SOME RECENT CONTRIBUTIONS TO OUR KNOWLEDGE OF THE SUN [1]

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With Thirteen Plates

Mr. Secretary, Ladies and Gentlemen: When I was honored by an invitation to deliver the Hamilton Lecture, and to describe in it some of our recent solar investigations, I accepted with special pleasure, since it would afford me a fitting opportunity to acknowledge the important debt owed by the Mount Wilson Solar Observatory to the Smithsonian Institution. Soon after the Carnegie Institution of Washington was organized, Doctor Walcott, then Secretary of its Executive Committee, requested Secretary Langley, of the Smithsonian Institution, to express an opinion as to the advisability of establishing a solar observatory at some mountain station. Doctor Langley, who knew, from personal experience at Mount Whitney and other elevated points, the importance of conducting solar research above the denser and more disturbed portions of the atmosphere, strongly recommended to the Carnegie Institution that provision be made for the proposed observatory. In the subsequent consideration of this project by the Executive Committee, Doctor Walcott gave it his full support, and thus contributed in an important way toward the favorable decision finally reached. It is therefore easy to understand why we of the Solar Observatory owe a debt of gratitude to these Secretaries of the Smithsonian Institution. I beg to assure Doctor Walcott that his interest in our work is most heartily appreciated.

When one pauses to reflect that the United States possesses more astronomical observatories than any other nation, and that it is unsurpassed in its contributions to astronomical discovery, one may naturally ask why it seemed advisable to establish another new observatory. If it were a question of duplicating existing instruments, or of entering fields of research already well occupied, it is probable

[1] Lecture delivered at Washington, D. C., April 22, 1908, under the auspices of the Hamilton Fund of the Smithsonian Institution.

that a more effective use of available funds might have been found. But the aim of the Solar Observatory differs essentially from that of any other American institution. Hitherto the study of the Sun has been conducted at a disadvantage, partly for lack of suitable instrumental means and partly because of the obstacles arising from unfavorable atmospheric conditions; yet it would be easy to demonstrate that no other star in the heavens is so well worthy of our investigation. As the central body of the solar system, controlling the motions of the planets, and making life possible upon the Earth, the Sun has always been an object of admiration, and sometimes even of worship, to mankind. A permanent decrease of one hundred degrees (about 0.6 per cent) in the effective temperature of the Sun is considered by good authorities to be sufficient to produce another Ice Age on the Earth. So great a change could hardly occur; but smaller variations, due to internal causes, or to modifications in the absorbing power of the Sun's atmosphere, are very probable. Since solar phenomena follow more or less definite cycles of change, a better understanding of them might conceivably permit variations in its radiating power, sufficient to determine seasons of good or bad harvest, to be in some degree anticipated. The importance of solar research from this standpoint is thus sufficiently obvious.

But if the Sun commands our attention as the source and support of terrestrial life, it must appeal no less strongly to every intelligent person as the unique means of opening to us a knowledge of stellar development; for the student who would untangle the secrets of the universe recognizes in the Sun a typical star, placed conveniently within reach and exemplifying the physical and chemical conditions which are repeated in millions of other stars so far removed that they appear to us only as minute points of light. If we are to form a true estimate of the nature of these distant stars, and find the means of tracing out the progressive stages in their development from the nebulæ, we must base our investigations upon solar research.

The great disk which the Sun exhibits in our telescopes would shrink to the size of a needle point if removed to the distance of the other stars. This may be made clearer through a simple comparison. Consider the dimensions of the solar system so reduced that the diameter of the Earth would be one foot and that of the Sun 109 feet. The distance between them would then diminish from 95,000,000 to 2.2 miles, but the proportionate distance of the nearest fixed star would be 600,000 miles. This illustrates the comparative nearness of the Sun and the great advantages thus afforded of observing its various phenomena.

In this presence it is quite unnecessary to dilate upon the importance of the general question of evolution, or to discuss the relationship of the problems of the astronomer to the more complex ones encountered by the student of evolution in biology. It is evident that if we are to acquire a correct understanding of evolution in all of its phases, we should start from a knowledge of those processes which result in the formation of stars and the development of planetary systems. The generalizations of thinkers like Kant, Laplace, and more recent writers who have furnished hypotheses to explain the origin of suns and planets must be put to the test of observation. But these hypotheses leave untouched scores of questions relating to the physical state of stars in various stages of growth; their relation to one another and to their environment; their connection in systems, and the part they play in the universe as a whole. All of these questions lie within the province of the student of stellar evolution and call for the exertion of his best efforts to contribute toward their solution.

We thus see that solar research may be divided into two classes: (1) measurement of the intensity of the Sun's radiation, to determine whether the heat received by the Earth is constant or undergoes fluctuations; and (2) observation of the various phenomena of the Sun's disk, to determine the laws by which they are governed. The first of these subjects has been investigated with great success by the Smithsonian Astrophysical Observatory, established by the late Secretary Langley and directed by Mr. Abbot. The work of the Mount Wilson Solar Observatory lies in the second field. The two departments are closely related, and I am glad to say that through a plan arranged with Doctor Langley and extended by Doctor Walcott, the work inaugurated here in Washington is being continued by Mr. Abbot on the summit of Mount Wilson, in close coöperation with our own investigations.

It has been conclusively shown by Köppen, and confirmed by Newcomb, that the average temperature of the Earth, as determined by the combination of a great number of thermometer observations made at several stations, indicates a fluctuation of from 0°.3 to 0°.7 C. during the eleven-year Sun-spot period. The mean temperature is greatest at the time of minimum Sun-spots, and least at the time of maximum Sun-spots. This relationship having been proved to exist, it remains to inquire whether there is any direct connection between the mean temperature of the Earth at a given time and the total heat radiation of the Sun as measured at a point outside of the Earth's atmosphere. Since all observations must be made within the atmosphere, the determination of the correction to be applied to eliminate the loss by absorption becomes the most important and, at the same time, the most difficult part of this investigation. It is in this connection that the transparency and the uniformity of the atmosphere on Mount Wilson have proved to be so great an advantage in the work of the Smithsonian expeditions. The results already obtained by Mr. Abbot show that the heat radiation of the Sun ranges in value from 1.93 to 2.14 calories per square centimeter per minute, and seem to indicate a real variability outside of the Earth's atmosphere.

Newcomb. in his recent paper on "A Search for Fluctuations in the Sun's Thermal Radiation through their Influence on Terrestrial Temperature," is inclined to believe that such apparent variability must be due to changes in the absorption of our atmosphere, rather than in the heat radiation of the Sun. He was led to this conclusion by the fact that short-period temperature changes, such as would result from a change in the Sun's heat, are not shown to exist in an extensive examination of the Earth's mean temperature as recorded during a period of 34 years at 13 stations. Langley and Abbot, on the contrary, maintain that the method employed in their observations eliminates the effect of atmospheric absorption so completely that the observed variations must be due to changes within the Sun. The fact that the thermometer records employed by Newcomb were all made at seacoast stations, where the steadying effect of the ocean might tend to eliminate short period fluctuations, leads Abbot to doubt the validity of Newcomb's conclusions. His method having proved capable of showing the small progressive differences in the solar heat due to the change in the Earth's distance from the Sun during the period of observation, he sees no reason to dispute the solar origin of the larger differences. Since variations in the Sun's heat radiation could not fail to be accompanied by changes in other solar phenomena, investigations on the nature of these phenomena, and on their relationship to the so-called "solar constant," may yield reliable information as to the origin of such differences as Abbot has observed. The possibility of predicting variations in the mean temperature of the Earth caused by the influence of the Sun must depend upon the acquirement of much more complete knowledge than we now possess of the solar constitution. We thus perceive the intimate connection which unites the work of the Smithsonian Astrophysical Observatory with that of the Mount Wilson Solar Observatory, and recognize the importance, from this standpoint, of continuing and greatly extending solar research in all its phases.

Coöperation in Solar Research

The widespread appreciation of the importance of solar investigations is illustrated by the formation of the International Union for Coöperation in Solar Research, which counts among its members astronomers and physicists in many parts of the world. In the establishment of the Union the initiative was taken by our National Academy of Sciences, which invited various academies, as well as astronomical and physical societies in Europe and America, to send delegates to a preliminary meeting at Saint Louis in September, 1904. The favorable responses and the presence of delegates from the academies of Paris, Stockholm, Saint Petersburg, and Vienna, the Royal Society and the Royal Astronomical Society of London, the physical societies of Paris and Berlin, and other leading scientific bodies on both sides of the Atlantic promised well for the future of the Union. The preliminary organization effected at Saint Louis was given more definite form at Oxford a year later, where coöperative work was set on foot in the study of the spectra of Sun-spots, solar photography with the spectroheliograph, and the measurement of the solar radiation. It was also decided to adopt a new system of standard wave-lengths, based upon Michelson's determination of the length of the international meter in terms of the wave-length of the cadmium lines. The high degree of precision attained by Rowland in his *Table of Solar Spectrum Wave-lengths* no longer suffices for the needs of spectroscopists. The new system, based upon standards measured with extraordinary accuracy by the interferometer method, should provide a firm foundation for all spectroscopic investigations, whether of an astronomical or physical nature, for many years to come. As the primary standards are being measured by French, German, and American physicists, it will soon be possible to prepare new tables of the wave-lengths of the lines in solar, metallic, and gaseous spectra. A grant to assist in this work has been made by the Bache Fund, and it is hoped that the publication of the tables may be undertaken by the National Academy.

The spectra of Sun-spots, as will be shown later, contain a great number of lines, which require the most careful study. Hitherto our knowledge of spot spectra has been derived almost exclusively from the results of visual observations, made by individual observers without the aid of a general plan. As a natural consequence certain regions of the spectrum have been altogether neglected, and the time required for the identification of the lines has seriously limited the amount of work accomplished. A committee of the Solar Union, numbering among its members most of the active observers in this field, has now divided the spectrum into limited regions, one of which is selected by each observer. With the aid of the photographic map mentioned below, an observer may easily make an exhaustive study of the lines he has chosen. Although it will be shown that photographic observations are far superior to visual ones in most work on spot spectra, there are various phenomena in which the eye still has the advantage of the sensitive plate. The Solar Union has already secured valuable results through this coöperation, and many more may be expected in the future.

In accordance with a plan prepared by another committee of the Solar Union, the Sun is photographed almost every hour of the twenty-four with spectroheliographs in India, Sicily, Germany, France, Spain, England, Wisconsin, and California. This nearly continuous record of the calcium flocculi will soon be supplemented by similar work in Mexico, and there is some reason to hope that the Japanese and Australian governments will assist in overcoming the breaks in the record due to the absence of spectroheliographs between California and India.

Other committees are formulating plans for a coöperative attack on the problem of the solar rotation, securing greater uniformity in the methods of recording observations of the solar prominences and inquiring as to the advisability of coördinating the plans of eclipse expeditions. In every phase of the work the results to be derived from personal initiative and individual effort are recognized as likely to transcend in importance any that may follow from routine coöperation. From this standpoint the best accomplishment of the Solar Union is the creation of a renewed interest in solar research and in related problems of physics and astronomy. Every member is strongly encouraged to develop and extend his own ideas and methods, an aim by no means incompatible with the prosecution of coöperative work in fields where routine observations are essential. It is hoped that the large attendance and hearty interest which characterized the recent meeting of the Solar Union in Paris may not be lacking when the members again come together on Mount Wilson in 1910.

The Mount Wilson Solar Observatory

The Carnegie Institution was not slow to recognize the exceptional opportunities which, through a fortunate combination of circumstances, lay open to its proposed solar observatory. These included:

1. The application to the study of the Sun and stars of powerful

Fig. 1.—AT THE YERKES OBSERVATORY
Exposure $9^h\ 47^m$

Fig. 2.—AT MOUNT WILSON
Exposure $3^h\ 48^m$

THE PLEIADES

Photographed with the Bruce telescope (Barnard) spectroscopes and other instruments developed during the preceding quarter of a century in the physical laboratory, but still unused in the observatory.

2. The development of the spectroheliograph and of other research methods involving new principles.

3. The development of the reflecting telescope, in forms adapted for solar research and for physical investigations of the stars and nebulæ.

4. The more adequate recognition of the close union which should unite laboratory researches with solar and stellar investigations.

The opportunities enumerated above relate to the possibility of improving and extending the methods of astrophysical research. Another special opportunity had its origin in the basic principles which underlie the Carnegie Institution. A large proportion of the world's observatories are connected with universities or with institutions affected by local interests. The Carnegie Institution establishes its laboratories and observatories on the islands of the Carribbean Sea, the deserts of Arizona, the mountains of California, and at other points where their work can be done most effectively. On Mount Wilson, the long periods of cloudless weather, the purity of the atmosphere, and the absence, during a large part of the year, of winds and atmospheric fluctuations which seriously hamper astronomical work in most parts of the world afford great advantages. To illustrate the purity of the night sky, two photographs of the Pleiades, one made with an exposure of $9^h\ 47^m$ at Williams Bay, Wisconsin (1,200 feet), the other made at Mount Wilson (5,886 feet), with an exposure of only $3^h\ 48^m$, are reproduced in Plate XXIV. These were both taken by Professor Barnard with the 10-inch Bruce photographic telescope, on plates of equal sensitiveness and on nights of normal clearness at each station. Though the exposure time was two and one-half times longer at Williams Bay, yet the number of stars recorded at Mount Wilson is fully as great and the details of the nebula much sharper. Other proofs of the fine quality of the Mount Wilson atmosphere are afforded by many visual and photographic observations, made by night and by day, during the past three or four years.

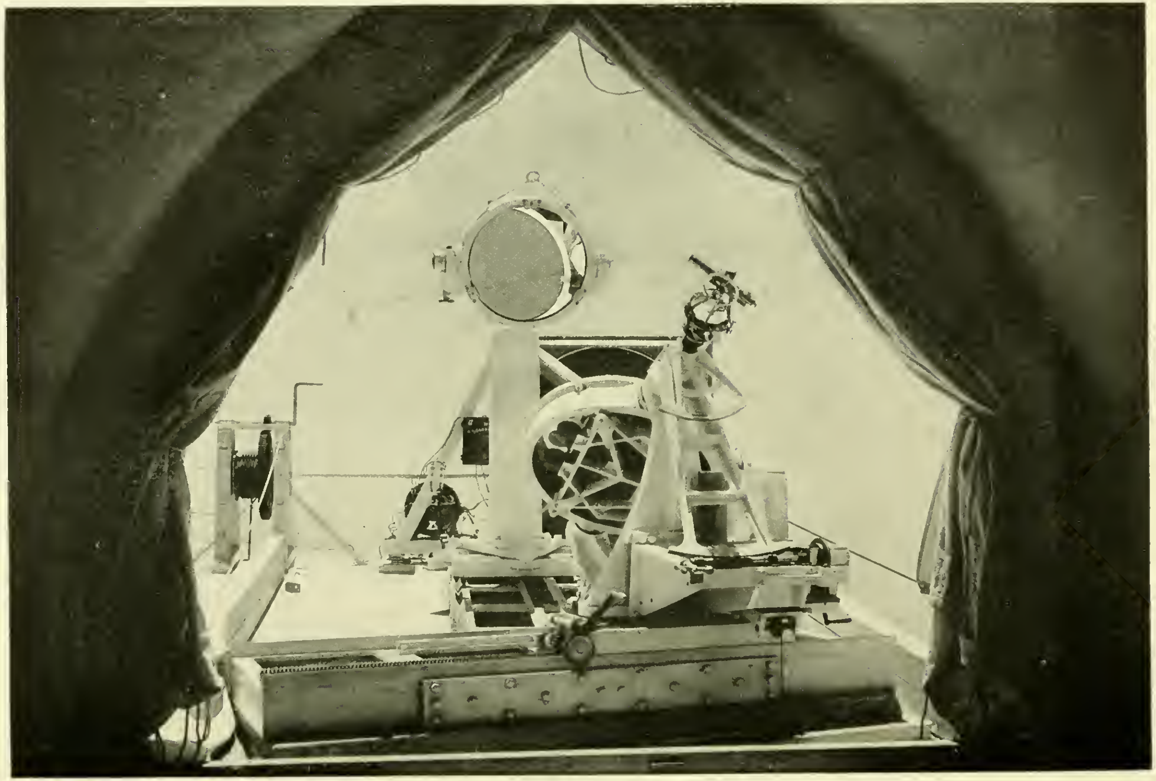
Plate XXV shows the summit of Mount Wilson, where a large tract of land has been set apart for the purposes of the observatory. This site commands a magnificent view of southern California, extending on the east to the snowy peaks of the San Bernardino Range, on the west to islands lying far out in the Pacific, on the north to an endless succession of mountains tributary to the high Sierras, and on the south to the Mexican frontier. In the San Gabriel Valley, lying at the base of Mount Wilson, and about eight miles distant in an air line, is the city of Pasadena. Here a large part of the observatory work, such as various laboratory investigations, the design and construction of instruments, and the measurement and discussion of astronomical photographs taken on the mountain, is conducted. By confining the work on Mount Wilson almost entirely to observations, the expense of maintaining the rest of the establishment there is avoided and many other advantages are secured.

In enumerating the various opportunities which lay open to the Solar Observatory at the time of its inception, the possibility of bringing into use large and powerful spectroscopes, which had been developed in physical laboratories, was first mentioned. In 1859 Kirchhoff discovered with the spectroscope the chemical composition of the Sun, and proved that this instrument is capable of analyzing the light which reaches us from any luminous source. When applied later to a study of the phenomena of the Sun and stars, the spectroscope, then of small dimensions, was simply attached to the end of a telescope tube. The invention of the concave grating by Rowland in 1882, and the widespread use of this powerful instrument in physical laboratories, introduced a new era, through the great increase in precision of measurement rendered possible by its high dispersion. In astronomy, however, the equatorial refractor continued to be the popular form of telescope, and the spectroscope, though improved in many particulars, did not increase greatly in size. It was obviously impossible to attach a concave grating spectroscope over 21 feet in length to the end of a moving telescope tube. Consequently the precision of measurement in astronomical spectroscopy has been far inferior to that attained in the laboratory.

The Snow Telescope

At the period when the plans for the Solar Observatory were taking form, the principles which should govern the construction of a fixed telescope were partly understood, and had been frequently applied in eclipse observations. Almost simultaneously with our experiments with fixed telescopes at the Yerkes Observatory, a large instrument of this type, giving a solar image well suited for bolometric work, was constructed for the Smithsonian Astrophysical Observatory. Such telescopes, however, had not been used for researches demanding a large and sharply defined solar image. The Snow telescope, constructed in the instrument shop of the Yerkes

MOUNT WILSON AS SEEN FROM MOUNT HARVARD



COELOSTAT AND SECOND MIRROR OF SNOW TELESCOPE

Observatory, with the aid of funds given by Miss Snow, of Chicago, had its first trial shortly before our work on Mount Wilson was undertaken. It was afterwards brought to California in connection with an expedition sent out by the Yerkes Observatory, with the aid of a grant from the Carnegie Institution, and was ultimately purchased by the Mount Wilson Solar Observatory as a part of its permanent equipment.

This instrument is designed to give a sharply defined image of the Sun, nearly 7 inches in diameter, at a fixed position within a laboratory, where its various details can be investigated with spectroscopes or spectroheliographs of any desired dimensions. The cœlostat shown in Plate XXVI carries a mirror 30 inches in diameter, mounted so that the plane of its front (silvered) surface is exactly parallel to the Earth's axis. When this mirror is rotated by a driving-clock at such a rate that it would complete a revolution in forty-eight hours, a beam of sunlight reflected from it is maintained in a fixed position, in spite of the apparent motion of the Sun through the heavens. This beam falls upon a second silvered mirror, 24 inches in diameter, which sends the rays toward the north. Both of these mirrors have optically plane surfaces, and their function is merely to bring the Sun's rays into the telescope house and to direct them upon a concave mirror 24 inches in diameter, mounted 95 feet north of the cœlostat. This mirror, which may be regarded as the telescope proper, returns the rays 60 feet toward the south to a point just outside of the entering beam, where it forms an image of the Sun nearly 7 inches in diameter. By setting the concave mirror at the proper angle, the solar image can be made to fall upon the slit of a spectrograph of 18 feet focal length, or upon the slit of a large spectroheliograph. Both of these instruments are mounted on massive stone piers. Thus all restrictions as to the dimensions and weight of such auxiliary apparatus are removed.

The house in which the Snow telescope is mounted (Plate XXVII) was designed with the object of keeping the temperature of the air within it as nearly as possible the same as that of the outer air. It is constructed of a light steel framework covered with canvas louvers and provided with a ventilated roof. Without such precautions the air within the house would become heated during the day, and the difference in temperature between the inner and outer air would cause distortion of the solar image and consequent blurring of its details. In practice, on day after day in the summer months, the image of the Sun given by the telescope during the early morning hours is nearly as clear and distinct as a steel engraving.

If this solar image (obtained with reduced aperture of the concave mirror) is permitted to fall for less than the thousandth part of a second upon a photographic plate, a picture of the Sun will result. Such pictures are made every clear day, in the early morning or late afternoon, when the atmospheric conditions are at their best. They show the Sun as it appears to the eye in visual observations. The principal solar phenomena visible on such photographs are the Sun-spots, several of which appear in Plate XXVIII. These spots, when observed under the best conditions, are found to have an extremely intricate structure, which changes from hour to hour, and sometimes from minute to minute, under the observer's eye. Individual spots sometimes exceed 90,000 miles in length, but their area is very small as compared with that of the entire solar disk. Thus the great group of February, 1892, had a length of 166,000 miles and a breadth of 65,000 miles. Its area was eighteen times as great as that of the Earth, but only 0.15 of one per cent of the solar surface.[1]

Photographic Investigations of Sun-spot Spectra

In spite of the fact that Sun-spots have been under observation for nearly three hundred years, little is known as to their true nature. Various theories to account for them have been brought forward, but the complexity of the phenomena and the lack of sufficient observational data have stood in the way of accurate knowledge. It is not certainly known, for example, whether Sun-spots are to be regarded as elevated regions or as depressions below the general level of the solar surface. Even the cause of their darkness has remained uncertain, and astronomers have differed as to their temperature, some contending that they are much hotter than other parts of the Sun, and others believing them to be comparatively cool. In support of his theory that the chemical elements are broken up into simpler constituents at very high temperatures, Lockyer adduced observational evidence of a periodic change in the Sun-spot spectrum. At times of maximum solar activity, when spots are numerous on the Sun, Lockyer found the most conspicuous lines in their spectrum to be of unknown origin. Five or six years later, when the solar activity had declined to a minimum, these lines seemed to be replaced by the well-known lines of iron and other familiar substances. Lockyer accordingly concluded that at the maximum the temperature of Sun-spots was sufficiently high to break up iron and

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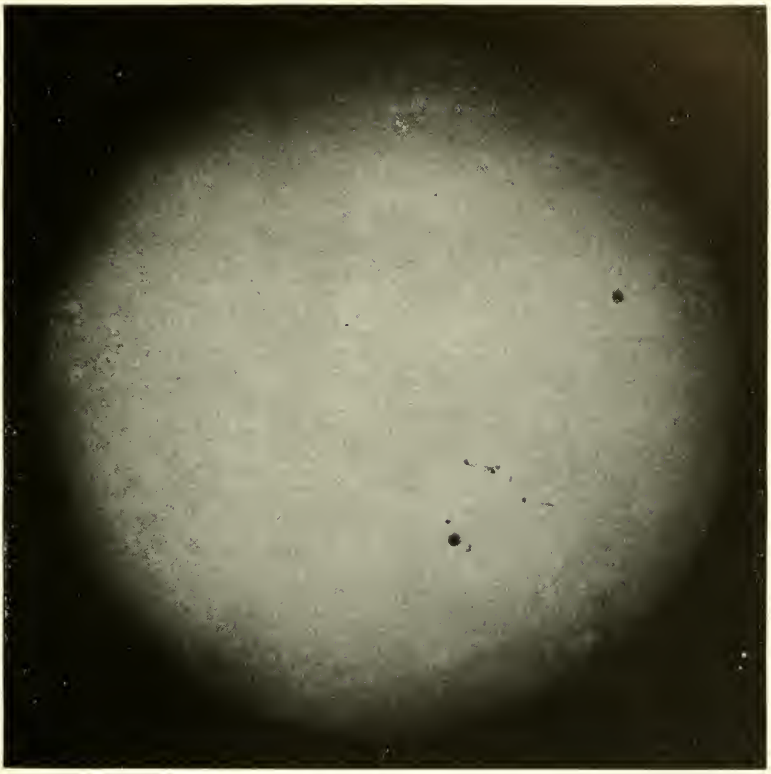
[1] Maunder, *Journal British Astronomical Association*, vol. XVII, p. 126.

SOUTH END OF SNOW TELESCOPE HOUSE ON MOUNT WILSON



DIRECT PHOTOGRAPH OF THE SUN

August 25, 1906, 6^h 09^m A. M.

other elements into simpler substances, whose spectra, being unknown on the Earth, could not be identified.

If we analyze the light of a Sun-spot with a spectroscope, we find that the Fraunhofer lines of the solar spectrum are almost all present, though their relative intensities are greatly changed. Many solar lines, for example, are much strengthened or widened where they cross the spot, while others are weakened or, in some cases, completely obliterated. Lockyer's method of observation is to record, day after day, the most conspicuous lines in the spot spectrum—those of the solar lines which are most widened or strengthened. Under the ordinary conditions of visual observation, the study of the spot spectrum is a difficult operation, on account of the immense number of lines affected. Recognizing this, Lockyer confined his attention to only twelve lines, in the expectation that their variations would sufficiently indicate the nature of any changes going on within the spot. The inadequacy of this method has been shown by recent results, which give no indication that the spot spectrum undergoes a radical change in passing from maximum to minimum solar activity, and demonstrate that an interpretation of the true meaning of the strengthened and weakened lines must involve the systematic study not merely of twelve lines, but of a far larger number.

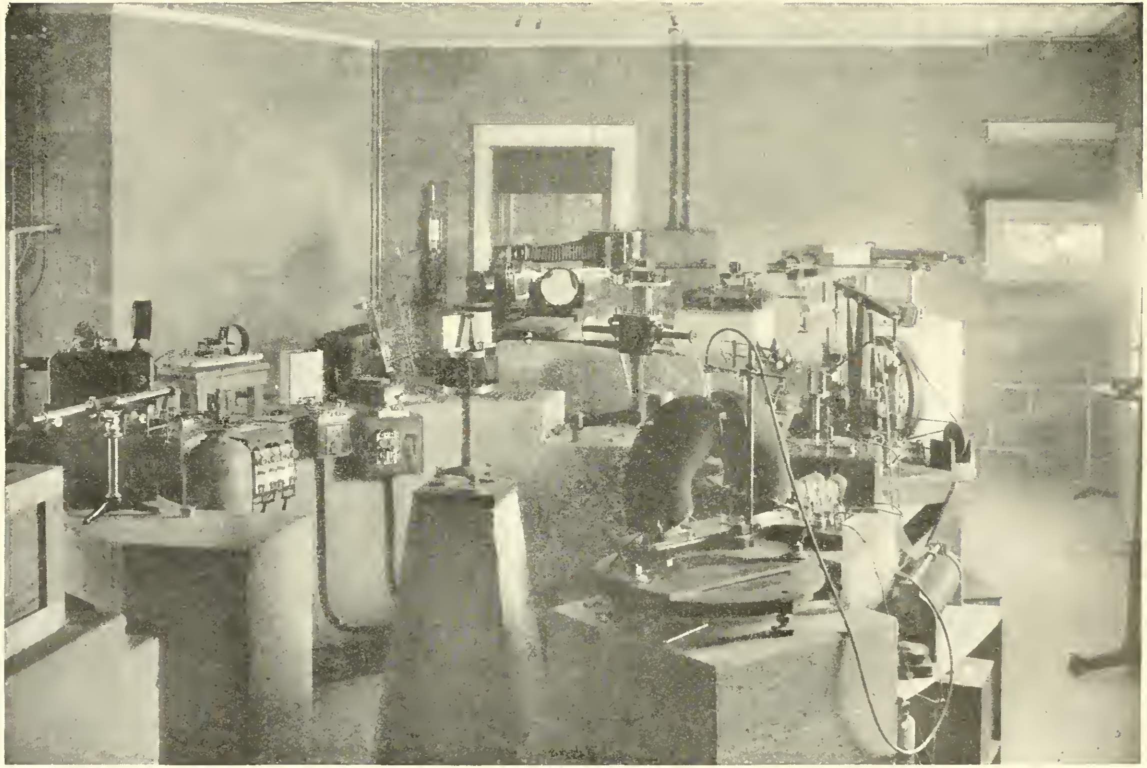
When the Snow telescope was first employed for this work, only a few hundreds of lines had been catalogued in the entire Sun-spot spectrum. Previous experiments at the Kenwood and Yerkes observatories had indicated that the application of photography would probably make possible an important advance, provided a spectrograph of sufficiently high dispersion were employed. A Littrow spectrograph of 18 feet focal length, having a plane Rowland grating ruled with 14,438 lines to the inch, was accordingly constructed for use with the Snow telescope. Good photographs of spot spectra were soon obtained with this instrument. After some minor technical difficulties had been overcome, it appeared that the photographs could be counted upon to show nearly all that can be seen visually, while at the same time they would permit the positions of the lines to be accurately measured and their relative intensities to be determined. From negatives taken with the Snow telescope, Ellerman prepared a preliminary map of the Sun-spot spectrum, extending from the violet to the extreme red. Casual inspection of this map, which comprises twenty-six sections of one hundred Ångströms each, is sufficient to show that the number of lines whose intensities are affected in Sun-spots is several thousands. In the hands of observers coöperating in the work of the International Solar Union, this map has greatly facilitated visual observations, and has considerably strengthened the view, now almost universally held, that the Sun-spot spectrum undergoes few striking variations from spot to spot or at different periods in the eleven-year cycle of solar activity.

The negatives having been secured and a preliminary map of the spectrum prepared, it became necessary to draw up a catalogue of all the lines affected, showing their intensities in the spot and in the ordinary solar spectrum. The first section of this catalogue, extending from λ 4000 (the extremity of the visible spectrum) to λ 4500 in the violet, has been published by Adams.[1] In this limited region of the spectrum, where the Sun-spot and solar spectrum were previously regarded as identical, about eight hundred lines of altered intensity are recorded. The publication of the second section of the catalogue has been somewhat delayed by the fact that negatives of the spot spectrum made with the 30-foot spectrograph of the new "tower" telescope (p. 356) are so much superior to the earlier plates that the results obtained from them must also be added. As the complexity of the spot spectrum increases from this region toward the green and yellow, it is evident that the complete catalogue will comprise many thousands of lines.

Having thus acquired suitable data, the next step was to attempt to interpret the true meaning of the Sun-spot spectrum. At this point the need of laboratory experiments presents itself. Take, for example, the spectrum of iron in a Sun-spot. The photographs show that many of the iron lines are relatively much stronger than the corresponding ones in the solar spectrum, others are reduced in intensity, and others are essentially unchanged. From experiments on the spectrum of iron as observed in the laboratory, it is known that the relative intensities of its lines depend upon the physical conditions under which the vapor is observed—*i. e.*, that variations in the pressure, temperature, density, or electrical state of the vapor are competent to affect their relative intensities. Adequate information on this subject, however, is lacking. It was therefore necessary to observe the effect of varying these physical conditions, in the hope that the results might be applied to the interpretation of spot phenomena.

The apparatus provided on Mount Wilson for work of this character is illustrated in Plate XXIX. Around the annular pier are ar-

[1] *Contributions from the Solar Observatory*, No. 22, *Astrophysical Journal*, vol. 22, pp. 45–65, January, 1908.



THE SPECTROSCOPIC LABORATORY ON MOUNT WILSON

ranged various light sources, in each of which the physical conditions can be controlled by the observer. One of the simplest ways of vaporizing iron is to place fragments of the metal between the carbon poles of an ordinary arc light. By varying the amount of metal present in the arc, the effect of change of density of the vapor can be observed. To study the influence of change of pressure. the arc must be inclosed within a chamber, so constructed that air or some other gas can be admitted and raised to the desired pressure. The effect is to shift the lines of the spectrum toward the red, and by measuring the displacement produced by an increase in pressure of one atmosphere, the pressure within a Sun-spot or in a star, corresponding to any observed shift of the lines, can be determined. To ascertain the effect of change of temperature upon the spectrum, the iron vapor at the very hot center of the arc may be compared with the cooler vapor in the outer part of the flame. If the highest temperature of the arc is not sufficiently great, a powerful electric spark, taken between two poles of iron, will afford a still hotter light-source. Apparatus suitable for all of these purposes and for other similar ones is arranged upon the annular pier. When the light from any particular source is to be investigated, it is reflected from a plane mirror at the center of the circle to a concave mirror (shown near the middle of Plate XXIX), which forms an image of the source on the slit of a powerful spectrograph.

For various reasons it seemed probable that reduced temperature might be the cause of the strengthening and weakening of lines in spot spectra. Accordingly, special attention was directed to a study of the effect of temperature change on the relative intensities of the lines. After an extensive investigation it was found that the iron lines whose relative intensities increase at reduced temperatures are invariably among the lines which are strengthened in Sun-spots. Moreover it was also found that the iron lines which are weakened at reduced temperatures are weakened in Sun-spots. After these experiments had been extended from iron to titanium, vanadium, chromium, manganese, cobalt, nickel, and other substances conspicuously represented in Sun-spots, the conclusion was reached that a reduction in temperature of the spot vapors is competent to explain a large part of the characteristic spectral phenomena. Assuming this hypothesis to be correct, one would naturally be led to ask whether the temperature of the spot vapors is sufficiently reduced to permit elements existing uncombined at the higher temperature of the solar surface to enter into combination within the spot. Titanium and oxygen, for example, both occur among the vapors which lie above the photosphere. Is the temperature within the spot low enough to permit these substances to combine?

For many years the spot spectrum had been known to contain a number of bands and of faint lines, but none of these had been identified. Fortunately, the photographs obtained with the Snow telescope show these bands far better than they can be seen visually, and bring to light many new bands and thousands of faint lines of unknown origin. Fig. 1, Plate XXX, illustrates a comparison of one of the red titanium oxide bands, made up of a great number of fine lines terminating in three distinct heads, with the corresponding region in a photograph of the spot spectrum. It will be seen that practically all of the lines of the band photographed in the flame of the electric arc are present in the spot. As many other titanium bands have been found on the photographs, we now know not only that many hundreds of the spot lines can be accounted for in this way, but also that the hypothesis of reduced temperature is partially confirmed. This identification of the titanium oxide flutings is due to Adams. Soon after its publication, Fowler, of London, found some of the bands in the green portion of our photographic map to be due to magnesium hydride, another compound capable of withstanding high temperatures. Still later, Olmsted discovered in our Mount Wilson laboratory that certain spot bands in the red are due to calcium hydride. He is continuing the search for other compounds with improved apparatus in our new Pasadena laboratory. The investigation may be an extensive one, because the spectra of only a few of these compounds, which are formed at the high temperature of the electric furnace, have hitherto been observed. Even in these cases no large scale photographs, or sufficiently accurate measurements of the lines, have been published.

The presence of compounds in spots appears favorable to the hypothesis of reduced temperature, though it does not settle the question beyond doubt. It next became interesting to inquire whether analogous conditions could be found among the stars. As already remarked, the stars are so distant that their images in the most powerful telescopes are mere needle points, so that objects like Sun-spots, if they exist on the stars, cannot be observed. According to current ideas of stellar evolution, the stars pass through a long process of development, during which their temperature, perhaps comparatively low in the embryonic stage represented by the condensing nebulæ, reaches a maximum in the white stars, and then declines during the period of old age exemplified in the red stars. If, then, a Sun-spot is a mass of solar vapors reduced somewhat in

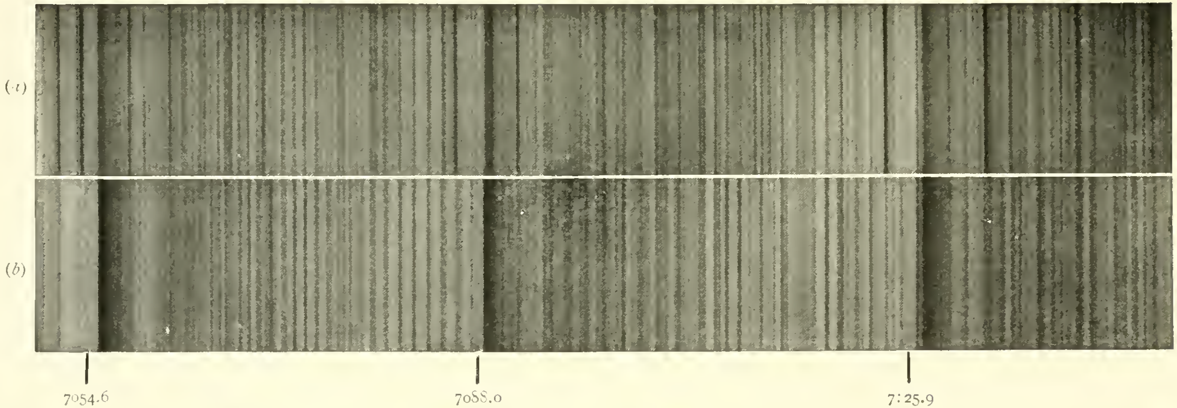


Fig. 1.—TITANIUM OXIDE FLUTINGS IN SPECTRA OF (*a*) SUN-SPOT AND (*b*) FLAME OF ELECTRIC ARC

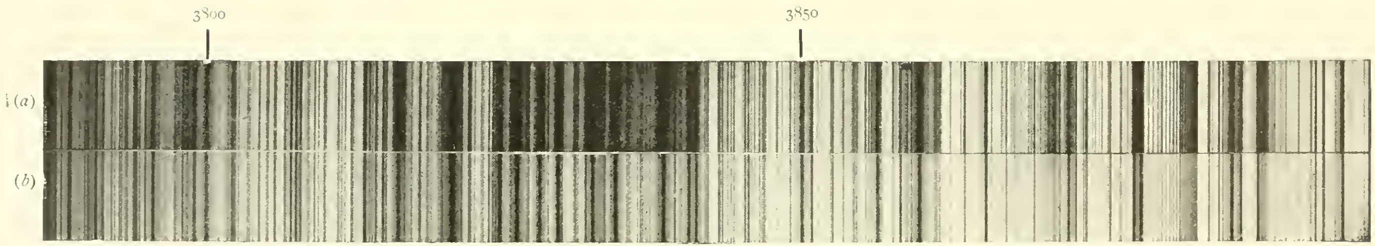


Fig. 2.—SPECTRUM OF SUN (*a*) AT CENTER AND (*b* NEAR LIMB

temperature, a red star, assumed to have the same composition as the Sun, might be expected to give a spectrum resembling that of a Sun-spot, if its temperature were the same.

In order to test this question with sufficient precision, the spectra of *Arcturus,* an incipient red star, and of *α Orionis,* a conspicuous red star in the constellation of *Orion,* were photographed with a very powerful spectrograph. Here, again, the principle of using a high dispersion spectrograph, mounted on a massive stone pier in a constant temperature chamber, was substituted for the ordinary method of attaching a small spectrograph to the tube of a moving telescope. The Snow telescope provided a fixed image of the star, and it was only necessary to maintain this upon the slit of the spectrograph during an exposure long enough to permit the greatly dispersed light to impress itself upon the photographic plate. With the comparatively small aperture of the Snow telescope, exposures of from fifteen to twenty hours, carried on through several successive nights, were required. The great amount of light which will be collected by our 60-inch reflector will reduce these exposures and will also permit fainter stars to be photographed with high dispersion.

A study of the plates thus obtained showed an interesting parallelism between the relative intensities of the lines in the spectra of these stars and those of Sun-spots. Many of the lines that are strengthened in spots are strengthened in these stars, and many of the lines that are weakened in spots are weakened in these stars. There are some important points of difference, probably due to the fact that the relative intensities of the lines in spots and stars are not determined solely by temperature condition. In general, however, the agreement is sufficiently close to indicate the probability that a common cause—reduced temperature—is at work in both cases. If any doubts remained as to the resemblance between the spectra of red stars and Sun-spots, they were removed when the titanium oxide bands were discovered in our photographs of spot spectra. These bands are the characteristic feature of one of the two great classes of red stars, their spectra showing them in all degrees of intensity, from the comparative faintness which delayed their discovery in Sun-spots to the blackness observed in such deep red stars as *α Herculis* and *Antares.* The absence of these bands in the other great class of red stars, in whose spectra the bands of carbon (not found in Sun-spots) predominate, suggests interesting possibilities in future work on the Sun's stellar relationships.

These results leave unanswered scores of questions involved in the complete interpretation of Sun-spot spectra, and do not even afford conclusive evidence that reduced temperature is the principal agent in determining the relative intensities of the lines. They nevertheless carry us a step forward in our study of solar physics and are of special service in illustrating the interdependence of solar, laboratory, and stellar investigations. They render evident the importance of increasing our knowledge of the Sun, of imitating solar phenomena and interpreting solar observations by means of laboratory experiments, and of using these investigations as a guide to the study of the stars and nebulæ.

Spectra of the Limb and Center of the Sun

Many years ago, when a student at Yale, Hastings made a comparative study of the spectra of different parts of the Sun's disk, devoting special attention to any differences that might distinguish the light of the center from that derived from points very near the limb. Although his instruments were inadequate for the task and his observations necessarily visual, he nevertheless noticed slight differences in the appearance of a few lines. Strangely enough, the importance of this work was overlooked by later investigators, though Halm, two years ago, without perceiving the differences noted by Hastings, detected a slight displacement of certain lines at the limb as compared with their positions at the center of the Sun. Halm's work was also visual and accomplished with a comparatively small spectroscope. Had he used a more powerful instrument and benefited by the aid of photography, he would doubtless have discovered the interesting series of phenomena which the Snow telescope and 18-foot spectrograph have brought to light.

Some of these are illustrated in Fig. 2, Plate XXX, which represents only one region of the spectrum. The broad diffuse wings which accompany many lines are greatly reduced in intensity near the limb, and in a number of cases disappear entirely. The relative intensities of the lines themselves undergo marked changes, resembling in most instances the changes observed in Sun-spots; that is to say, the lines that are strengthened in Sun-spots are usually strengthened near the Sun's limb, while the lines that are weakened in Sun-spots are weakened near the limb. However, the phenomena are by no means strictly parallel, and much work will be required to arrive at their true meaning. Perhaps the most interesting effects observed at the limb are the displacements of the solar lines with respect to their positions at the center of the Sun. In general, the relative displacements for different lines agree fairly well in magnitude with those observed for the same lines in the laboratory when a source of light containing the vapor in question is observed under pressure. That increased effective pressure near the limb is probably the cause of the line-shifts is further illustrated by the fact that the lines in bands or flutings, such as those of cyanogen (shown in Fig. 1, Plate XXX), which are not displaced by pressure in the laboratory, retain the same relative positions at the center and limb.

These changes, and many others which it would be tedious to enumerate, have been observed on photographs taken by Adams and myself for the purpose of extending and perfecting our interpretation of Sun-spot spectra. Almost the entire extent of the spectrum has been photographed and a large scale-map showing the differences between the spectra of the limb and center is now in preparation. The work of measurement is necessarily long and trying, since the positions of hundreds of lines must be determined on many photographs with the extreme precision required to reveal the minute displacements concerned. For the interpretation of the results extensive laboratory investigations on the effect of pressure must be carried out, and special apparatus for this purpose is now being prepared. Moreover, the possibility that anomalous dispersion and other physical phenomena are involved must not be overlooked; and here, again, much laboratory work must be done.

The Solar Rotation

In mentioning the cyanogen band, I remarked that it occupies the same position at the center of the Sun and at the limb. This is true, of course, only after the effect of the solar rotation has been corrected. All the lines of the spectrum, when observed at the east limb of the Sun, are displaced toward the violet, while at the west limb they are displaced toward the red, with respect to their normal place as given by the light of the center of the Sun. The displacements here involved are due to the Sun's axial rotation, and afford the most accurate means we possess of determining its velocity. The east limb of the Sun, in the region of the equator, is moving toward us at the rate of 2.08 km. per second. Such a motion of a luminous source shifts the lines of its spectrum a small distance toward the violet. At the west limb, the motion being away from the observer, the displacement is toward the red. In practice, the spectrum of the east limb is photographed side by side with that of the west limb, so that the double displacements may be measured.

These displacements have been studied by Adams, who has utilized the facilities offered by the Snow telescope and the 18-foot spectrograph to carry out what is probably the most accurate spectroscopic investigation of the solar rotation hitherto accomplished. In the earlier investigations of Dunér and Halm, both of which exhibit a high degree of precision, visual observations were employed, and as all of the measures had to be made at the telescope, the observers restricted themselves to the use of only two lines. The advantages of photography are obvious when it is remembered that in a single short exposure a portion of the spectrum from 15 to 20 inches long, showing opposite limbs of the Sun and containing thousands of lines suitable for measurement, can be recorded upon a sensitive plate. The work on Mount Wilson is limited to making the photographs, which are afterwards measured in the Computing Division at Pasadena, with measuring machines which give the positions of the lines within about one-thousandth of a millimeter. Since iron, calcium, carbon, sodium, hydrogen, and other elements are represented on the plates, it is possible, by measuring the displacements of the corresponding lines, to determine the velocity of rotation of the vapor due to any one of these elements.

The lines measured by Adams (assisted by Miss Lasby) include some for each of the following elements: iron, manganese, nickel, titanium, lanthanum, carbon, chromium, and zirconium. The following table gives the values obtained for different latitudes:[1]

Latitudes.	Velocity, km. per second.	Daily angular motion.	Rotation period, days.
°		°	
0.2	2.078	14.75	24.39
7.7	2.023	14.50	24.83
15.0	1.957	14.39	25.01
22.7	1.808	13.92	25.86
29.7	1.673	13.68	26.32
37.7	1.461	13.11	27.46
44.7	1.279	12.77	28.19
52.7	1.055	12.35	29.15
59.6	0.864	12.13	29.68
65.7	0.696	11.99	30.02
74.9	0.434	11.85	30.38
80.4	0.277	11.84	30.40

It will be seen that, as in the case of Sun-spots, the period of the Sun's rotation increases from the equator toward the poles. Theoretical investigations suggest that this remarkable law of rota-

[1] Adams: *Contributions from the Solar Observatory*, No. 20, *Astrophysical Journal*, vol. XXVI, pp. 203–224, November, 1907.

tion dates from a former epoch in the Sun's history, and that it perhaps arose from the motion of the gases concerned in the formation of the Sun from a nebula. After the lapse of some millions of years, the effect of internal friction will tend to bring the velocities corresponding to different latitudes more and more closely into harmony, and finally the Sun will rotate as a solid sphere.

One of the most important results obtained by Adams is the discovery that the lines of carbon and lanthanum, elements which lie at a low level in the Sun's atmosphere, give values for the daily rate about 0°.1 less than the mean values for all of the lines measured. Two lines of manganese, on the contrary, give systematically high results. It seems probable that these differences are due to differences in the level of the vapors of these elements in the solar atmosphere, and that those substances which lie at high altitudes complete a rotation in a shorter period than the vapors beneath them. This supposition is confirmed by the fact that Adams's recent measures of the velocity of hydrogen, which rises higher above the solar surface than any of the vapors included in the above investigation, give very high values. Moreover, as the following table shows, the rotational velocities of hydrogen in low and high latitudes are in close agreement, and the equatorial acceleration characteristic of lower levels does not exist.

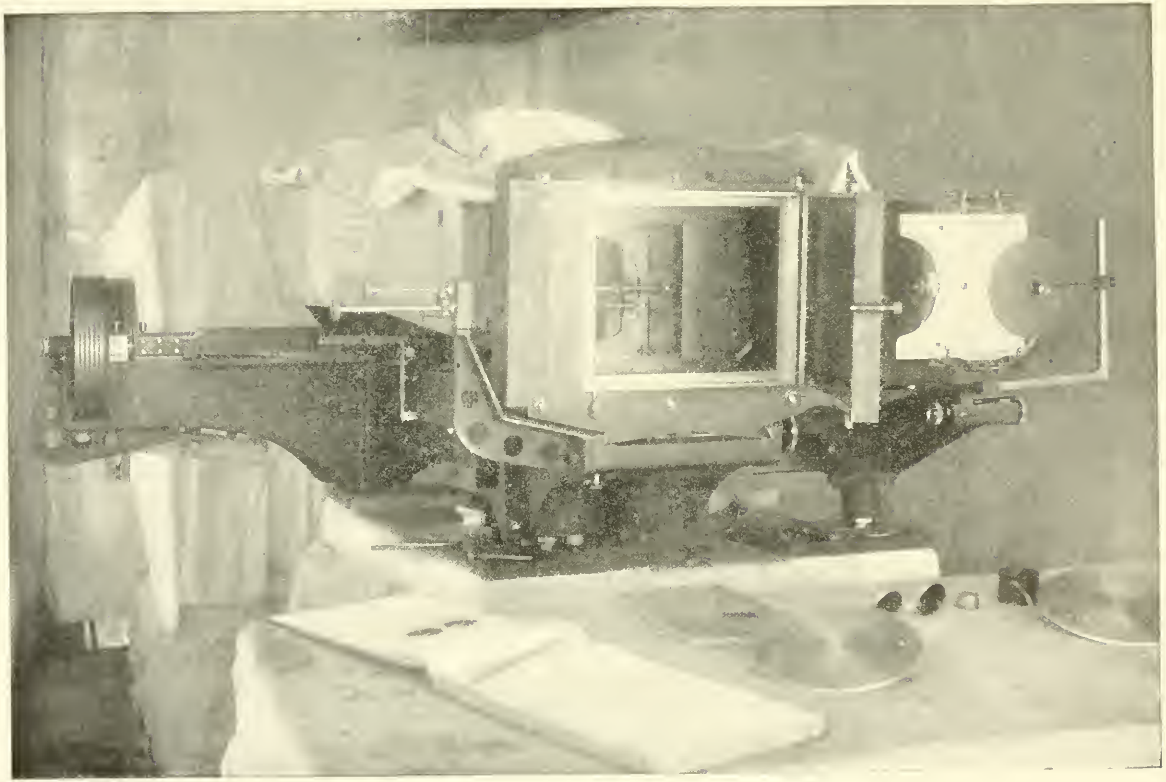
Latitudes.	Linear velocity, km. per second.	Daily angular motion.	Rotation period, days.
° —0.1	2.21	° 15.7	22.9
9.3	2.15	15.5	23.2
14.8	2.10	15.4	23.4
22.7	2.03	15.6	23.1
29.7	1.87	15.3	23.5
44.5	1.55	15.4	23.4
59.3	1.12	15.6	23.1
73.5	0.67	16.7	21.6

This important discovery leads us to inquire whether hydrogen clouds in the solar atmosphere, if observed in projection against the Sun's disk, would show daily motions corresponding to these results obtained with the spectroscope. Fortunately, the spectroheliograph permits these clouds to be photographed, as will be explained in the next section of this lecture.

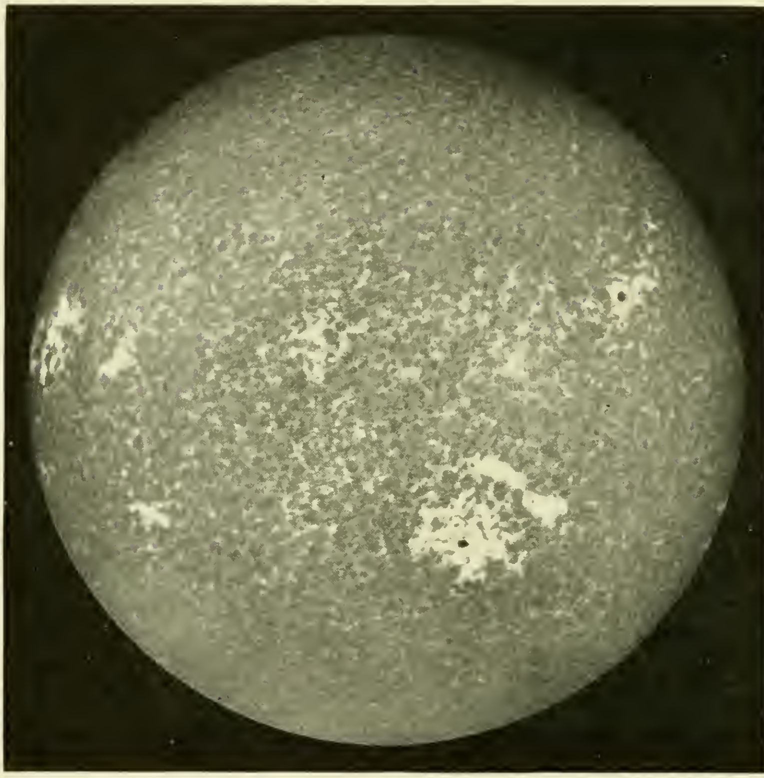
Work with the Spectroheliograph

The spectroheliograph is an instrument for photographing the Sun with the monochromatic light of any of the vapors present in its atmosphere. The instrument consists essentially of a spectroscope, on the slit of which an image of the Sun is formed. The spectroscope analyzes the light of that portion of the Sun's image which enters the slit, and spreads it out into a spectrum, crossed by lines characteristic of the various elements. If a luminous cloud of calcium vapor in the Sun's atmosphere happens to be intersected by the slit, the dark calcium line of the solar spectrum will show a bright line corresponding to a section of this cloud. Suppose the eye-piece of a spectroscope to be replaced by a slit, and assume this slit to be adjusted so that only the line of calcium passes through it. If a photographic plate is placed almost in contact with the slit, and the spectroscope is moved at a uniform rate across the fixed solar image, the second slit moving with it across the fixed photographic plate, it is evident that an image of the Sun will be built up on the plate from the successive images of the slit. The only light that enters into the formation of this image is that of calcium vapor, and the resulting picture therefore represents the distribution of this vapor in the solar atmosphere.

The advantages of using a fixed telescope are as great in the case of the spectroheliograph as in that of the spectrographs already described. The limitations in size imposed by the necessity of carrying a spectroheliograph at the end of a moving equatorial telescope do not obtain here, so that the instrument can be built of the dimensions required to accomplish its purpose to the best advantage. Plate XXXI represents the spectroheliograph constructed in the instrument shop of the Solar Observatory for use with the Snow telescope. The image of the Sun, 6.7 inches in diameter, falls on the first slit of the instrument in about the position of the metallic disk shown on the right of the plate (this disk is removed when the solar surface is photographed). The light, after passing through the slit, falls upon an 8-inch photographic objective, which renders the rays parallel. They then meet the surface of a plane mirror, from which they are reflected to two large prisms. The prisms disperse the light into a spectrum, an image of which is formed on the second slit by a second 8-inch objective. The prisms are so adjusted that the curved second slit, which may be seen near the middle of Plate XXXI, coincides accurately with the calcium line H_2. The photographic plate is placed in the supporting frame in front of the slit and the door



THE 5-FOOT SPECTROHELIOGRAPH, MOUNTED FOR USE WITH THE SNOW TELESCOPE



THE SUN, PHOTOGRAPHED WITH THE 5-FOOT SPECTROHELIOGRAPH

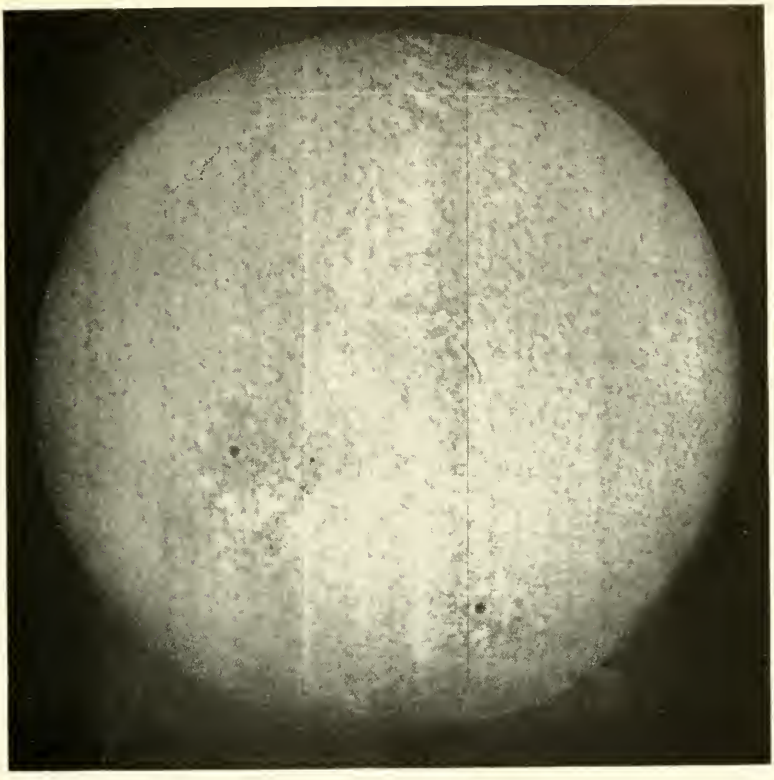
August 25, 1906, 6h 18m A. M. Camera slit set on H_2 line of calcium closed, excluding from the plate all light except that which comes through the slit. An electric motor is then started, causing the iron bed-plate, which is mounted on steel balls and carries the two slits, the lenses and the prism-train, to move at a uniform rate across the solar image.

Plate XXXII reproduces a photograph made in this way, for comparison with a direct photograph (Plate XXVIII) showing the Sun as it appears to the eye in the telescope. The luminous clouds of calcium vapor, or "flocculi," are well shown on the monochromatic image, but do not appear in the direct photograph. It will therefore be recognized that this method opens up an extensive field, by permitting the invisible phenomena of the solar atmosphere to be investigated. The wide range of the new information thus to be derived will be appreciated when it is remembered that by photographing the Sun with the lines of hydrogen, iron, sodium, magnesium, or any other element represented among the thousands of lines of the solar spectrum, the distribution of the corresponding vapor can be recorded. For example, Plate XXXIII is a picture of the hydrogen flocculi, made six minutes after the calcium image in Plate XXXII was obtained. It will be seen that most of the hydrogen clouds, instead of giving bright images like those obtained with calcium, are comparatively dark, though certain eruptive phenomena and regions in the neighborhood of Sun-spots appear bright on the hydrogen plates. This spectroheliograph is also used to photograph the iron vapors in the Sun, but, as will be explained later, a larger instrument is required to yield satisfactory solar photographs with the narrower lines of other elements.

The 5-foot spectroheliograph has been in regular use with the Snow telescope since October, 1905. Photographs of the Sun are made with the calcium, hydrogen and iron lines every clear day, both in the morning and in the afternoon. About 3,700 negatives thus obtained give a connected history of the Sun during the period in question, and provide the material for such investigations as will now be described.

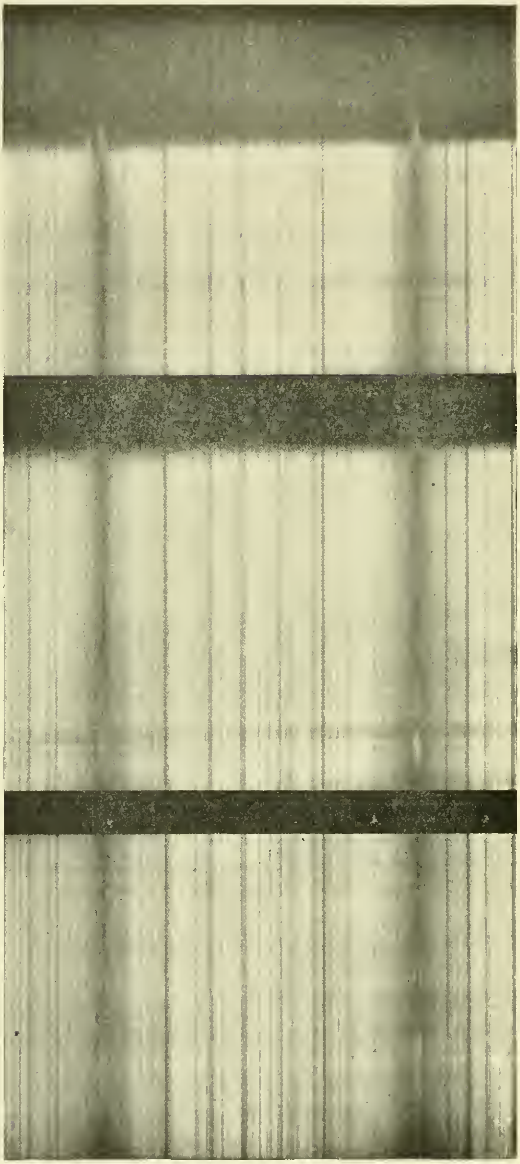
The first use of these plates that suggests itself is a study of the solar rotation as determined by the rate of motion of the flocculi. The flocculi change more or less in form from hour to hour, but some of them may be identified on plates taken on several consecutive days. Two plates, taken about twenty-four hours apart, are closely compared and only those flocculi which undergo small change of form are marked for measurement. The process of measurement involves the determination of the latitude and longitude of each of these points, referred to the center of the Sun. As the flocculi are seen in projection on the surface of a sphere, it is evident that a considerable amount of calculation would be required to deduce the latitudes and longitudes if the ordinary methods of measurement, giving their distance along a radius from the center of the disk, and the angle between this radius and the north pole of the Sun, were employed. To obviate this computing, the heliomicrometer was devised for the measurement of these photographs, and constructed in the instrument shop of the Solar Observatory. This instrument consists essentially of two 4-inch telescopes, one of them pointed at the solar photograph, the other at a silvered bronze globe, placed near it. By a suitable device the images given by the two telescopes are brought together in a single eye-piece, so that the observer sees the photographs projected upon the surface of the globe. If, then, the globe is ruled with meridians and parallels one degree apart, and the axis of the globe is inclined at such an angle as to correspond with that of the Sun on the date of the photograph, it is evident that the latitude and longitude of any point on the photograph can be read off to a tenth of a degree, with reference to the nearest meridian and parallel. In practice, many refinements are introduced to increase the precision of measurement. For convenience, the two telescopes are mounted immediately above the globe and photographic plate and pointed at two plane mirrors 30 feet away, in which the globe and plate are seen. It has been found that the rapidity and precision of measurement with this instrument are as great as with the ordinary method, while all of the extensive computations are eliminated.

During the summer season of 1907 the Sun was photographed with the Snow telescope on 113 consecutive days. Such an unbroken series of negatives provides the best of material for the study of changing solar phenomena, since the successive phases can be observed without the interruptions encountered under less favorable atmospheric conditions. In the determination of the solar rotation, for example, a cloudy period of two or three days may prevent the measurement of a large proportion of the calcium flocculi, because their changes of form are so rapid. 2,585 positions of calcium flocculi have been measured on 76 plates, by Miss Ware, with the heliomicrometer, and the combined results furnish the following values for the rotation periods of the calcium flocculi at different latitudes.



THE SUN, PHOTOGRAPHED WITH THE 5-FOOT SPECTROHELIOGRAPH

August 25, 1906, 6^h 36^m A. M. Camera slit set on $H\delta$ line of hydrogen



BRIGHT H AND K LINES ON THE DISK (*a*), (*b*), AND (*c*), IN THE CHROMOSPHERE (*b*), AND IN A PROMINENCE (*a*)

Latitude.	Daily angular motion.	Number of measures.	Rotation period, days.
0° ± 5°	14°.43	364	24.95
± 5 ± 10	14 .33	391	25.12
± 10 ± 15	14 .29	518	25.19
± 15 ± 20	14 .26	530	25.25
± 20 ± 25	14 .27	423	25.23
± 25 ± 30	14 .07	215	25.59
± 30 ± 35	13 .86	144	25.97

The measurement of the hydrogen flocculi is complicated by their changes in form, which are much more rapid than in the case of calcium. It is not surprising that this should be true, if the hypothesis provisionally adopted to account for the nature of the flocculi is correct. According to this hypothesis, the calcium flocculi shown by the spectroheliograph correspond to three different levels, defined in any case by the position of the second slit with reference to the H or K line. These lines are of complex structure, as Plate XXXIV illustrates. H consists of a broad hazy band, designated as H_1; superposed on this is a narrow bright line, called H_2; and near the center of this bright line is a very narrow dark line, called H_3. K is similar to H (though somewhat stronger) and contains the constituents K_1, K_2, and K_3. If the second slit of the spectroheliograph is set at some point on the broad H_1 or K_1 band, only the low-lying calcium vapor which is dense enough to produce a band of this width is capable of showing its presence on the photograph (Fig. 1, Plate XXXV). When the second slit is set so as to include H_2 or K_2, the less dense vapor, lying at a higher level (a few thousands of miles above the photosphere), produces the calcium flocculi measured in the above mentioned determination of the solar rotation (Fig. 2, Plate XXXV). The H_2 photographs frequently show evidences of the absorbing effect of vapors lying at the H_3 level, which give rise to *dark* calcium flocculi. When the spectra of these flocculi are photographed, the H_3 and K_3 lines are found to be greatly widened and strengthened in them. There can therefore be but little doubt that they correspond to absorption effects produced at a comparatively high level. Independent evidence in favor of this view is afforded by the fact that spectroheliograph pictures of the Sun's limb frequently show prominences, many thousands of miles in height, to be present at points where dark flocculi extend on to the disk. This question has been specially investigated by Michie Smith and Evershed, at Kodaikanal, India, and their conclusion that these dark flocculi are prominences, absorbing the light of the disk, is in perfect harmony with the Mount Wilson results. In some cases, however, it is probable that calcium vapor lying in the upper chromosphere, below the level of prominences, may produce dark flocculi.

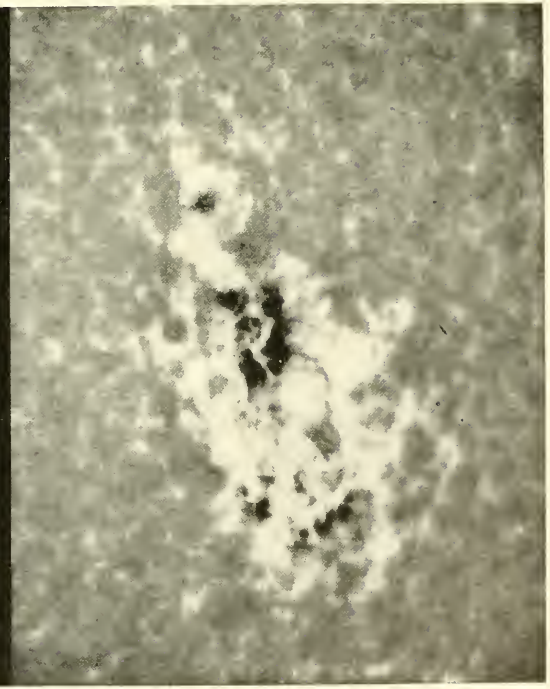
Our discovery at the Yerkes Observatory of the dark calcium flocculi was made soon after we had first photographed the hydrogen flocculi and found them (in most cases) to be dark. On the hydrogen plates there occasionally appeared exceptionally dark flocculi, and when one of these plates was compared with a calcium plate taken at about the same time, a dark object, similar in form to that shown by the hydrogen plate, was found to be present. We thus have strong presumptive evidence, since the hydrogen and calcium plates show these effects in the same way, that these particular hydrogen flocculi are comparatively high-level phenomena.

While it of course does not follow that the ordinary hydrogen flocculi, which are not so dark as these exceptional ones, lie at the same level, the very fact that they are dark suggests the view that they are due to the absorptive effect of the cooler hydrogen in the upper chromosphere. The bright hydrogen flocculi, so frequently recorded in the neighborhood of Sun-spots, are supposed to be due to radiation from hydrogen at a higher temperature.

Assuming for the present the validity of this hypothesis, it appears that the ordinary dark hydrogen flocculi recorded in our daily photographs of the Sun represent a higher level than the bright calcium flocculi obtained in the daily series made with the H_2 line. Thus we might reasonably expect that the rotation period derived from a study of the motion of these flocculi would differ from that of the bright calcium flocculi.

The measures of the daily change in longitude of the hydrogen flocculi at present available are too few in number to give a reliable determination of the solar rotation. Indeed, the marked proper motions of these objects in all directions on the solar surface, and their rapid change of form, will make it necessary to obtain a great number of these measures before final conclusions can be drawn; 547 flocculi measured on 20 different plates give the results obtained in the following table.

Latitude.	No. points.	Daily angular motion.	Rotation period, days.
0° ± 5°	91	14.3°	25.2
5 ± 10	77	14.4	25.0
10 ± 15	95	14.6	24.7
15 ± 20	73	14.5	24.8
20 ± 25	71	14.7	24.5
25 ± 30	65	14.7	24.5
30 ± 35	33	14.9	24.2
35 ± 40	23	14.6	24.7
40 ± 45	19	14.4	25.0



GREAT SUN-SPOT OF OCTOBER, 1903

FIG. 1

October 9, 3^h 43^m. Calcium flocculi as shown with second slit set on H_1

FIG. 2

October 9, 3^h 30^m. Calcium flocculi as shown with second slit set on H_2

The following table brings together the results of various determinations of the solar rotation:

Latitude.	Spots.				Faculæ.	
	Carrington.	Spoerer.	Maunder.	Unweighted means.	Stratonoff.	Reversing layer, Adams.
± 0° ± 5°	14.42	14.34	14.44	14.40	14.68	14.70
± 5 ± 10	14.35	14.30	14.41	14.35	14.61	14.58
± 10 ± 15	14.21	14.21	14.34	14.25	14.31	14.43
± 15 ± 20	14.06	14.08	14.25	14.13	14.18	14.23
± 20 ± 25	13.90	13.90	14.13	13.98	14.19	14.00
± 25 ± 30	13.73	13.69	13.99	13.80	14.08	13.72
± 30 ± 35	13.54	13.44	13.83	13.60	13.60	13.43

Latitude.	Calcium flocculi (H_2).				Flocculi ($H\delta$).	(Spectrographic.
	Kenwood.	Fox. 1903–04.	Mount Wilson.	Unweighted means.		
± 0° ± 5°	14.66	14.49	14.43	14.53	14°.6	15°.05
± 5 ± 10	14.52	14.42	14.33	14.42		
± 10 ± 15	14.37	14.24	14.29	14.30		
± 15 ± 20	14.22	13.94	14.26	14.14		
± 20 ± 25	14.12	13.67	14.27	14.02		
± 25 ± 30	13.90	13.96	14.07	13.98		
± 30 ± 35	13.76	13.70	13.86	13.77		

The long series of observations by Carrington, Spoerer, and Maunder furnish ample material for the study of Sun-spot motions, but it is doubtful whether such results should be combined, since they cover long time intervals, during which (as some evidence suggests) the rotation period may undergo variation. The same may be said of the flocculi. The unweighted means of determinations of the motions of the calcium flocculi, made at the Kenwood, Yerkes and Mount Wilson Observatories, differ so little from the mean motions of the spots that no safe conclusions can be drawn. Stratonoff's results for the faculæ are of rather low weight, since they comprise a comparatively small number of measures, necessarily made near the Sun's limb (since the faculæ are not visible near the center of the disk), and therefore subject to greater errors of setting.

But if we are not warranted in concluding that the calcium flocculi move more rapidly than the spots, we may at least recognize the striking differences which distinguish their rotational motions from those of the hydrogen flocculi. The lower calcium clouds follow the motions of the spots, and show the same marked acceleration of angular velocity toward the equator. The hydrogen flocculi, floating at higher levels, and thus escaping the effects of friction experienced by the calcium vapor, move at greater velocities in the higher latitudes, and show little increase in the equatorial zones.

It will be observed that the spectrographic velocities, both in the low-lying vapors of the reversing layer and even more markedly in the case of hydrogen, are decidedly greater than the results obtained by measuring the daily motions of spots, faculæ or flocculi. Is it possible that the flocculi, rising from lower levels, retain, in part, the lower velocities characteristic of these levels? It will be a matter of great interest to study this question, as more measures become available.

Red and Violet Hydrogen Flocculi

Adams's spectrographic measures of hydrogen make it probable (though hardly certain, as yet) that the rotational displacements of the red hydrogen line ($H\alpha$) are greater, on the average, than those of the blue and violet lines ($H\beta$ and $H\gamma$; $H\delta$ was too diffuse for accurate measurement). The $H\alpha$ line is also greatly strengthened and widened near the Sun's limb, while the other lines retain about the same intensity they exhibit at the center of the disk. Hence it might be suspected that photographs of the hydrogen flocculi, made with $H\alpha$, would exhibit corresponding peculiarities.

Fortunately the new "Pan-iso" plates, for which we are indebted to Wallace, are remarkably sensitive to red light. They enabled us to try the experiment of photographing the Sun with the $H\alpha$ line, using the high dispersion of a spectroheliograph of 30 feet focal length, employed with the new tower telescope. The first plate showed large bright hydrogen flocculi, in a region (near a group of small Sun-spots) where an $H\delta$ photograph, taken simultaneously with the 5-foot spectroheliograph and Snow telescope, showed only dark flocculi. This first plate, however, was under-exposed, and full timing also revealed dark $H\alpha$ flocculi. Later it was found possible to make excellent $H\alpha$ photographs of the entire Sun with the 5-foot spectroheliograph. Curiously enough, both the bright and dark flocculi shown by these plates differ in many particulars from the $H\delta$ flocculi, though there is a general resemblance of various details (Plate XXXVI).

These results have been obtained very recently and no complete explanation of the differences between the $H\alpha$ and the $H\delta$ flocculi has yet been worked out. We found at the Yerkes Observatory that the $H\beta$, $H\gamma$ and $H\delta$ flocculi closely resemble one another, and this

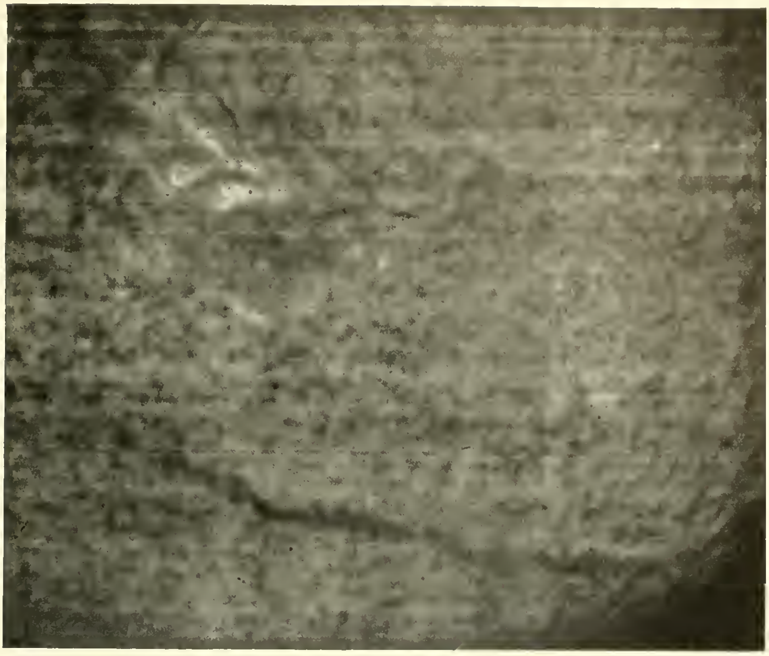


Fig. 1.—HYDROGEN FLOCCULI, PHOTOGRAPHED WITH THE $H\alpha$ LINE

1901, May 1, $4^h\ 48^m$ P. M. Scale: Sun's diameter = 0.2 meter

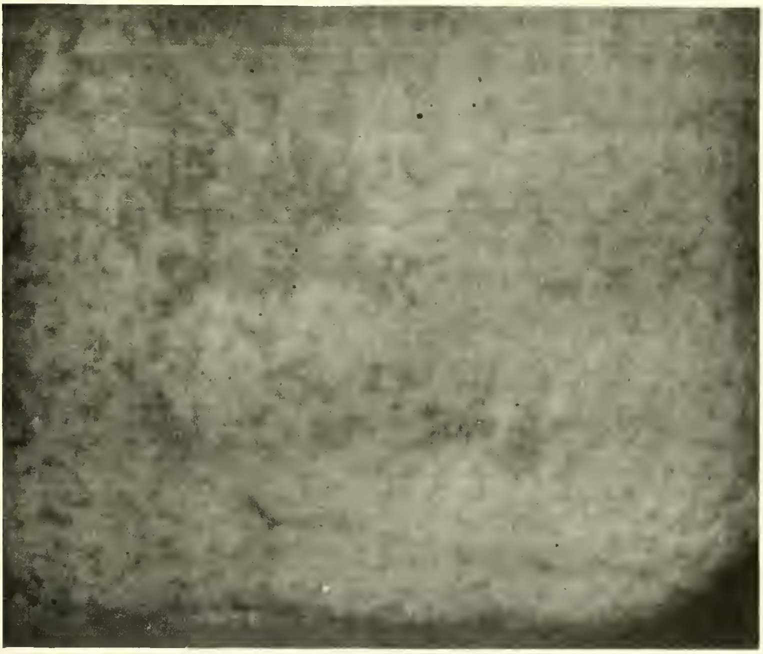


Fig. 2.—HYDROGEN FLOCCULI, PHOTOGRAPHED WITH THE $H\delta$ LINE

1908, May 1, $5^h\ 07^m$ P. M. Scale: Sun's diameter = 0.2 meter

has recently been confirmed on Mount Wilson. $H\alpha$, therefore, is the exceptional line, as its spectroscopic peculiarities also indicate. We are at once reminded of the remarkable behavior of the hydrogen lines in the Wolf-Rayet stars, where $H\alpha$ is sometimes bright and the other hydrogen lines invisible or dark. Kayser has explained this condition of things by a simple application of the law of radiation and absorption. But in the well-known variable star *o Ceti,* and others of its type, $H\alpha$ and $H\beta$ are invisible, while $H\gamma$ and $H\delta$, and the more refrangible hydrogen lines, are bright. In R *Andromedæ* $H\beta$ is the chief bright line, while $H\alpha$ is absent. Moreover, the bright line spectra of the nebulæ contain $H\beta$ and $H\gamma$, but $H\alpha$, when visible at all, is very faint. Finally, such stars as γ *Cassiopeiæ* show $H\alpha$ and the other hydrogen lines with the same relative brightness they exhibit in a hydrogen tube.

As the relative temperatures of the radiating and absorbing gases may play a dominant part in determining the character of the spectral lines, and therefore the appearance of the flocculi, the question of their level in the solar atmosphere assumes greater importance than ever. An attempt to photograph prominences at the Sun's limb with the $H\alpha$ line met with instant success, and brought out a most interesting fact: a large prominence appeared at exactly the point where a dark $H\alpha$ flocculus was being carried over the limb by the Sun's rotation. As the structure of the prominence closely resembles that of the flocculus, it is very probable that the latter was simply the prominence seen in projection on the disk, its darkness being due to the fact that the temperature of the gas was low enough to produce perceptible absorption. Most of the $H\delta$ image of the prominence was very weak on the photograph, and thus the absence of a corresponding dark $H\delta$ flocculus is readily accounted for. Furthermore, a portion of the $H\delta$ prominence, which was as bright as the corresponding portion of the $H\alpha$ prominence, is clearly shown as a dark flocculus on the $H\delta$ image of the disk. Hereafter the $H\alpha$ prominences, as well as the $H\alpha$ flocculi, will be photographed daily for comparison.[1]

[1] For an account of the discovery of vortices and magnetic fields associated with Sun-spots, which resulted from work with the $H\alpha$ line soon after this lecture was delivered, see Hale, "Solar Vortices," *Contributions from the Mount Wilson Solar Observatory*, No. 26, *Astrophysical Journal,* September, 1908, and Hale, "On the Probable Existence of a Magnetic Field in Sun-spots," *Contributions from the Mount Wilson Solar Observatory,* No. 30, *Astrophysical Journal,* November, 1908.

Solar Activity and Terrestrial Phenomena

In the introductory part of this lecture reference was made to the relationship between solar phenomena and terrestrial temperatures. The fact that the temperature of our atmosphere undergoes small fluctuations which correspond with the Sun-spot period indicates that the solar heat radiation varies with the number of Sun-spots. Unfortunately, however, since the total area of Sun-spots is only a very small fraction of that of the Sun's disk, and since intervals of several weeks sometimes elapse during which no Sun-spots are seen, the spot area may not prove to be the most reliable index of the solar activity. The total area of the flocculi is always much greater than that of the spots, and even at Sun-spot minimum these objects are never entirely absent from the Sun. For this reason it seems probable that measurements of their area will serve as the best index to the state of the Sun and the surest means of detecting rapid fluctuations in activity, which may be associated with changes in the solar heat radiation or in terrestrial temperatures.

The selection of the flocculi whose areas are to be measured is necessarily a more or less arbitrary matter, depending upon the judgment of the person engaged in the work. As will be seen from Plate XXXII, the calcium flocculi range in size from extensive regions covering a considerable area of the solar surface to minute points barely discernible by the unaided eye on the original negatives. Moreover, the range in brightness of the flocculi is almost as great as the range in area. Evidently many of the fainter and smaller flocculi must be excluded from consideration, especially as their visibility depends upon the quality of the photographs, which differs from day to day with the conditions of the atmosphere. After all has been said, however, the difficulties of selection appear to be no greater than in the case of the faculæ measured on direct photographs at Greenwich. The faculæ are clearly visible only in the immediate neighborhood of the Sun's limb and gradually disappear as they approach the center. Their total area, as measured on any given photograph, is far less than the area of the calcium (H_2) flocculi of the same date, and the effect of atmospheric conditions on their visibility is more marked than in the case of the flocculi.

After experimenting with several methods of measuring the areas of the flocculi, a simple photometric device was adopted. A piece of clear glass is placed over the solar negative and the image of each flocculus selected for measurement is painted over with opaque black paint. The corresponding area is inversely proportional to the measured amount of light, from a source of known intensity, which is transmitted by the blackened plate.

In practice, the investigation has been planned so as to permit the determination, not only of the total area of the calcium flocculi, but also their distribution in latitude and longitude. For this purpose the points on the solar negative corresponding to the intersections of meridians and parallels 10° apart are marked on the glass side with the heliomicrometer, which is provided with an electrical marking pen for this work. The area of the flocculi lying within each square, 10° on a side, is then measured. The sum of these areas gives the total area of the calcium flocculi for the date in question, while the values obtained for the individual squares permit the variations in solar latitude and longitude to be studied. In order to avoid errors incident to the measurement of areas at points near the Sun's limb, the region investigated is confined to the middle of the Sun's disk and extends 40° east and west, and 40° north and south, from the central point.

A large number of photographs have been measured in this way at the Solar Observatory, and in the course of time it will be possible to learn whether these results indicate any significant relationship between solar and terrestrial phenomena.

Conclusion

I trust this account of recent investigations will make clear some of the means at present employed to extend our knowledge of the Sun. Every advance in this department must contribute toward the solution of the great problem of stellar evolution, as well as the lesser problem of the solar constitution. The latter is of special interest to the inhabitants of the Earth, since our very lives depend upon the constancy of the solar radiation, and thus upon the mechanism which maintains it. But the problem of stellar evolution is of even greater philosophical interest. As the biologist withdraws, one by one, the veils which enshrouded the mysteries of organic development, and as the paleontologist reconstructs for us the life of former times, the desire to learn of the earliest steps along the great highway of evolution must grow in every intelligent mind. Fortunately the problems of the astronomer, difficult though they be, are more open to attack than those which confront his biological colleague. With the powerful telescopes and spectroscopes of the present day, and the climatic advantages which well-placed mountain observatories enjoy, unlimited opportunities lie at his command. But if he is to give effective aid in solving the innumerable questions raised by the distant stars, he must first of all profit by the advantages which the proximity of one star affords. From this standpoint I commend to you the far-reaching possibilities of solar research.