On a clear night an amazing spectacle is to be seen from the summit of Mount Wilson—not the panorama of valley and mountain nor the stars of heaven spread across the sky, but the seemingly innumerable lights which stud the floor of the valley—evidence more convincing, even, than that of daylight hours that the habitations of several hundred thousand human beings lie below. In the foreground is the city of Pasadena, and beyond, Los Angeles, with the intervening space almost continuously illuminated; and still more remote, the lights of adjoining towns and villages reach out in slender lines that here and there touch larger groups along the coast. From mountain-foot to coast-line, a stretch of more than thirty miles, there is scarcely a break in the continuity of these conspicuous evidences of human life and activity. In other directions are many isolated groups, some including only a few tiny glittering points of light, others larger, though more compact, but likewise isolated, except as the brilliant headlight of an electric train or the lights of motor cars, slowly threading their way across the valley, suggest and symbolize all the intimate relationships that knit together the life of modern towns and cities.

There is much in the spectacle to touch the imagination, but it is not the imaginative suggestiveness of the scene that requires our interest now, so much as a certain parallelism with the heavens above. Many things have been learned about the stars, but to understand them, to comprehend and make them a really vital part of our knowledge of the world about us, they must be pictured in terms of every-day experience, translated into language so familiar that we give no thought to the medium in which the facts are set before us. On a black and moonless night, the glittering lights of the valley are

[1] Delivered March 15, 1918.

PLATE XLVII. Lights in the Valley Below Mount Wilson.

not unlike a glorious constellation; and the analogies that may be traced between them and the distant stars smooth away many difficulties which otherwise would be encountered.

1. THE FIXED STARS—EARLY CONCEPTIONS

To the ancients the stars were the "fixed stars," distinguished from the wandering stars or planets by the fact that they hold unchanged their positions with respect to one another. The objects which for the Chaldean shepherd comprised the constellation of *Orion* still appear above the southern horizon during winter evenings, with the configuration they had three thousand years ago. They were just glittering points of light securely attached to the surface of the celestial vault, whose daily rotation carried them about the stationary Earth from which he watched them rise and set and sweep across the sky.

And thus the stars remained, fixed, until two hundred years ago, when Halley, in 1718, showed that *Sirius, Procyon,* and *Arcturus* had perceptibly changed their positions with respect to neighboring stars. Previously there had been no evidence that the stars might be in motion, that the permanence of form so long attributed to the stellar firmament would one day lose its meaning.

As to the size and distance of the stars the ancient mind could only speculate. Copernicus in the 16th century said they must be very distant because they did not reflect the motion of the Earth in its path about the Sun. The phenomenon to which he referred is similar to what occurs when one moves over the mountain top. The lights in the valley seem also to shift about, and if you watch attentively you will find they mimic every movement that you make, but with motions opposite in direction to your own. Walk a hundred paces toward the west and the lights in the foreground just below you shift perceptibly toward the east with respect to those farther off; return to the point from which you started and they promptly reverse their motions and retreat to their former places. And you will note that the shift of any given light depends upon its distance. For those nearest to you the motion is unmistakable. For more distant lights, though perceptible, it is much less conspicuous; but beyond a certain point the unaided eye no longer sees the shift. The displacement is too minute to be detected without instrumental aid.

And just so, the stars should mimic the larger excursions of the observer in his annual motion about the Sun. But no such change of place had been detected, because, as Copernicus said, the stars are so very distant. His opponents, however, said this was only to be expected, for since the Earth did *not* revolve about the Sun, such a shift could not occur.

Nevertheless, the Copernican point of view slowly gained adherents, and conviction gradually grew in the minds of men that a central Sun surrounded by revolving planets is the correct conception of our solar system. And, finally, the precise and skillful measures by Bradley, which led to the discovery of the aberration of light, put the matter beyond a doubt. The chances were shown to be overwhelmingly in favor of a motion of the Earth about the Sun; and yet there was no evidence of any corresponding change in the postions of the stars.

2. The Stars Are Suns—Extent of the Stellar System

The accuracy of Bradley's measures was such as to reveal any displacement as great as 2″, and made it probable, for a certain star at least, that the actual shift did not exceed 0.5″. The implications of this result are not at once apparent. A second of arc is an exceedingly small angle. To subtend such an angle an object, say a short rod, must be looked at from a distance of more than 200,000 times its length. The difference in direction between the two ends of a foot ruler seen from a distance of forty miles is almost exactly a second of arc; and the diameter of a small coin, a ten-cent piece, at a distance of two and a fraction miles gives the same result.

Bradley's measures thus meant that the distance of even the nearer stars must be several hundred thousand times that between the Earth and Sun. Although some conception of the magnitude of the universe had gradually been developing, his observations set a lower limit to its size, and showed that, at most, the Sun and all the planets could be but an astonishingly insignificant part of the stellar system.

Further, objects at so great a distance as the stars must possess luminosity of extraordinary intensity. Their intrinsic brightness must be enormously great, otherwise they could not be seen. The apparent brightness of any source of light, a distant star, or a light in the valley viewed from the mountain top, depends upon two things—intrinsic brightness and distance from the observer. Intrinsic brightness, in the case of ordinary lamps, is expressed in candle power. With increasing distance the apparent brightness rapidly diminishes, and from the mountain one is able to see in the remoter parts of the valley only those lights which intrinsically are most luminous. Conversely, with some notion of the distance of any light, it would be possible, roughly at least, to estimate its candle-power. Thus from Bradley's figures it was a matter of easy arithmetic to calculate that, in the average, the stars must be of the same general order of intrinsic luminosity, and presumably also of the same order of size, as our own Sun. Actually, the differences from star to star are very great; nevertheless it was clear that all might properly be regarded as suns, or from another standpoint, that our own Sun could justly be ranked among the stars.

These conclusions have not yet reached their full development. Evidence of stellar motion was not available until the beginning of the 18th century, and it was more than a century after Bradley's observations, and only eighty years ago, that definite measures of a star's distance were first obtained.[2] The determination of stellar motions and distances, which thus began almost within our own generation, requires the utmost skill in measurement, and became possible only with the development of precise and sensitive instruments. In the meantime, much attention had been given to the brightness of the stars as the only field of investigation that could throw light upon the great problem of the structure of the stellar system. If we were to observe and count the lights visible from the mountain, we could at least learn their number and their range in brightness. Combining these results with the directions in which the lights are seen, we could detect tendencies toward symmetry of arrangement, and easily distinguish the chaotic straggling village from one built in accordance with an orderly plan.

[2] For an account of stellar parallaxes and their measurement, see van Maanen's article, *Publ. Astron. Soc. Pac.*, **30**, 29, 1918.

3. THE MAGNITUDE SCALE

Ptolemy, in his catalogue which forms a part of the *Almagest,* divided the stars visible to the unaided eye into six classes or magnitudes, according to their brightness. The system thus introduced two thousand years ago was extended by later observers; in the 19th century it was given precise definition, and is the one we use today. The magnitude is a unit used to express brightness, as the inch or yard is used for the expression of length and distance; but note that it measures a physiological perception, namely, the sensation of brightness produced in the eye of the observer by the star's luminosity, and is not to be confused with the intensity or energy of the light causing the sensation.

Magnitudes increase numerically as the stars become fainter. The relation of magnitude and intensity, of sensation and stimulus, is not one of simple proportionality, but logarithmic in character. To produce the sensations measured by the magnitudes 1, 2, 3, 4, etc., the intensities must decrease in a geometrical progression, whose factor is 1/2.512......, and are thus proportional to 1, 1/2.512, $1/(2.512)^2$, $1/(2.512)^3$, etc. Simplifying the sixth term of this sequence we find its value to be exactly 1/100. Hence, two stars whose light-intensities are to each other as one to a hundred differ in brightness by five magnitudes. This simple relation in round numbers is the definition introduced a generation ago which placed stellar photometry on a precise numerical basis. The factor 1/2.512, the intensity-ratio corresponding to a difference of one magnitude, is a consequence of the definition. Its unwieldiness is of no disadvantage, for the simple reason that in practice it is not directly used.

We are to remember, therefore, that magnitude is primarily a measure of sensation, while light-intensity expresses the stimulus producing the sensation; and that a ratio of about 1 to 2.5 in the intensity corresponds to a difference of one unit of the magnitude scale.

In undertaking measurements of any kind we must be provided with a scale, something like the yardstick with which we measure lengths, or the standard weights used in the ordinary operation of weighing. The unit of brightness has been defined; but practically we require something more tangible than a general statement of a dozen words or more. For the actual measurement of stellar brightness we have selected certain stars near the North Pole, and by methods that need not be described here have determined the magnitude of each. These stars are analogous to the standard weights with which other objects may be compared; and, similarly, we find the brightness of any star by comparing it with the standards of known magnitude at the Pole. The brightness of many thousand stars has been thus determined. Although standard magnitudes in other parts of the sky are often used, the principle remains the same.

4. The Number of the Stars

What conclusions may be drawn from measurements of stellar brightness? What light do they shed upon the problems of the stars? In Ptolemy's catalogue the brightest stars were assigned the magnitude 1, but in the modern readjustment of the scale they are more nearly of zero magnitude. Roughly we may take the 6th magnitude as the limit of unaided vision, while with great telescopes such as the 60-inch reflector on Mount Wilson a photographic exposure of three or four hours will reach the 20th magnitude.

The range of 20 magnitudes thus within our reach is not an adequate expression of what we really have to deal with. The extremes of intensity, or of energy, are vastly more impressive. Since an interval of 5 magnitudes corresponds to an intensity ratio of 1/100, 10 magnitudes implies a ratio of (1/100) $\times$ (1/100) or 1/10,000; and it follows, similarly, that stars of zero magnitude have an intensity 100,000,000 times greater than those 20 magnitudes fainter. The diversity in the light of the stars is therefore very great. The extent to which differences in distance contribute to this result will be discussed later.

Even the casual observer recognizes that the faint stars are much more numerous than the brighter objects. For the telescopic stars our counts are not complete, but with allowance for this defect, the totals, for the whole sky, of objects brighter than each successive magnitude are as shown in Table I.[3] These results are subject to revision, the numbers in parentheses being very uncertain, although their general order of magnitude is probably correct.

TABLE 1

TOTAL NUMBER OF STARS BRIGHTER THAN EACH UNIT OF THE HARVARD SCALE OF VISUAL MAGNITUDES

Magnitude	No. of Stars	Ratio	Magnitude	No. of Stars	Ratio
0	3		10	380,200	
		3.7			2.7
1	11		11	1,026,000	
		3.5			2.5
2	39		12	2,588,000	
		3.4			2.3
3	133		13	5,894,000	
		3.4			2.2
4	446		14	13,120,000	
		3.3			2.1
5	1,466		15	27,540,000	
		3.2			2.1
6	4,732		16	57,150,000	
		3.2			(1.9)
7	15,000		17	(107,200,000)	
		3.1			(1.8)
8	46,240		18	(197,200,000)	
		3.0			(1.7)
9	139,300		19	(335,000,000)	
		2.7			(1.6)
10	380,200		20	(530,900,000)	

The numbers of faint stars seem astonishingly large. Why should they be so greatly in excess of the brighter stars? At first we knew nothing of differences in size and luminosity of individual stars nor anything of their distribution in space. It was natural, therefore, to make tentative inquiries based on the assumption that, intrinsically, all stars are equally luminous and uniformly distributed throughout an endless space. The fainter stars were accordingly fainter because they were farther away. Initially, this hypothesis was as plausible as any other;

[3] Derived from *Gröningen Publication*, No. 27, p. 63. Beyond the 16th magnitude the results are extrapolated, but receive general confirmation through uncompleted investigations at Mount Wilson.

and it is interesting to see what it yields for the total numbers of stars down to the limits fixed by each unit of magnitude.

It is not difficult to show that the total to any magnitude will be $(2.512)^{3/2}$ or 3.98 times the total to the next brighter magnitude. In fact, this result holds even when the individual stars are not all intrinsically of the same luminosity, provided the mixture of objects of different brightness is the same at all distances. Anything like a uniform distribution of stars throughout space, therefore, necessarily implies the existence of enormous numbers of faint stars. It is like the old problem of shoeing the horse, in which the cost of each succeeding nail is doubled. The total is an incredible sum; but with the stars the numbers increase much more rapidly, for with each succeeding magnitude the totals are quadrupled instead of being only doubled.

Examining the ratios of adjacent totals found by actual counts, which are also given in Table I, we find that in no case do they reach the theoretical maximum of 3.98. For the brighter stars they fall little short of the maximum, but near the lower limit of brightness now accessible to observation the ratio is only half that calculated on the hypothesis of uniform distribution.

5. Limitation of the Stellar System

What may we conclude from this result? Obviously that the stars are not uniformly scattered throughout space, that with increasing distance the number in a given volume becomes less and less.

In the vicinity of the Sun the stars are most numerous, but in the remoter regions they thin out gradually. From the progression of the totals given in Table I it is evident that there are vast numbers of still fainter stars, invisible even with our most powerful telescopes; but beyond some limit of distance there seem to be no stars belonging to the aggregation to which our counts refer. If the decrease in the ratio for successive totals *continues undiminished* beyond the 16th magnitude, there can be few if any stars fainter than the 28th or 30th magnitude;[4] but the assumption involved is very pre-

[4] This is not intended to apply to star clusters, spiral nebulae, or possible aggregations of stars similar to our own galactic system but disconnected from it and very distant.

carious indeed. Probably there is no definite lower limit; but perhaps we may safely say that the total of all stars fainter than the 30th magnitude is relatively very small.

From simple counts of the stars for each interval of magnitude we learn that our stellar system is limited, and that the stars gradually thin out as we approach its boundaries. We have assumed that the mixture of stars of different intrinsic brilliancy is everywhere the same, and we have neglected nothing but a possible loss or scattering of light in its passage through space. The distant lights of the valley are obliterated when the air is filled with mist and haze, while those still visible are much decreased in brightness; through the loss of light in the dust-laden atmosphere the content of the field of vision shrinks to a fraction of its normal size and brilliance. Were light absorbed or scattered in interstellar space, an infinite universe might appear as our own really does; but from independent evidence it seems practically certain that such absorption as may exist is insufficient or not properly distributed to affect appreciably our conclusions.

6. Form of the Stellar System—Reliability of Results

Other results may also be derived from counts of stars. Since the time of the elder Herschel it has been recognized that the Milky Way is the backbone of our stellar system. Stars of all degrees of brightness are more numerous in its vicinity, and it is clear that the galactic plane must be of great importance in all stellar problems.

We arrange our counts in zones parallel to this plane by supposing circles to be drawn about the celestial sphere parallel to the Milky Way, at intervals, say, of 10°. Counting the stars of each interval of magnitude between adjacent circles, we find that zones equidistant from the Galaxy, north and south, contain approximately the same number of stars. The plane through the Milky Way is therefore a plane of symmetry, and to simplify results we average the totals for such pairs of equidistant zones. We thus obtain Table II.

The first column, with each successive column, gives for the different zones results analogous to those for the whole sky in Table I. The numbers of stars, however, now refer to a unit area of one square degree. The distance of the middle of each zone from the galactic plane—its galactic latitude—is at the head of the column.

TABLE II

TOTAL NUMBERS OF STARS PER SQUARE DEGREE BRIGHTER THAN A GIVEN MAGNITUDE AT DIFFERENT DISTANCES FROM THE MILKY WAY

MAG.	GALACTIC LATITUDE							
	5°	15°	25°	35°	45°	55°	65°	80°
8.5	3.3	2.4	1.9	1.5	1.4	1.3	1.3	1.2
9.5	10.4	7.3	5.5	4.4	3.9	3.7	3.5	3.4
10.5	29	20	14	11	10	9	8	8
11.5	81	53	36	28	23	21	19	17
12.5	209	130	86	63	51	44	39	35
13.5	507	301	192	135	105	88	75	64
14.5	1138	676	398	267	200	160	132	112
15.5	2483	1479	800	514	369	282	229	195
16.5	5495	3162	1585	933	661	501	398	331
17.5	12020	6607	3090	1660	1148	871	692	550

What first strikes attention is the crowding of stars near the Milky Way. For all magnitudes the numbers increase with decreasing distance from the galactic plane, but for the fainter stars the crowding is most pronounced. This is clearly shown by comparing the ratios of the numbers in the 5° zone with those at 80°. Such a ratio is called the galactic concentration for the magnitude to which it refers. The increase in the concentration, as fainter and fainter stars are included in the totals, is strikingly shown in Table III.

TABLE III

GALACTIC CONCENTRATION FOR DIFFERENT LIMITING MAGNITUDES

MAG.	GALACTIC CONCENTRATION	MAG.	GALACTIC CONCENTRATION
2.5	2.4	10.5	3.7
3.5	2.2	11.5	4.7
4.5	2.2	12.5	6.1
5.5	2.1	13.5	8.0
6.5	2.2	14.5	10.1
7.5	2.3	15.5	12.7
8.5	2.6	16.5	16.6
9.5	3.1	17.5	21.9

Here again the numbers are subject to some revision, particularly for the fainter stars, but in the main they must be substantially correct. The bright stars near the Milky Way are only two or three times as numerous as those near the poles, but, as fainter stars are added, the ratio increases until at magnitude 17.5 the totals near the Galaxy are more than twenty times those in the higher latitudes.

TABLE IV

RATIOS OF TOTAL NUMBERS OF STARS BRIGHTER THAN SUCCESSIVE UNITS OF MAGNITUDE

MAG.	GALACTIC LATITUDE							
	5°	15°	25°	35°	45°	55°	65°	80°
8.5								
	3.2	3.0	2.9	2.9	2.8	2.8	2.7	2.7
9.5								
	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.3
10.5								
	2.8	2.7	2.6	2.5	2.4	2.4	2.3	2.2
11.5								
	2.6	2.5	2.4	2.3	2.2	2.1	2.1	2.0
12.5								
	2.4	2.3	2.2	2.1	2.1	2.0	1.9	1.8
13.5								
	2.2	2.2	2.1	2.0	1.9	1.8	1.8	1.8
14.5								
	2.2	2.2	2.0	1.9	1.8	1.8	1.7	1.7
15.5								
	2.2	2.1	2.0	1.8	1.8	1.8	1.7	1.7
16.5								
	2.2	2.1	2.0	1.8	1.7	1.7	1.7	1.7
17.5								

Examining now the ratios of adjacent numbers in each column of Table II, which are analogous to the corresponding ratios in Table I and are separately listed in Table IV, we find that near the Milky Way they are larger than the averages for the whole sky, while near the galactic poles just the reverse is true.

The interpretation of these facts requires only an extension of the result derived from Table I. The numbers of faint stars increase much faster in the Milky Way than they do in higher latitudes, but even in the Galaxy itself the increase is far below that corresponding to a uniform distribution throughout space. The stars therefore thin out in all directions, but much more rapidly toward the poles of the Milky Way than in the Milky Way itself. This is equivalent to saying that the great bulk of the stars is contained in a much-flattened spheroidal region of space, whose greatest extension lies in the plane of the Galaxy.

In a general way these results have long been known, although certain details, notably the rapid increase in the galactic concentration, have only lately been placed beyond doubt. The conclusions are based upon simple statistical discussions, but it should not be overlooked that the counts are assumed to have been made to accurately determined limits of brightness; thus the existence of a reliable scale of magnitude is presupposed. Unless the brightness of the standard stars used for the determination of the magnitudes of the great mass of stars is precisely known, the conclusions will be vitiated and rendered uncertain to a corresponding degree. And herein has lain the difficulty. It is only recently that the magnitude scale has been extended to the fainter stars with such precision as would justify confidence in the results. The serious obstacle has been the enormous range in the intensity of the light of bright and faint stars which had to be compared with one another. We have seen that a range of 20 magnitudes corresponds to an intensity ratio of 1 to 100,000,000; that for 17.5 magnitudes, the interval over which we have reliable counts, is 1 to 10,000,000. The distance from San Francisco to Chicago is approximately 2,000 miles or about 10,000,000 feet. The problem therefore is analogous to that of comparing the length of a foot rule with this continental distance, but much more difficult, for the percentage error in measurements of brightness is very much larger than that affecting measurements of length.

7. The Color of the Stars

The results described in the preceding sections are by no means all that may be derived from measures of stellar brightness. Thus far we have been concerned with the light as it appears to the eye; but starlight, like sunlight, is a mixture of many colors, and it requires only the most casual observation to learn that the mixture cannot in all cases be the same. For example, *Vega* and *Sirius* are white or bluish white, *Capella* is a golden yellow, while *Betelgeuse, Antares,* and *Aldebaran* have various hues of red. To produce this sequence of colors as seen by the eye, the mixtures in the several cases must contain less and less of blue and violet light, and hence an increasing preponderance of red and yellow. With *Antares,* for example, the excess of red is such that the mixture of all the colors radiated is the deep ruby tint which makes the star so conspicuous an object in the summer sky.

The color of a star, as we see it in the heavens, therefore depends upon the relative amounts or intensities of the separate colors which it radiates. Were it possible to measure the sensation of brightness produced by each of these, just as we have already done for the mixture of them all, we should be able to find a numerical expression for the color of the star. Practically, the conditions are such that if we measure the relative intensities of any two of the constituent colors which are sufficiently separated in the spectral band, such as blue and yellow, or the relative amounts of different groups of colors, say of blue and violet as compared with yellow and orange, we shall be able to determine the resultant color as it appears to the eye. The extension and development of the methods of measuring brightness thus suggested must now be described; but first we may consider how important a knowledge of the color is likely to be.

The color of the light radiated from a luminous source is intimately connected with temperature. No one who has watched a piece of iron when heated through all the shades of red to white heat can fail to recognize the closeness of this relationship. Moreover, with the stars at least, temperature conditions immediately suggest the processes of growth and decay, for it is improbable, and quite out of accordance with usually accepted ideas, that the temperature of a star should remain constant. We are certain, therefore, to obtain from observations of color important information as to the physical condition of a star and the stage of its development. We shall also find important relations between the color of stars and their positions with respect to the Milky Way, so that the adaptation of photometric methods to the measurement of colors must also add to our knowledge of the structure of the stellar system.

No one needs now to be reminded of the significance of observations made with the spectroscope; but spectrum analysis is only a refined method of color analysis. Photometric measures of color, therefore, overlap to some extent the field of spectroscopy. Really they supplement spectroscopic observations, for they may be applied to stars too faint for examination with the spectroscope.

8. PHOTOGRAPHIC AND PHOTOVISUAL MAGNITUDES

Since magnitude is primarily a measure of physiological sensation, it depends not only on the star and its distance, but also upon the perceptive peculiarities of the eye. The light sent out by a star includes a wide range of wave-lengths or colors to which the eye is not equally sensitive. The visual sensibility is a maximum in the yellow-orange region of the spectrum, and falls gradually in either direction toward the red and violet.

The relation which makes an interval of 5 magnitudes the equivalent of an intensity-ratio of 1 to 100 naturally applies to those colors which rouse the sensation of luminosity. Since, in any given star, these occur with unequal intensities, the resultant sensation is very complex, and, owing to differences in different eyes, cannot be sharply defined. The measure of the resultant visual sensation is called a visual magnitude, and refers to the normal eye. To one who is color blind the apparent brightness of the star may be very different.

Since a definite numerical relation connects magnitude-interval and intensity-ratio, magnitudes may be calculated independently of any visual sensation, provided the star's effective intensity can be determined. The photographic plate provides the required means of measuring intensities, and we have accordingly systems of magnitudes unrelated to the eye and the measurement of sensation, except that they are made to agree as closely as possible with the visual scale of magnitudes.

The ordinary photographic plate is restricted in its sensibility to blue and violet light. For all ordinary exposures the impression produced by yellow, red, and orange is negligible. Such a plate therefore measures mainly the intensity in blue and violet, and, expressed in magnitudes with the aid of the fundamental relation, the result is called a photographic magnitude.

Every photographer is familiar with the so-called isochromatic plate. Its name would indicate that it is equally sensitive to all colors, but such is not the case. Although affected by yellow and orange, it is far more sensitive to blue and violet. Exposed behind a suitable yellow filter, which transmits freely the former group of colors but only slightly the blue and violet, it can be used to measure the intensities of those colors which affect the eye. The combination of plate and filter is practically an equivalent of the normal eye. Numerically the resulting photovisual magnitudes are sensibly the same as visual magnitudes, but otherwise have certain advantages over the visual system. They can be more reliably and more rapidly determined, and, by using a reflecting telescope and a standard brand of plate and filter, the results are sensibly free from the kind of error which in visual magnitudes arises from peculiarities in the eye.

9. COLOR INDEX. THE EXPOSURE RATIO

Of the three kinds of magnitudes, visual and photovisual are a measure of intensity mainly in the yellow region of the spectrum, while photographic magnitude measures the blue and violet. A knowledge of photographic and visual magnitudes for the same star therefore tells us the relative amounts of blue and yellow light sent out by that particular object, and hence indicates its color. For the actual measurement of stellar colors we introduce a quantity called the color index, defined by the equation

Color Index = Photographic Mag. — Visual Mag.

It is a matter of convention as to the particular intensity assumed to correspond to the zero of photographic magnitude, and for convenience it is determined in such a way that for white stars photographic and visual magnitudes are equal. Such objects therefore have a zero color index. A red star, being deficient in blue and violet light, is faint photographically, although relatively bright in light to which the eye is strongly sensitive. Its photographic magnitude is therefore numerically greater than its visual magnitude, and its color index is accordingly a positive quantity, which for the reddest stars amounts to about two magnitudes. Conversely, for blue stars the color index is negative, but never very large, the extreme value being about — 0.4 magnitudes. When once the indices corresponding to known colors have been determined, observations of magnitudes afford a very useful means of measuring color.

The photographic plate can be used in quite another way to measure color. The isochromatic plate in conjunction with the yellow filter, as we have seen, is most strongly affected by yellow light, and may be said to produce a "yellow" image. Without the filter, its sensitiveness to blue and violet is relatively so great that the image is essentially "blue". To measure the color of any star, we determine the ratio of the exposure times producing "blue" and "yellow" images of equal size. Obviously this ratio must differ for different mixtures of blue and yellow light, and can therefore be used as an indication of the star's color. The result is called the exposure ratio (exposure to blue *divided by* exposure to yellow).

It is not the purpose of this account to deal with the numerous applications of the spectroscope to stellar problems; nevertheless, to disregard them altogether would give an entirely erroneous impression, for at many points spectroscopic and photometric methods are very closely related. The earliest measures of star colors that we have were obtained from spectra and expressed in terms of spectral type or class. Thus the familiar notation B, A, F, G, K, M signifies not only the presence of certain typical groupings of lines and bands in the respective spectra, but also a certain regular progression of color, whose relation to color index is given below.

Spectral Class	B	A	F	G	K	M
Color Index	–0.4	0.0	+0.4	+0.8	+1.2	+1.6
Color Class	*b*	*a*	*f*	*g*	*k*	*m*

We shall see presently that the relation of color to spectrum is not invariable, that stars with spectra showing the same number and arrangement of lines may differ appreciably in color. For certain purposes it is convenient to use a notation bearing a constant relation to color. The idea of color class is therefore introduced, with the symbols shown in the third line of the tabulation. Thus the letters *b, a, f......m* always correspond to the color indices which stand immediately above. At the same time, by virtue of the intimate relation between color and spectrum, they indicate the spectral class within narrow limits.

Although spectral type is not an exact index of a star's color, the spectrum contains information from which the color could be accurately determined. Nevertheless direct measures of color, such as those given by the color index and the exposure ratio, are both convenient and important. Even for stars so bright that their spectra can be easily obtained, direct measures of color are more expeditious, while for the fainter objects, beyond the reach of the spectrograph, they are the only methods that can be applied.

10. NUMBERS AND DISTRIBUTION OF STARS OF DIFFERENT COLORS

Measures of color index and exposure ratio have only recently been undertaken. The data thus far obtained are accordingly very meager, and, for the most part, relate to the brighter stars. In the meantime, spectral types have been determined for large numbers of stars, but these are necessarily restricted to the brighter objects. The colors found from spectra therefore relate to stars which are comparatively near, for in general, the brighter stars are much less distant than the fainter objects.

Counts of about nine thousand stars from the *Revised Harvard Photometry* give for the number of stars brighter than a specified magnitude the totals shown in Table V[5], which is similar to Table I, but includes no stars fainter than magnitude 6.5.

We note first that the ratios for adjacent totals given in the right-hand part of the last column, for all the stars together, agree sensibly with those of Table I. This in fact must be the case, for the six principal spectral classes here considered include the great majority of all the stars. The ratios for the G, K, M stars are nearly the same as those for

[5] Derived from *Harvard Annals,* 64, 138, 140.

N

E

PLATE XLVIII. KAPTEYN SELECTED AREA NO. 40.

α 20^h 46^m 5.3^s; δ + 45° 0.5′ (1910).

The central star opposite the arrow points (at the right and at the bottom) is 8.52 magnitude.

all classes together; but for the blue and white stars we find a very interesting result. The numbers for the B stars increase very slowly, while for the A, F stars the totals accumulate with unusual rapidity. The star-ratios show clearly the phenomenon in question; those for the B stars decrease rapidly, and apparently would become equal to unity near magnitude 7.5; below this limit the totals would be constant, and we should conclude that there are no B stars fainter than about magnitude 7.5. These objects therefore must thin out very rapidly with increasing distance.

TABLE V

Numbers of Stars Brighter than a Given Magnitude and the Star Ratio for Different Colors

MAG	B		A, F		G, K, M		ALL	
2.5	22		23		28		73	
		3.1		2.9		4.0		3.4
3.5	68		66		111		245	
		2.7		3.2		3.5		3.2
4.5	184		211		393		788	
		2.6		4.4		3.2		3.4
5.5	485		937		1264		2686	
		1.7		4.1		3.2		3.3
6.5	821		3850		4103		8774	

For the A, F stars an opposite condition prevails. The ratios increase and actually exceed the theoretical maximum of 3.98, which we have seen holds for a uniform distribution in space; but they cannot increase indefinitely and, in fact, from some magnitude on, must diminish, otherwise the ratios in Table I for all stars together could not decrease as they do.

About 6,100 of the stars of Table V—those brighter than magnitude 6.25—have been classified in Table VI, according to spectral type and position with respect to the galactic plane. The tabular values are numbers of stars of each spectral class in regions of constant area whose mean distances from the Galaxy are given in the first column. For all classes the numbers increase with decreasing galactic latitude, but the behavior for different spectra is quite different.

TABLE VI

SPECTRUM AND GALACTIC LATITUDE—NUMBERS OF STARS[6]

GALACTIC LAT.	B	A	F	G	K	M	ALL
62.3°	37	296	156	128	378	101	1096
39.8	85	345	152	128	377	108	1195
21.6	227	539	200	170	459	126	1721
8.1	367	705	212	183	505	122	2094
SUMS	716	1885	720	609	1719	457	6106
GAL. CONC.	20.0	3.0	1.6	1.6	1.5	1.5	2.2

The B stars show a high concentration toward the Galaxy, while the K and M stars are much more evenly scattered and display but little crowding toward the Milky Way. The ratios for 5° and 80°—values of the galactic concentration—cannot be accurately determined from these data, but approximately are as given in the last line of the table, ranging from 20 for the B stars to only 1.5 for the K and M stars. The value of the galactic concentration in the last column for all spectral classes together, namely, 2.2, is in agreement with that in Section 6 found from quite different data (see Table III).

TABLE VII

NUMBERS OF STARS OF DIFFERENT COLORS AT 0° AND 60° GALACTIC LATITUDE AND THEIR AVERAGE MOTIONS.[7]

COLOR INDEX	NO. OF STARS 0°	NO. OF STARS 60°	PROPER MOTION	PARALLACTIC MOTION
—0.43	45	19	2.4″	3.5″
—0.05	230	102	3.1	2.9
+0.34	167	110	7.8	8.9
+0.69	103	47	19.8	20.8
+0.96	63	63	10.0	8.6
+1.13	151	126	7.7	7.6
+1.26	116	83	5.0	4.9
+1.38	106	78	4.1	4.0
+1.52	50	21	4.1	4.6
+1.73	7	0	3.2	—

[6] Derived from *Harvard Annals*, 64, 144.

[7] Derived from *Göttingen Aktinometrie*, B, 34-37. The color indices have been reduced to the Mount Wilson color system.

The behavior of the B stars, the bluest stars of all, is very peculiar. Apparently they comprise a very limited aggregation, closely confined to the plane of the Milky Way. The concentration of the A stars toward the Galaxy is marked, and apparently a large fraction of the fainter stars in low galactic latitudes belong to this class. The redder spectral classes are much more uniformly distributed, their galactic concentration being much below the average concentration for all the stars together.

Very similar results are shown in Table VII, whose second and third columns contain the numbers of stars in the Milky Way and in galactic latitude 60°, corresponding to the observed color indices in the first column. The relations are more clearly shown by Fig. 17, which is based upon the data of Table VII.

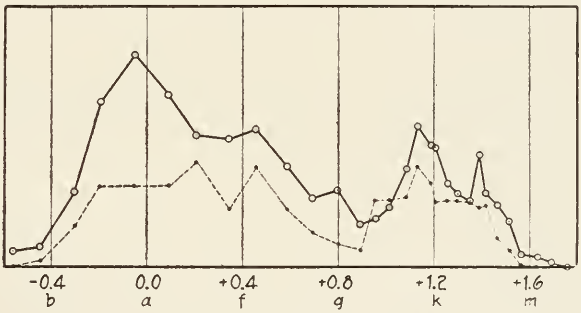

FIG. 17. VERTICAL DISTANCES REPRESENT NUMBERS OF STARS HAVING THE COLORS INDICATED AT THE BOTTOM OF THE DIAGRAM. The continuous line shows the relatively larger number of blue and white stars in the Milky Way as compared with the number in regions 60° distant therefrom, the latter being indicated by the broken line.

Here again we find the blue and white stars to be relatively more numerous in the Milky Way than in higher latitudes. For the bluest stars the numbers and curves are somewhat misleading, since they do not include objects brighter than the 4th magnitude, many of which belong to color class *b*. Table VII is therefore not altogether comparable with Table VI.

The thinning out of the B stars and their apparent disappearance at about magnitude 7.5 raises a very interesting question as to the behavior of the faint stars in relation to color. Are there no blue stars to be found among them, or do such objects reappear at some point farther down the scale of magnitude; and what of the other color classes? The results thus far obtained are fragmentary but very suggestive.

In the region of the North Pole and the variable star S *Cygni,* we find that the color indices gradually increase as we consider fainter and fainter stars. Among the brighter objects we find zero and even negative values of the index; but with decreasing brightness the blue and white stars gradually disappear, so that at the 16th magnitude there are no color indices less than 0.5 magnitude. In these regions, at least, the faint stars belong to the redder color classes, and we find none bluer than class *f*. These results are illustrated in Fig. 18, in which the color indices are plotted as vertical distances, opposite the magnitudes of the individual stars. The curved lines along the lower boundary of each group of points show the gradual increase in the smallest value of the color index occurring among the stars of any given magnitude. At the 16th magnitude, for example, the bounding curves are one square distant from the zero line, and indicate, as already stated, an index of 0.5 magnitude.

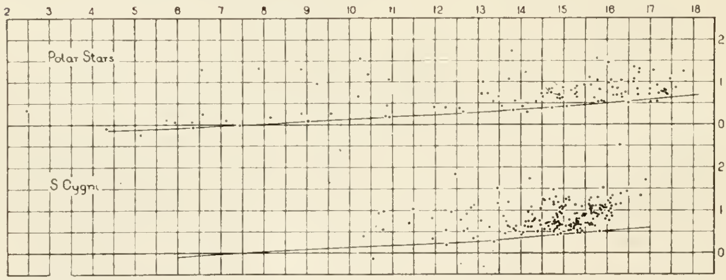

FIG. 18. HORIZONTAL DISTANCES ARE PHOTOGRAPHIC MAGNITUDES; VERTICAL DISTANCES, COLOR-INDICES. The smallest value of the index increases with the magnitude. In the two regions illustrated there are no blue or white stars among the fainter objects.

For the region of S *Cygni* the results are less certain; those for the Pole have been confirmed by observations of the exposure ratio, and are well established. For faint objects in the star clouds of the Milky Way determinations of color index and exposure ratio prove that here, at least, blue and white stars are to be found among the lower magnitudes; but we do not know at present whether they are confined to the Milky Way itself, or whether there is a gradual change in the color of the faint stars with increasing distance from the Galaxy, thus providing a gradual transition to the conditions prevailing at the North Pole in galactic latitude 27°.

Our knowledge of the distribution of the various color classes over the face of the sky and among the objects of differing brightness is very much less than we should wish, and much less than it will shortly be. But we recognize that color stands in close relation to the detailed structure of the stellar system, and that the plan and organization of the system are to some extent reflected by the physical condition of the individual stars.

Before turning to other matters, another circumstance, clearly shown by both Tables VI and VII and by the curves of Fig. 17, needs a word of comment. The stars of color class *g* are seemingly much less numerous than those lying just above or just below in the scale of color. That this is true for various parts of the sky, may be seen from the numbers in each line of Table VI, or from those in the second and third columns of Table VII, or, better still, from the fact that both the curves of Fig. 17 approach the axis near the point marked *g*. The result is well established for the stars included in the counts, namely, all those to a certain limit of apparent brightness; but we must not incautiously conclude that it holds for all the stars in the sky, or for those within any specified distance. The relative numbers, as well as their absolute values, depend upon the way in which the stars have been selected. The question of selection is important, and to understand its influence in the present case, we must study the conditions that determine the brightness of a star as we see it in the sky.

11. ABSOLUTE MAGNITUDE—A MEASURE OF INTRINSIC BRIGHTNESS

Aside from the peculiarities of the eye or of the photographic plate, two factors, distance and intrinsic brightness, determine the magnitude—the apparent magnitude—of a star. From the summit of the mountain the brightness of the lights in the valley depends upon their distance and their candle-power; two lights of different candle-powers may appear equally bright if that of higher power is more distant than the other. In the case of a star, to distinguish the influence of intrinsic brightness from that of distance, we use its absolute magnitude, a quantity analogous to candle-power; and just as candle-power is a measure of the intrinsic luminosity of a light viewed from a distance of one yard, so is absolute magnitude an expression of a star's intrinsic brightness when seen from a standard distance; it is what the star's apparent magnitude would be were it viewed from a distance corresponding to a parallax of 0.1″*. Seen from this distance our Sun would be near the limit of visibility, with an apparent magnitude of 5; hence the Sun's absolute magnitude is 5. The absolute magnitudes of a group of stars therefore express the range in their actual brightness, with the same numerical relations between intrinsic intensity and absolute magnitude that hold for apparent intensity and apparent magnitude. A difference of 5 in the absolute magnitudes means that the light of one star is actually one hundred times more intense than that of the other; similarly a difference of 10 corresponds to a ratio in intrinsic intensities of 1 to 10,000.

The three quantities—absolute magnitude, M, apparent magnitude, m, and the distance expressed as a parallax, π, are connected by a simple equation

$$M = m + 5 + 5 \log \pi. \qquad (1)$$

When any two of the three quantities are known, the third can be determined. Thus for stars whose distances and apparent magnitudes have been measured, absolute magnitudes can be computed from the formula, just as it would be possible to calculate the candle-powers of distant lights in the valley if we knew how far away they were and had measured their apparent brightness. Because of difficulties described in an earlier section, the distances of only a few objects have been directly measured, and these alone tell us little of the real brightness of the stars.

Fortunately, as has been shown by Adams and Kohlschütter, it is possible to find the absolute magnitude directly from the

* This is equivalent to saying that the radius of the Earth's orbit seen from the standard distance would subtend an angle of 0.1″. A length of one foot at a distance of 400 miles subtends the same angle. The value of the standard distance commonly used, in light-years, is 33.

spectrum, at least for all but the bluest spectral types. The relative intensities of certain pairs of lines, even in spectra of the same class, vary with the intrinsic brightness of the star; and by observing these critical lines, the absolute magnitude is quickly and accurately determined.

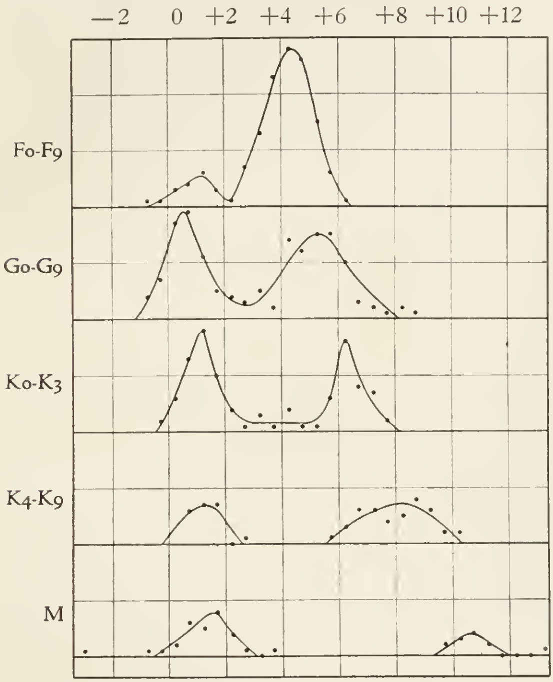

FIG. 19. VERTICAL DISTANCES REPRESENT NUMBERS OF STARS HAVING THE ABSOLUTE MAGNITUDES GIVEN AT THE TOP OF THE DIAGRAM, different spectral classes being shown separately. The grouping of the stars as giants and dwarfs is clearly indicated, the former having an absolute magnitude of about +1, while the magnitude of the dwarfs increases as the M stars are approached. The curves are from the investigation by Adams and Joy, *Mt. Wilson Contr.*, No. 142; *Astrophysical Journal*, 46, 335, 1917.

The classification and study of such absolute magnitudes as are now available lead to a very remarkable result. The bluest stars, on the average, are about one hundred times more luminous than the Sun. Their mean absolute magnitude is not far from zero, and the individuals differ but little from the mean. A similar result holds for the A stars, but with a wider range in the individual values. For the redder spectral classes the behavior of the absolute magnitudes is that shown by Fig. 19, in which vertical distances represent numbers of stars having the absolute magnitudes shown at the top. With increasing spectrum or color the range of intrinsic brightness increases until for the M stars we find objects as bright as magnitude —3 and as faint as +13. Beginning with F there are for each type two values of the absolute luminosity which occur more frequently than any others, as is shown by the presence of two maxima in each of the curves. One of these is always near absolute magnitude +1, while the other has the gradually increasing values, +4, +5, +6, +8, and +11 for each of the successive spectral intervals illustrated in the figure. For example, the two groups of G stars differ in their mean absolute brightness by nearly five magnitudes. For the M stars the difference is nearly 10 magnitudes, corresponding to a ratio of 1 to 10,000 in the intensities. In this case the two groups are clearly separated by an interval of about 6 magnitudes within which there are no M stars whatever.

Were we to measure the candle-power of a large number of the lights in the valley, we should find a similar result; the arc lamps used for street illumination would be separated by a wide interval of brightness from the incandescent bulbs of 100 candle-power or more. The illustration here is more or less trivial, but it would seem less so had we no previous knowledge of the practice in illumination and were we, as in the case of the stars, unable to estimate approximately with the unaided eye the relative distances of the lights observed.

The very extraordinary splitting up of the redder spectral types into two sharply marked subdivisions has led to the introduction of the terms "giant" and "dwarf". It is remarkable and undoubtedly a significant fact in the history of a star's development that objects having similar spectra should differ so greatly in absolute luminosity as do the giants and dwarfs. The similarity of spectrum and color means that the surface temperature, and hence the amount of light radiated from a constant area of the surface, is approximately the same for both classes of stars; hence the range of 1 to 10,000 in the average absolute luminosities of giant and dwarf M stars must

W

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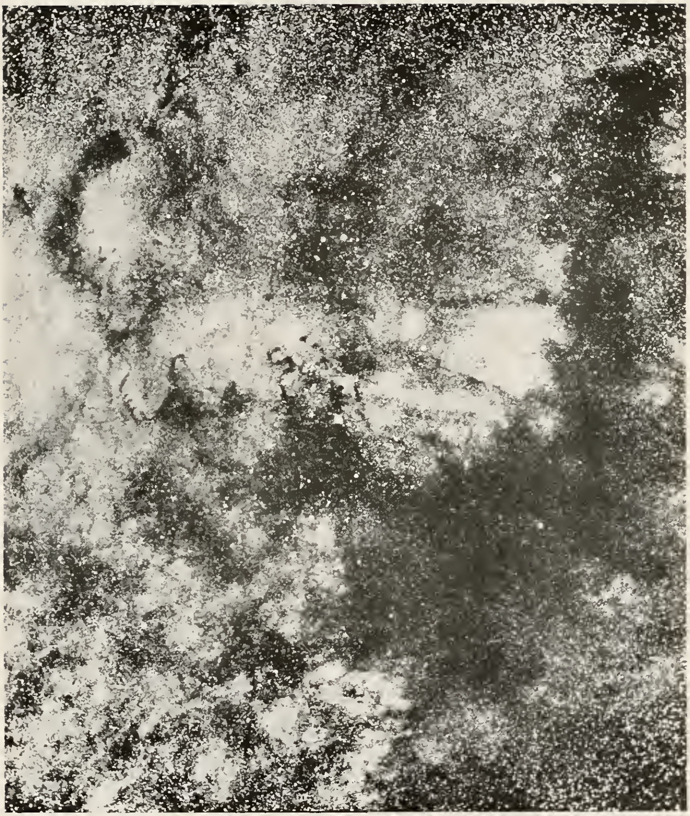

PLATE XLIX. Star Clouds and Vacant Lanes Near Θ Ophiuchi.

From a photograph with the Bruce telescope, by E. E. Barnard.

be attributed to differences in their linear dimensions. To radiate more light, the giants must be larger than the dwarfs; and that their surfaces may be in the required ratio of 10,000 to 1, the diameters of the giants must be a hundred times those of the dwarfs.

But note what this implies—a ratio in the volumes of 1,000,000 to 1. What are we to infer as to the masses and densities of these stars? Without additional evidence the question cannot be answered; but we may make two extreme assumptions: (a) The densities of giant and dwarf stars are the same; the masses of the former will then be a million times those of the latter. (b) The masses are equal; the density of the giants can then be only one-millionth that of the dwarfs. The available evidence indicates that the second supposition is much nearer the truth than the former, and that the great difference in volume between giant and dwarf stars is to be explained by differences in attenuation of the material of which they are composed rather than by differences in the amount of that material.

The critical factor underlying these conclusions as to the linear dimensions of giant and dwarf stars is emphasized by the fact that they do not hold for the electric arcs and incandescent bulbs—the giants and dwarfs among the lights of the valley. The stars compared have the same general type of spectrum, and hence nearly the same surface temperatures; but the lights represent wide differences in temperature, and, from candle-power alone, we can conclude nothing as to the extent of the luminous surface emitting the light seen by an observer on the mountain.

12. Relation of Color to Absolute Magnitude

We have referred to the fact that the spectrum of a star is not an exact measure of its color, and that objects having the same type of spectrum may show appreciable differences in color. Investigations by several observers have shown that these differences are related to the absolute magnitudes of the stars, the more luminous objects being the redder.

Determinations of the exposure ratio for a group of giant and dwarf stars illustrate the nature of the dependence. The results are illustrated in Fig. 20, in which vertical distances represent the logarithm of the exposure ratio, while horizontal distances correspond to spectral types. The circles indicate giant stars and the points dwarfs. The dotted line gives the variation in the logarithm of the exposure ratio for the colors

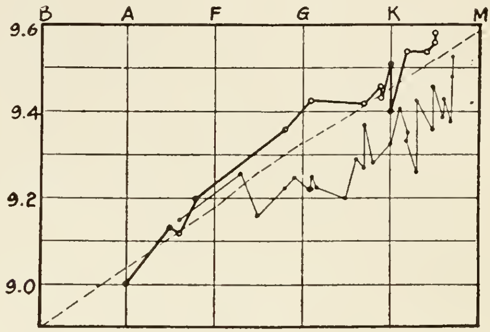

FIG. 20. VARIATION OF COLOR WITH SPECTRUM FOR GIANT (HEAVY LINE) AND DWARF (LIGHT LINE) STARS. Vertical distances represent logarithms of the ratio of exposure for blue light to exposure for yellow light necessary to produce the same photographic effect. For stars having G and K spectra the giants are appreciably redder than the dwarfs.

normally assumed, in the Mount Wilson color system, to correspond to the different spectral types, and was derived from the color indices and spectra of the Polar Standards of magnitude. None of the giants differs greatly from zero absolute magnitude, and the progession of exposure ratio with spectrum for these stars is fairly regular. The dwarf stars average 4 or 5 magnitudes fainter than the giants, and although the scattering of the points is considerable, the change in the exposure ratio with spectral class, and the relation of color to absolute brightness are clearly enough shown.

Since the ratio is: exposure to blue *divided by* exposure to yellow, a large value of the ratio implies a deficiency of blue light, and hence an excess of red light. The giant stars are clearly redder than the dwarfs, as already stated, the difference, expressed in color index, easily amounting to half a magnitude. For the late A and early F spectra the color difference is inappreciable, and the diagram suggests that further observations may show that the curves for giants and dwarfs cross at this point, thus giving a reversal of the effect for the B stars.

13. Relation Between the Distances of Stars and their Apparent Motions

In an earlier section we have seen something of the difficulties encountered in attempting to measure directly the distances of the stars. A more expeditious method is to make use of equation (1), by means of which the parallax, π, can be calculated when the absolute and apparent magnitudes have been determined. Intrinsic brightness, as we have seen, can be derived from the spectrum for all but the bluer spectral classes, and apparent magnitude can be measured by the method outlined in Section 3.

This is the most valuable method that we possess for the determination of the distances of large numbers of individual stars; but it has only recently been developed, and in the meantime relations between the distance and apparent motions of the stars give valuable information as to the average distance of any particular class of stars, say those of the sixth apparent magnitude, or those having G-type spectra.

The principles involved are simple. Suppose we observe from the mountain, not the lamps that light the streets of a distant town, but those of the moving motor cars within its limits. These will be traveling here and there in all directions, with a considerable range of speed. During a given interval, say one minute, the direction in which each car is seen will change a certain amount. The average of all these changes in direction depends upon the average speed, in miles per hour, with which the cars are moving. Suppose that the average change in direction has also been determined for the motors of a second town, and assume, further, that the average speed per hour is in both places the same. The relative distances of the two towns from the observer can then be found. If the average change in the positions of the moving cars is the same, the towns are equally distant; and if one average is smaller than the other, the town to which it corresponds is the more distant of the two.

The total annual change in the direction in which a star is seen is called its proper motion. If we suppose that the average speed of the stars, in miles per second, is everywhere the same, it follows that the average proper motion of distant stars will be smaller than that of nearer objects; and by comparing the average motions of different groups of stars we can find their relative distances. Finally, from the motions of stars whose distances have been directly measured, we derive a relation between average proper motion and parallax which can be used to find the average distance of any group of stars whose motions have been observed.

By way of illustration, there is given in the fourth column of Table VII the average proper motion during an interval of a hundred years, for each of the groups of stars whose mean color indices appear in the first column of the table. These numbers increase to a maximum and then decline again; and from them we infer that the stars showing the extremes of color are the most distant, while those of the intermediate color classes, with indices of about +0.7, are nearest to us.

There is another and even more important method of using the apparent motions of the stars to find the average distance of any class of objects. Suppose the observer on the mountain to walk along its top, as in an earlier illustration—toward the west, we assume, and with a known rate of motion. During a minute he will have moved say a hundred yards. In the meantime the lights in the valley to the south will apparently have shifted toward the east by a definite angular amount, whose value can be found by measurement. The problem of determining the distance of the lights is just that of calculating the distance from which a length of one hundred yards subtends an angle equal to the observed change in direction. If the lights are not in motion, observation of any one of them determines the distance of the town to which it belongs.

But suppose that we again observe the lights of the moving motor cars within the town. During the minute in which the observer walks the hundred yards, each motor moves a certain distance. Apparent changes in direction are produced by the observer's motion as before, but these are modified by the motions of the cars themselves. For some the eastward displacement is increased, for others, diminished; but for a large number of cars, moving at random, and with random speeds, the individual motions compensate each other and the average displacement toward the east is the same as though the cars were all at rest. The distance of the town can therefore be calculated as accurately as before.

And thus we can compute the average distance of a certain group or class of stars when their individual motions are at random. The Sun and its attendant planets, moving through space in a definite direction with known speed, carry with them the observer who, after an interval, measures the changes in direction of the stars. Their apparent motions are the result of the observer's change in position, combined with the motions of the stars themselves.

Each individual proper motion is analyzed into two components, one parallel to the motion of the Sun, the other perpendicular to this motion. The latter must be due entirely to the real motion of the star, but the former—the parallactic component as it is called—is produced partly by the motion of the star and partly by the motion of the Sun. For objects moving at random, the part due to the real motions of the stars will vary in amount, and sometimes will be in the same direction as the solar motion and sometimes opposite thereto. If, therefore, we form the average of the parallactic components for a large number of stars, their individual motions will compensate each other and the mean will be the same as though the stars were all at rest. The result, which represents the effect of the observer's motion upon the direction in which the stars are seen, is the parallactic drift or motion of the group of stars observed, and corresponds to the eastward displacement of the lights produced by the change in the position of the observer on the mountain top.

The parallactic drift, combined with the known motion of the Sun, gives at once the mean distance of the group of stars observed. The method is not applicable to stars directly in the line of the observer's motion, but gives useful results for objects in other parts of the sky. The fact that he is in the midst of the stellar system, with stars on every hand, does not alter the problem essentially.

The mean parallactic drift for an interval of a hundred years is also given in Table VII for stars of different color index. The numbers vary inversely as the distances, and confirm our earlier conclusion as to the relative distance of the stars of different color. The *f* and *g* stars are nearest to us, and, occupying a smaller volume of space than the other color classes, we should expect them to be less numerous. This perhaps accounts for part of the deficiency in the numbers of these objects, to which reference has already been made. The matter is not altogether clear, however, for the smaller distances of these stars indicate that their mean absolute luminosities are below the average of the other color classes. The parallactic motions of the very red stars are of the same order of magnitude as those of the blue stars. The mean distances and luminosities of both these classes of stars must therefore be sensibly the same. By consulting Fig. 19 we see that this result apparently can be brought about only by excluding the dwarf K and M stars. It is probable, therefore, that our counts contain none of the dwarfs of these spectral classes. The F and G dwarfs, however, being appreciably brighter, may fall within the limit of apparent magnitude used in the selection of the data. This would account for the relatively low average luminosity of the F and G stars, but, on the other hand, would seem to indicate that the manner of selection had introduced a larger percentage of F and G stars than of K's and M's, i.e., giant stars plus some dwarfs, whereas, of the others, we have only giants. The actual number of the F's and G's included, as we have seen, is comparatively small and may therefore indicate a real deficiency for these spectral classes. These details show the artificial character of apparent magnitude as a limit in choosing data, and illustrate some of the disturbing effects of selection referred to at the end of Section 10.

14. Relation of Absolute Magnitude to Velocity of Motion

Recent accumulations of data bearing on the intrinsic brightness of the stars have brought to light a very significant relation between the absolute magnitude of a star and the speed with which it moves through space. The nature of the relation is illustrated by Fig. 21, in which vertical distances represent absolute magnitudes, and horizontal distances the speed in kilometers per second with which the star is moving.

The figure summarizes the results by Adams and Strömberg from about 1,300 stars, which were divided into two groups, one including F and G spectra (points), the other K and M spectra (crosses). For both groups there is a regular and sensibly linear increase in average radial velocity with increasing absolute magnitude. The gain in velocity amounts to about 1.5 kilometers per second for each unit of magnitude, and applies to both giants and dwarfs. The gap between the K and M stars of high and low luminosity is clearly shown between the upper two and the lower three crosses of the diagram. For the F's and G's, as shown by Fig. 19, the giants and dwarfs are not entirely separated, so that points in Fig. 21 are more uniformly spaced.

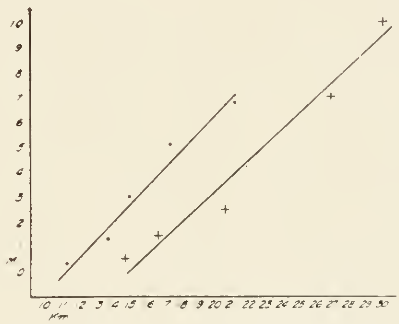

Fig. 21. Variation of Radial Velocity (Horizontal Distances) With Absolute Magnitude (Vertical Distances). Points represent groups of stars having F and G spectra; crosses represent similar groups of K and M stars. From the investigation by Adams and Strömberg, *Mt. Wilson Contr.*, No. 131; *Astrophysical Journal,* **45**, 293, 1917.

Finally, it will be noted that for the same absolute magnitude, the K and M stars appear to be moving with higher average speeds than the F's and G's.

The explanation of these relations and their significance as a mechanical feature of the stellar universe are not at present known. They may depend upon the masses of the stars, the smaller objects moving faster, on the average, than those of greater mass. On the other hand, the dwarfs may represent a later stage in the development which we commonly suppose each star to undergo, and there may be circumstances which cause a gradual acceleration of motion during the progress of the star's development. These are only suggestions; a satisfactory explanation must await the accumulation of further data.

15. THE SYSTEMATIC MOTIONS OF THE STARS

For two centuries we have known that the stars have motions of their own, but for only a short time has it been clear that they do not move at random. We now know many groups of stars which seem to be definitely organized physical systems, whose members travel through space along parallel paths at a constant speed. The bright stars of *Ursa Major,* the *Pleiades,* a part of the Constellation of *Taurus,* a cluster in *Perseus* and one in *Scorpio,* and the B-type stars in the vicinity of *Orion,* not to mention many smaller aggregations, move as groups and thereby suggest that, besides their community of motion, they possess other characteristics in common. But these moving clusters comprise only a minute fraction of the total number of stars, and apparently have no close relation to the two great streams which appear to be one of the chief characteristics of the organization of our stellar system. The phenomenon of stream motion, which now requires our attention, is probably as significant a factor for stellar movements, as is the crowding of the stars in the Milky Way for the form of the stellar universe.

Until 1904 it was commonly assumed, as has been done in the preceding sections, that the vast majority of the stars might be regarded as moving at random. Kapteyn, however, has shown that this is not even approximately the truth. The facts of the case can be learned by a study of proper motions; but these must be known with precision for a large number of stars well scattered over the sky.

The principle underlying the analysis is not difficult to understand. For a chosen region of the sky, with not too great an area, we count the numbers of proper motions having definite directions on the surface of the celestial sphere; we find a certain number toward the north, so many directed 10° east of north, so many 20° east of north, and, similarly, on around the circuit of 360°. Now let us construct a diagram with lines radiating from a central point at intervals of 10°, the length of each line being proportional to the number of proper motions in one of the specified directions; the ends of the radiating lines are then connected by a closed curve, and the result is called a velocity diagram.

For stars moving at random, and a solar system fixed with respect to the center of gravity of the system of the stars, the proper motions will be equally numerous in all directions; the radii which represent them will be equal, and the velocity diagram will be a circle. If we still suppose random motions for the stars, but assume the observer to be in motion, the velocity diagram becomes an oval with the point of origin for the radii no longer at the middle of the figure. The elongation of the oval, in direction and amount, and the position of the origin of the radii depend upon the observer's motion.

The result of analyzing the proper motions actually observed varies with the region of the sky considered, but is always a velocity diagram differing in a very characteristic way from those described above. The diagrams are no longer simple ovals, but usually pear-shaped figures, which can be accounted for only by supposing that the proper motions have a marked preference for two certain directions. A comparison of these preferential directions, which can be determined from the velocity diagrams of different regions, shows that they fall into two groups, and that the directions of each group converge and practically intersect in a single point called the apex.

Kapteyn showed that the phenomena are satisfactorily explained by supposing that the great majority of the stars belong to one or the other of the two great interpenetrating swarms whose motions, relative to the solar system, make with each other an angle of about 100°. The speeds are as 1.52 to 0.86, and the numbers of stars in each stream are as 3 to 2. The fundamental nature of the phenomenon is indicated by the fact that the motion of one swarm relative to the other is almost exactly parallel to the plane of the Milky Way. It is not to be supposed, however, that the hypothesis of two streams of stars is more than a first approximation to the systematic motions of the stellar system.

The question of systematic motions has also been investigated on the basis of velocities in the line of sight determined with the spectrograph. Here we use, not the number of motions, but the average value of the line-of-sight or radial velocity for the stars in each part of the sky. The results may be represented graphically in a manner similar to that used in preparing the velocity diagrams described above, except that now the radiating lines are not confined to a plane, but diverge in all directions into space, one for the direction of each region of the sky for which a group of radial velocities has been determined. The length of each radiating line is made proportional to the mean radial velocity of the stars selected in that direction, and through the extremities of them all is passed a closed surface called the velocity surface. The variation in the distance of this surface from the point of origin within represents the variation in the average radial velocity from point to point in the sky.

In a recent investigation by Strömberg, the data which included stars of F, G, and K spectral types were divided into three groups according to luminosity, with mean absolute magnitudes of approximately 1, 2, and 6. The groups were discussed separately with results which are represented in Figs. 22, 23, and 24. The points in the three diagrams lie in the plane of the Milky Way. The full-line curves are intersections of the galactic plane with the smooth velocity surface best representing the observed average velocities. The dotted curves are similar intersections with the best-fitting symmetrical surfaces.

It will be noted first that the linear dimensions of the figure for the most luminous stars are smallest, and largest for that corresponding to the faintest stars. This agrees perfectly with the relation between absolute luminosity and speed found in the preceding section. Next it will be seen that the general characteristics of the three figures are the same. The symmetrical curves all have their longest axes in longitudes near 170° ; in this direction, which agrees well with that of the stream motion, the average radial velocity is highest.

The curves corresponding to the velocity surfaces which more accurately represent the data are three-lobed, and the preferential directions of highest velocity no longer form a straight line, but are inclined at an angle which is smallest

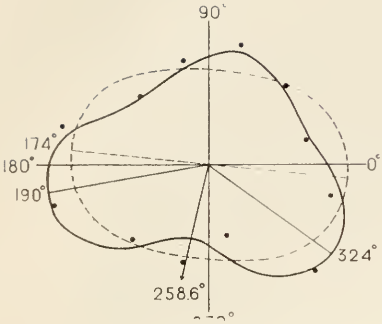

FIG. 22.

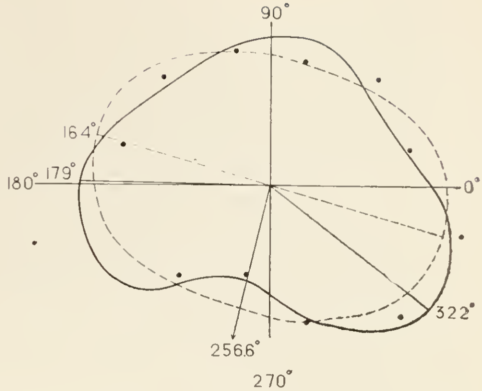

FIG. 23.

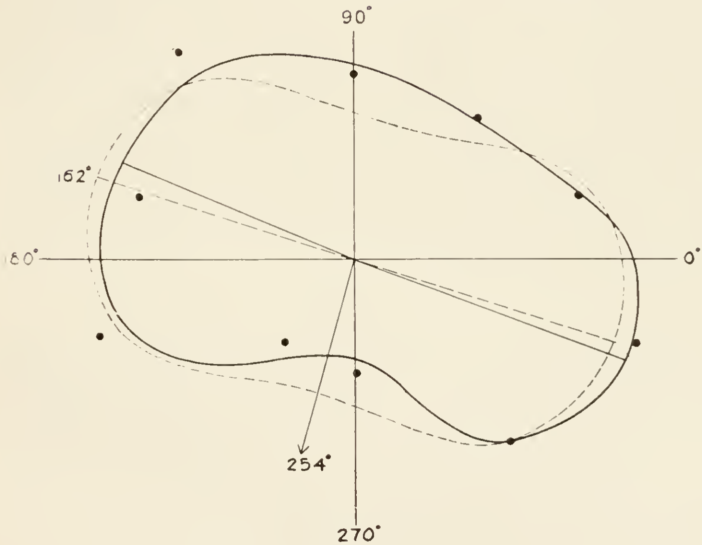

FIG. 24.

FIG. 22, 23, 24. INTERSECTIONS BETWEEN THE AVERAGE RADIAL-VELOCITY SURFACES AND THE GALACTIC EQUATOR FOR THREE GROUPS OF STARS: Fig. 22, for the stars intrinsically brightest and most distant; Fig. 24, for those intrinsically faintest and nearest; Fig. 23, for the stars intermediate in luminosity and distance. The distances of the points from the intersection of the reference lines represent the average radial velocity in regions near the galactic equator. The projections of the longest axes of the surfaces are indicated by straight lines; the arrows indicate the position of approximate planes of symmetry perpendicular to the galactic equator. From the investigation by Strömberg, *Mt. Wilson Contr.*, No. 144; *Astrophysical Journal*, 47, 7, 1918.

for the most distant stars. The arrows directed downward bisect these angles approximately, and indicate what, for other reasons, we believe to be the direction of the center of the stellar system. The axes of greatest mobility, therefore, seem to coincide better with a curve than with a straight line, and the directions of the preferential velocities are such as might be expected from a general circulation of the stars about the center of the system, with a strong tendency toward motion in the galactic plane; the data possibly indicate that something of the sort is taking place.

From the radial motions we have determined the directions of the highest average velocity, while from the proper motions we have found the line in space along which motions most frequently occur irrespective of their size. Although we might expect the resulting directions to coincide, the things investigated are quite distinct. The radial velocities confirm, in a general way, the existence of the two star streams, but at the same time suggest a modification of this explanation of the systematic motions of the stars, which may ultimately throw much light on the structure and mechanics of the universe.

16. SUMMARY

The main part of the preceding account deals with the brightness of the stars and with numerous questions connected with the determination of magnitudes. Simple counts of stars, if made to specified limits of a precisely determined scale of magnitudes, give much information about the form and extent of the stellar system, which appears to be a great flattened cluster, many thousand light-years in diameter, with the Milky Way as a structural feature of first importance.

Observing the colors of the stars, either with the spectrograph, or by comparing their visual and photographic magnitudes, we learn that objects in different physical states are not scattered at random throughout space, but show a characteristic arrangement with respect to the galactic plane.

From determinations of stellar distance and apparent magnitude, we find that the stars display an extraordinary range of intrinsic brightness. Occasional objects are 10,000 times as luminous as our Sun, while, at the other extreme, there are probably stars with only 1/10,000 part of the solar luminosity.

All the blue and white stars, intrinsically, are intensely bright, but for the redder color classes we find the remarkable subdivision into giants and dwarfs, with wide differences, not only in absolute magnitude, but perhaps also in density.

We also find important correlations of absolute magnitude with color and with the velocity of motion through space; and finally, we learn that the stellar system represents a high degree of organization in its motions, as well as in its form and structure.

THE 100-INCH REFLECTING TELESCOPE AT MOUNT WILSON[1]

In September, 1906, Director George E. Hale announced that Mr. John D. Hooker, of Los Angeles, had presented to the Carnegie Institution of Washington the sum of $45,000 to be used to purchase for the Solar Observatory a disk of glass 100 inches (2.54 m.) in diameter and 13 inches (33 cm.) thick and to meet other expenses incident to the construction of a 100-inch mirror for a reflecting telescope of 50 feet (15.24 m.) focal length.

Mr. Hooker had been interested in the Solar Observatory from the beginning. In 1904 he provided the funds which permitted Professor Barnard to bring the Bruce photographic telescope from the Yerkes Observatory to Mount Wilson and to spend the period from December, 1904, to September, 1905, in photographing portions of the Milky Way not readily accessible from more northern stations. These photographs,[2] we may note in passing, were excellent, and fully confirmed the favorable opinions which had been formed of the suitability for astronomical work of the atmospheric conditions on Mount Wilson.

In his deed of gift Mr. Hooker specifically left the Carnegie Institution free of any obligation to accept the mirror or to provide a mounting for it. He recognized the fact that the

[1] An illustrated lecture describing this powerful telescope was delivered in San Francisco on April 19, 1918, by Professor G. W. Ritchey to conclude the second series of Adolfo Stahl Lectures in Astronomy. Unfortunately, it has been impossible for Mr. Ritchey to put this lecture into written form, since his time has been completely occupied in war service for the United States Government. It was therefore decided, after consultation with members of the staff of the Mount Wilson Observatory, and with Mr. Ritchey's consent, to substitute for his address the present paper compiled by the editor of this volume.

The compilation is based chiefly upon the data in the Annual Reports of the Director of the Solar Observatory, supplemented by data kindly supplied by Mr. F. G. Pease, the man most closely associated with the design and construction of the mounting of the great telescope. Other published statements have also been used, and particularly the abstract of Professor Hale's recent address to the Royal Astronomical Society printed in the December, 1918, number of *The Observatory*. It has seemed unnecessary, in general, to use quotation marks in a paper which consists almost entirely of direct and indirect quotations. R. G. A.

[2] See Plate XLIX for a reproduction of one of these photographs. Many of the finer details shown on the original negative are of course lost in the process of reproduction.

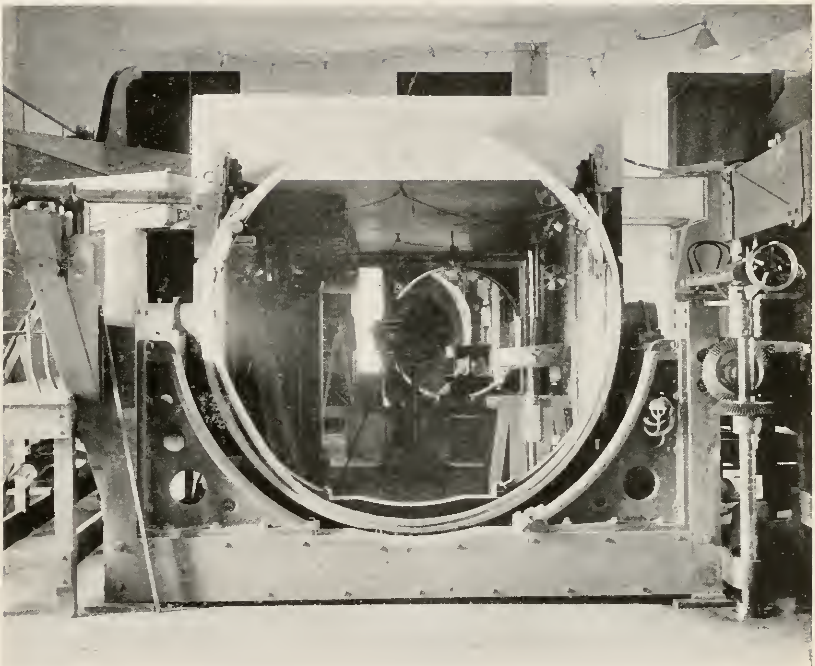

PLATE L. THE 100-INCH MIRROR.

(In the optical testing room, Pasadena.)

construction of a reflector of such great dimensions must be regarded as an experiment. It involved, in the first place, the casting of a block of glass of sufficient homogeneity weighing 4½ tons (the disk of the 60-inch reflector, then the largest silver-on-glass reflector in the world, weighs one ton!). Granting that this could be accomplished, and that it could be converted into a satisfactory mirror and provided with a mounting capable of carrying it with the necessary precision, it would still remain a question whether the atmospheric conditions on Mount Wilson or at any other station would prove sufficiently good to permit so great an aperture to be used to full advantage. While he was fully aware of these facts and did not underestimate the magnitude of the obstacles that must be overcome, he perceived and appreciated, with the understanding of one who had himself invented and developed mechanical appliances, that experiment was necessary to progress, and he did not hesitate to provide the means for undertaking an optical experiment on so large a scale.

He had evidently considered the matter very carefully before making his gift. He knew the reputation and the past performances of the French Plate Glass Companies of St. Gobain which had cast the block of glass for the 60-inch mirror; he had absolute confidence in the ability of Mr. Ritchey to make an essentially perfect mirror 100 inches in diameter; he did not question the power of engineers to design and build an adequate mounting; and he had a strong desire to realize the great possibilities in astrophysical research which such a large reflector would open. Even if it should prove that the great telescope could be utilized to the fullest advantage on only a very few nights in the year, its construction would still be desirable; and it had already been shown that the conditions on Mount Wilson were good enough on a large percentage of nights in the year to promise results fully commensurate with the size of the mirror in several classes of astronomical work in which large light-gathering power rather than the most perfect definition is essential—as, for example, the measurement of the heat radiation of the stars, or the spectroscopic study of very faint stars and spiral nebulae.

In announcing this gift Mr. Hale said: "No provision has yet been made for the mounting and dome. It is not known from what source funds for this purpose will come, but I believe a donor will be found by the time they are needed." This faith was justified by the event. Mr. Hale, in view of the very generous support it was already affording the Solar Observatory, had not intended to ask the Carnegie Institution for funds for the mounting and dome; but the splendid results obtained with the 60-inch and the greater possibilities of the 100-inch appealed so strongly to Mr. Andrew Carnegie that when making a new gift of ten million dollars to the Carnegie Institution, in 1912, he specified that provision should be made from this grant both for the mounting and for the dome.

In September, 1906, the 4½-ton block of glass was ordered from the French Plate Glass Companies of St. Gobain. The largest glass-melting pots they then had held only 1½ tons, hence it was necessary to make three pourings and to provide special appliances to combine these into a single block and to extend the time of annealing over a long period to reduce the danger of internal strain arising from cooling. By June, 1907, everything was in readiness and the first attempt was made early in July. It was not successful and repeated trials were necessary before a block was obtained which the firm considered suitable. This disk arrived in Pasadena late in 1908. Notwithstanding the pains taken in the casting, it was found at the first inspection by the opticians that there were large sheets of bubbles in the glass, due to the three separate pourings, and the disk was immediately rejected.

Though the work was trying and expensive, the glass company at once cheerfully proceeded to further experiments. They built a furnace in which twenty tons of glass could be melted at one time, and in 1910 and again in 1911 succeeded in making disks of the requisite size at a single pouring, but unfortunately on each occasion these cracked in the annealing. This long delay led to further examination of the disk already at Pasadena, and it was found that the sheets of air bubbles did not approach the surface so closely as to interfere with securing a perfect paraboloidal figure. Tests also showed that the glass as a whole was firmly knitted together in spite of the presence of the bubbles; the only obstacle to its successful use as an astronomical mirror, therefore, would be the existence of strains in the glass that would prevent it from maintaining its figure under changes of temperature. Whether or not such strains were present could only be determined by testing the glass under a greater range of temperature than that between the maximum to be expected in the dome (in summer) and the minimum (in winter).

While the experiments of the glass company were in progress, preparations were being made in Pasadena for the work of the opticians in figuring the mirror. These in themselves involved careful planning and not a little work. There was erected in Pasadena, in 1906-07, a special building (the Hooker Building) which included a fire-and-earthquake-proof room, 34 by 20 feet, in which to figure the glass, and, opening from it, a testing hall 100 feet long and 10 feet wide, both of which could be kept at constant temperature. The air entering the workroom was filtered, the walls of the room were varnished with shellac, and the floor was kept wet to prevent dust from rising and producing scratches on the glass. Since no mirror even approximating this one in size had ever been figured, it was necessary to design and construct a special grinding machine, special grinding and polishing tools, and other apparatus. A 60-inch disk for a plane mirror (*optically* plane) was received in 1909 and work on figuring and polishing it, in itself a problem of no small magnitude, was begun.

All of this preliminary work was sufficiently advanced to permit of making the temperature tests on the great disk in the course of the year 1911. The disk, for this purpose, was ground to a rough spherical surface; this figure was examined after the temperature had been reduced to 45° F. and maintained at that point for several days. As no distortion in figure could be observed, the temperature was next raised to 92° F. and the tests repeated. These also showed no distortion of figure and it thus seemed safe to proceed on the assumption that no prohibitive strains existed in the glass.

The work of figuring a great lens or mirror cannot be hurried. The grinding must be done with the greatest care, and frequent tests must be made to determine the precise stage reached; the farther the work proceeds the more often the tests must be made. During the three months of the year when it was necessary to employ artificial heat in the workroom in Pasadena it was found difficult to maintain satisfactory temperature conditions, and these months were accordingly devoted to the preliminary work on the subsidiary optical parts rather than to furthering the figuring of the main mirror. The plan of figuring adopted by Mr. Ritchey involved bringing the mirror first to a perfect spherical surface with a radius of curvature of about 84 feet, and then making the relatively small corrections needed to convert this surface into that of a paraboloid.

As an illustration of the minor problems that had to be solved, it may be noted that when the mirror began to approach the perfect spherical surface demanded it was found that, although fans had been installed to produce a thorough mixture of the air in the optical room and testing hall, sufficient stratification still existed to affect the tests seriously, and sufficient temperature variation between the top and bottom of the glass, when the mirror was set upright on its edge, to introduce a small amount of distortion. Special devices had to be employed to overcome these conditions.

Before the close of the year 1914 a satisfactory spherical surface had been obtained and the work of parabolizing was begun. By September, 1915, 80 per cent of the total change necessary had been accomplished, involving 90 days of actual figuring with the large machine. Optical tests were made each morning after a day's figuring; frequently repeated tests on different days were necessary before figuring could be resumed. These tests were made both at the center of curvature and at the focus of the paraboloid; the former method is better for determining the figure of the mirror as a whole, while the latter test is invaluable for detecting and correcting zonal errors in the general curvature. Throughout the figuring the Hartmann method of testing was used, the measurements of the photographic plates by Mr. Adams furnishing the most explicit data. Thus, through alternate figuring and testing, the mirror was skilfully brought to a perfect optical surface early in the year 1916. Members of the Astronomical Society of the Pacific who visited Pasadena in August, 1916, have vivid

PLATE LI.

A tube-section of the 100-inch telescope on the road up Mount Wilson. (See p. 252.)

memories of the great glass standing in the optical shop as shown in our illustration. Some idea of the precision with which the figuring and testing had to be done may be gained from the statement that at the center of the mirror, where the difference is greatest, the depth of the finished paraboloid differs from that of the nearest spherical surface (to which the glass was brought in preparation for parabolizing) by almost exactly 0.001 inch (0.025 mm.)!

The following numerical data may be of interest: When Mr. Hooker's gift was first announced in 1916 it was the intention, as stated in the first paragraph of this paper, to make the focal length 50 feet, giving a ratio of focal length to aperture of 6:1. Later it was decided to adopt a smaller ratio, approximately 5:1, and the actual focal length of the finished mirror is found to be 507.5 inches, the clear aperture being 100.4 inches. The depth of the curve at the center of the mirror is about 1.25 inches; the thickness of the glass at the edge, 12.75 inches; the weight is nearly 9,000 pounds. A curvature of only 1.25 inches in a diameter of 100.4 sounds small, but the concavity thus formed will hold 35 gallons of water.

Notwithstanding the great size and weight of the glass, the work of silvering its surface was accomplished without difficulty by placing the mirror upon the large polishing machine, which permitted rocking it during the operation and tipping it to pour off the solutions, both operations being accomplished by the motor-driven mechanism. The silver surface was produced by the approved modern method of pouring upon the glass simultaneously a dilute silver solution and a dilute reducing solution, thus forming, if skilfully done, a deposit of pure silver of uniform density over the entire disk. Thirty-two ounces of silver nitrate were used, and it required 15 minutes' time to form a coat of satisfactory density. This silver film, after being washed carefully with distilled water and allowed to dry, was burnished with the large polishing machine and a cushioned tool 34 inches in diameter, covered with six selected chamois skins.

Early in July, 1917, the great mirror was transported to the observatory prepared for it on Mount Wilson. The mirror was crated in a strong box lined with building paper and supported on its edge by a heavy framework bolted to the bed of the motor truck. To reduce the amount of vibration, numerous strong springs were inserted between the box and the framework. The top of the mirror box when placed on the truck was about 14 feet from the ground, and its weight, including the support, was 7.5 tons. Although the truck used had been specially designed to carry the heavy castings (one of nearly 11 tons weight) up the steep mountain road (the average gradient is about 1 in 11), and the road had been widened during the preceding years and carefully inspected just before the trip, one can readily imagine the feelings of relief of the members of the observatory staff when the mirror was safely at the summit. One of our illustrations gives a vivid idea of what might possibly have happened. In carrying a tube-section up the mountain a soft place in the road caused one wheel of the truck to drop a few inches. A chance tree and quick work alone prevented a disaster. A few more inches and truck and all might have rolled hundreds of feet down into a canyon. A "movie-man" accompanied the truck on nearly all trips when heavy pieces of the mounting were carried up to the observatory.

Plans for mounting the great mirror had engaged the attention of Director Hale, Professor Ritchey and other members of the staff from an early date. The great weight of the moving parts of the telescope had to be considered as well as the adaptability of the mounting to the various programs of work it was hoped might be undertaken. The designs of mounting and dome finally adopted are, as Mr. Hale puts it, really composite, being the work of Professor Ritchey in the earlier stages and later of Mr. F. G. Pease (who has also supervised their erection); but doubtless they incorporate also many suggestions by Mr. Hale, Mr. Adams and others. The mounting is of what is known as the English type, which has the advantage of compactness, and, in view of the great weight (100 tons) of the moving parts, is also, in the opinion of the designers, safer than any other type. By way of comparison, it may be noted that the moving parts of the great refractor of the Lick Observatory weigh only 14½ tons. The English type of mounting, however, has the disadvantage that the northern pier prevents the telescope from being turned upon a small

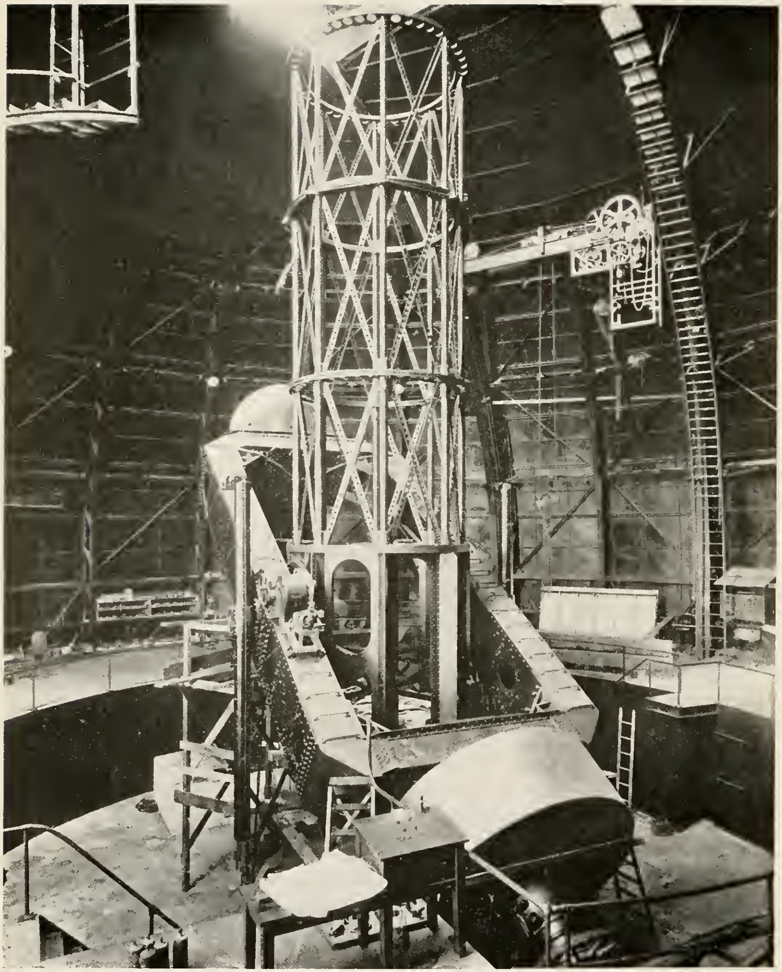

PLATE LII. The 100-Inch Reflector, October, 1917.

area of the sky centering at the north pole. As the illustration shows, the telescope is hung within a yoke or double fork, which measures 32 feet 8 inches by 16 feet 2 inches. To support the great weight, the system introduced by Dr. Common was used, in which the greater part of the weight is taken up by floating the polar axis in mercury. The upper float, on the northern pier, carries about 40 tons weight, the lower about 60 tons.[3]

The instrument is mounted upon a pier of reinforced concrete measuring 45 by 20 feet at the ground level and 32 feet 11 inches in height, raising the center of motion of the telescope to a distance of 50 feet above the ground. The top of the pier consists of a circular concrete floor 6 inches thick (18 inches over the pier proper) and 53 feet 10 inches in diameter. Massive reinforced concrete brackets extending outward from the pier on the east and west sides help to support this floor. The pier itself is hollow, and within it are two floors, the lower one for the reservoir for the large mirror temperature-control described in the following paragraph, the upper one for the driving-clock, worm, and quick-motion right-ascension mechanism. A room for resilvering the mirror, when necessary, is also included, and an electric elevator for handling the mirror moves through a 14-foot opening near the center of the pier.

The clock-work driving-worm goes into a wheel which is 17 feet in diameter. This wheel was cut in position on the mountain, each tooth being cut separately under the microscope, the wheel then hobbed and finally ground. All motions of the telescope are effected and controlled by electric motors. The mirror itself stands in its cell upon the usual lever-support system for the rear support and upon four edge-arcs resting upon knife-edges for edge supports. Behind the supporting plate there is a flat coil of copper pipe connected in series with several turns, one above the other, around the lower edge of the mirror. An anti-freezing solution whose temperature may be automatically controlled is circulated through these pipes from tanks in the pier. Fans blow over these coils and circulate the air all

[3] The heavier parts of the mounting were made at the Fore River Shipyards, near Boston, and it was necessary to send the four tube-sections by steamship to Los Angeles Harbor, for they were too large for railroad clearances. (The tube is 11 feet in diameter.) All the smaller parts and accessories were made in the observatory shops at Pasadena.

around the mirror. The mirror, supports, lower part of cell, coils, etc., are all enclosed in a cork-board chamber built integral with the telescope, the cover above the mirror being opened in the form of eight sectors when observations are made.

It is planned to use the mirror at the primary focus (507.5 inches) for a large proportion of the work; but two convex (hyperbolic) secondary mirrors are also provided to permit the use of the telescope in the Cassegrain form. One of these (28.75 inches in diameter and over 6.5 inches thick) gives, with the main mirror, an equivalent focal length of 1,606 inches; the other (25 inches in diameter and 5.5 inches thick), an equivalent focal length of approximately 3,011 inches. The tube-sections holding these smaller upper mirrors can be put into position with the aid of a crane attached to the dome and moving with it.

The mounting is so constructed that the telescope can be used also in the coudé form, the light gathered by the large mirror being thrown down the polar axis to the south by a secondary mirror. The pier proper has an extension running out to the south under the dome, the top sloping at an angle corresponding to the latitude of the observatory. A powerful concave-grating or plane-grating spectrograph rigidly attached to this extension, which is enclosed by an outer concrete wall and roof, will make it possible to secure spectra of the brighter stars on a very large scale, with an equivalent focal length of the telescope of 250 feet—a project which Mr. Hale has long cherished.

The circular steel building, 100 feet in diameter, which shelters the great telescope is of simple, almost austere, design, but it is fully worthy of the instrument within. The outstanding impression it makes upon the beholder is one of massive dignity. Resting upon two concentric rings of concrete piers as a foundation, it is as nearly as possible fire-and-earthquake-proof. The walls are double and the dome above is double-sheathed for protection against the Sun. The upper part of the dome, weighing 494 tons, rotates on rails. The upper floor, around the circular top of the great pier, forms part of the dome and rotates with it. This serves to stiffen

PLATE LIII. Dome of the 100-Inch Telescope, Mount Wilson.

As seen from the top of the 150-foot tower. Back range of the San Gabriel Mountains in the distance.

the dome and to enable it to turn very quickly and with little vibration. Electric motors turn the dome, operate the shutters, wind-screen, etc., while others are used to manipulate the telescope. In all, 35 motors are involved, and the electric wiring proved a task of very considerable difficulty.

In November, 1917, it was possible to make the preliminary tests of the 100-inch reflector under fair conditions of seeing. The instrument was not yet fully adjusted and the mirror temperature-control was not working. Nevertheless, the Moon and *Saturn* showed an extraordinary amount of detail; the star images, however, showed multiple, with considerable flare. War work was absorbing the energies and time of the staff to such an extent that the second test could not be made until September, 1918. Then, with the mirrors carefully lined up (a compression ring having been added to keep the convex mirror in position) and with the mirror temperature-control system in operation, it was found that the multiple images and all flare had disappeared and that the star images, in Mr. Ellerman's phrase, were "as hard and fine" as those seen in any telescope. The spectrograph for the Cassegrain focus at 1,606 inches has been completed except for the prism temperature-control, and on December 23, 1918, Mr. Pease secured several spectrograms with it. The ease with which the telescope worked he found to be remarkable; and the driving clock, which is designed to carry a maximum driving weight of two tons, ran with great surplus power with a weight of only 1,400 pounds, carrying the telescope from a position four hours east of the meridian to one four hours west without the slightest difficulty. Minor corrections and improvements still remain to be made to bring the instrument into the perfect adjustment at which its designers aim. For example, the polar axis will be more accurately aligned and a minute periodic error, which at present gives a drift of one-tenth of a second of arc, will be eliminated from the driving-clock. But it is safe to say that the telescope has now fairly passed the experimental stage and that it will be in use on a regular program of observation in the early spring of 1919.

What will it do that smaller telescopes can not do? This is the question that interests astronomers and laymen alike.

Prophecy is always dangerous, and Professor Hale and his associates are wisely reticent as to the answer. But a general statement may be ventured upon here.

First of all, it must be said most emphatically that sensational "discoveries" are not to be expected. Readers of Dr. Curtis's lecture on "Astronomical Discovery," in this volume, will hardly need to be reminded of this fact. Unexpected discoveries, in the popular sense, may come, of course, but advances in astronomy at the present day are made chiefly by the analysis of great quantities of material accumulated by patient and persistent observation, along lines laid down in carefully matured plans; and it is in work of this character that the new telescope will unquestionably be employed. Here it possesses two important advantages over other telescopes, arising from its great aperture, namely, the increase in light-gathering power and the increase in resolving power. The former brings within its grasp fainter stars; the latter makes it possible to study more minutely, photographically as well as visually, the details of various classes of celestial objects, such as the nebulae, for example.

The theoretical increase in light-gathering power of similar telescopes varies as the square of the aperture, and this increase in the case of the 100-inch with respect to the 60-inch will hold both at the primary focus and at the Cassegrain and coudé foci, for the proportion of light cut out by the secondary mirrors is about the same in the two instruments. Speaking in general terms, it may be said that the 60-inch reflector records the photographic images of stars as faint as the twentieth magnitude and gives, with reasonable exposure times, spectrograms of stars about 6.5 magnitude, which are comparable with those of stars of 5.5 magnitude taken with the Mills spectrograph attached to the 36-inch refractor of the Lick Observatory. The 100-inch should be able to proceed, in both cases, to stars about one magnitude fainter. Stated thus, the gains may seem unimportant; but turn to Table I, page 214, in the lecture by Professor Seares in this volume. It will then be seen that the gain of a single magnitude brings many tens of millions of fainter stars within the range of photographic records and fully triples the number of brighter stars available for spectrographic studies. These gains will be of the highest consequence in the solution of some of the fundamental problems of stellar motions and of stellar distribution in space; and experience with the 60-inch reflector indicates that the atmospheric conditions on Mount Wilson are amply good enough to permit their realization.

Whether or not the full power of the telescope can be realized in practice in studies requiring fine definition—as, for example, in the study of minute details of planetary surfaces or of the nebulae, or in the securing of stellar spectra of very high dispersion and resolution—it is impossible to predict, whatever our hopes and even expectations may be. We know that an aperture of 36 inches relatively to one of 6 inches magnifies the atmospheric disturbances almost in proportion to the gain in aperture. It is not certain that the same law will hold when we proceed from a 36-inch aperture to one of 100 inches. There are some indications from the experience with the 60-inch and with the new 72-inch (at the Dominion Astrophysical Observatory) that it will not. But even should this prove to be the case, there will be occasional nights when the conditions will be favorable to work requiring the finest definition, and we may rest assured that the fullest advantage will be taken of every such opportunity.