THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 87 MAY 1938 NUMBER 4

GEORGE ELLERY HALE
1868–1938

WALTER S. ADAMS

Dr. George Ellery Hale, distinguished and much beloved astronomer, died in Pasadena, California, on February 21 after an illness extending over several years. A scientist who made many remarkable contributions to his chosen field of solar research, the founder and almost throughout his life an editor of the *Astrophysical Journal*, founder and first director of the Yerkes and the Mount Wilson observatories, organizer of the International Union for Co-operation in Solar Research and of its successor, the International Astronomical Union, for many years foreign secretary of the National Academy of Sciences, and the founder of the National Research Council, Dr. Hale has left an impress upon the life of science which will endure for generations to come. In later years, when illness prevented him from carrying on actively the investigations he had most at heart, he conceived the project of the 200-inch telescope and secured the necessary financial support, leaving this great instrument as his final gift to the science he had loved so well.

The name of Hale is associated with so many important organizations in the creation and development of which he took the leading part that it is not always easy to realize that the instinct for research was the dominant feature of his life. He was a born investigator and was never so thoroughly content as when he could work uninterruptedly at the telescope and spectrograph or could analyze his results in the quiet of his office or laboratory. For this reason there can be little doubt that the happiest years of his life were those at Kenwood and the earlier years at the Yerkes and Mount Wilson observatories. They were periods of construction and development and gave full scope to his creative and experimental ability before the heavy responsibilities of the larger organizations had begun to be felt to any marked degree. But Hale also realized, to an extent much greater than most investigators, that the major problems of physical science are usually so extensive and complex that progress in their solution requires the co-operative effort of many individuals and many institutions. So, although by nature a strong individualist in his scientific work and in his outlook on life, he was constantly engaged in organizing plans for co-operative observations, in encouraging young investigators, and in securing the establishment of new institutions and wider and better facilities for research.

Of the conduct of his scientific work it would hardly be possible for any two, even of Hale's closest, associates to write in the same way, such were the characteristics of this gifted and many-sided man. His active and brilliant mind was constantly at work analyzing his problems, weighing new hypotheses, and designing new methods of attack, always with an enthusiasm resembling the creative joy of the artist. He had to a remarkable degree the gift of being able to distinguish the essential and salient features of an investigation; and it was rarely, indeed, that even a minor research which he attempted failed to bring productive results. One very striking characteristic was his interest in instruments and his remarkable skill in the designing of new apparatus. The invention of the spectroheliograph and the spectrohelioscope and the adaptation of the tower telescope and the vertical spectrograph for solar investigation are excellent examples of this quality of Hale's mind. In part it was probably due to his engineering training, but much more to his appreciation of the enormous importance of the value of improved instruments to astronomical progress, and to his creative ability and love of fine workmanship. He took immense pleasure in seeing a new instrument assume form; and, as he often said, "had I not been an astronomer, I should have liked to have been an instrument-maker."

The early years of Hale's scientific life and development form an exceedingly interesting story. We may almost say that, as in the case of Michelson, the phenomena of light fascinated him from the beginning. From childhood the microscope and telescope, the colors of the spectrum, and the infinite variety of forms in which light manifests itself in everyday life were an unfailing source of joy and satisfaction to him. Probably no boy ever used a diffraction grating at so early an age, and the story of Hale's first meeting with Rowland and the latter's remark that "any grating of mine should be good enough for an infant" was always quoted with much amusement by Hale in after-life. His father gave him constant encouragement in these interests, and gradually the equipment was built up which came to form the Kenwood Observatory.

Fortunately, we have in Hale's own words a most interesting statement regarding this formative period of his life and some of the influences which led him to take up astrophysical research as a career in after years. The statement is contained in some biographical notes, written by him in 1933, and represents his mature judgment on the factors which affected most greatly the direction of his intellectual interests. The notes also throw an amusing sidelight on one or two astronomical worthies of this period.

I cannot fix the date of my first interest in astronomy, but it must have been when I was thirteen or fourteen years old. I built a telescope; but as I used a large single lens, the images were not good. About this time I became acquainted with S. W. Burnham, then a stenographer in the Chicago law courts by day and an ardent observer of double stars by night. Through him I learned of a second-hand Clark refractor, of 4 inches aperture. This was purchased by my father, and I mounted it on the roof of the house. The astonishing views it afforded of Saturn, the moon, Jupiter, and other objects excited an intense desire to carry on actual research. So I attached a plateholder to the telescope and photographed a partial eclipse of the sun. I also began to observe sunspots, and made drawings of them. Thus I became an amateur astronomer.

At this period the $18\frac{1}{2}$-inch Dearborn refractor stood at the summit of a lofty tower forming part of the castellated building of the old University of Chicago (long since demolished, after the removal of the telescope to the Northwestern University at Evanston). Professor G. W. Hough, known for his observations of Jupiter and double stars, who was in charge of the instrument, was kind enough to let me look through it frequently. I was also permitted to aid the feeble gas-engine in turning the dome, or rather drum, of the observatory. Naturally, my own ambitions were thus stimulated, but neither Hough nor Burnham had the slightest interest in astrophysical research, and I could not have devoted my life to such work as they were doing, valuable as it was to science. The reason lay in the fact that I was born an experimentalist, and I was bound to find the way of combining physics and chemistry with astronomy. Fortunately, it was not far to seek.

In Cassell's book is a description of a spectroscope, with an account of the construction of a simple instrument, using either a luster prism or a hollow one filled with carbon disulphide. I built both forms, and the odor of the disulphide abides with me after a lapse of fifty years. Then my father, always ready to encourage serious efforts, enabled me to buy a small spectrometer. This had a single prism, and I lost no time in fitting it with a small plane grating. For by this time I had learned of the work of Rutherfurd and Rowland and had acquired some slight conception of the possibilities of high dispersion. Nothing could exceed my enthusiasm in observing the solar spectrum and in measuring the principal lines. I bought Lockyer's *Studies in Spectrum Analysis* and began the observation of flame and spark spectra and their comparison with the spectrum of the sun. At last I had found my true course, and I have held to it ever since.

In passing, however, I must emphasize the advantages I gained from my earlier work in other fields. It gave me a broad interest in many branches of science and taught me something of their mutual dependence. It led me to read *The Origin of Species* and initiated a lasting desire to study evolution. It taught me to regard the sun as a typical star, a link in the long evolutional chain, and thus helped me to avoid becoming exclusively a specialist in solar research. And it was the source of all the work I have done in helping to develop such institutions as the National Academy of Sciences, the California Institute of Technology, the National Research Council, and the International Research Council (now the International Council of Scientific Unions). I still look with delight at rotifers and other microscopic objects, and realize that the marvels I saw through the little microscope of my boyhood days are as astonishing as any revealed in the heavens by the largest of telescopes.

The early education which Hale received in Chicago was at the Oakland Public School and later at Allen Academy, where he was allowed to care for the "philosophical instruments" and to assist in demonstrations before the student body. At the suggestion of Daniel H. Burnham, the well-known architect, who was a close friend of Hale's father, the Massachusetts Institute of Technology was chosen for the college career of the son. Hale entered the Institute in the autumn of 1886 and was graduated in 1890. His courses were mainly in mathematics, physics, and chemistry, and for astronomy he was obliged to go elsewhere. Through special arrangement with E. C. Pickering he was able to serve as volunteer assistant at the Harvard College Observatory, where, among other experimental instruments, he tried his first form of spectroheliograph.

Hale's marriage to Miss Evelina Conklin occurred soon after he left the Massachusetts Institute, and on their western trip together they visited the Lick Observatory, where Hale was greatly impressed by the 36-inch telescope and the admirable spectroscopic investigations of planetary nebulae by Keeler. On his return to Chicago he passed three active years of research at the Kenwood Observatory, interrupted only by a trip in 1891 to Europe, where he met many astronomers and spectroscopists and studied their methods and equipment. The winter of 1893–94 he spent in study at the University of Berlin, where the lectures by Planck on thermodynamics and theories of radiation were of great value to him in his later work. He made frequent visits to Potsdam and became thoroughly familiar with the researches of Vogel, Scheiner, and others. It was during this European journey that he completed his plans for the establishment of the *Astrophysical Journal*.

After his stay in Berlin and an expedition to Mount Aetna, where he tried out his apparatus for photographing the corona without an eclipse, he returned to Chicago, where he continued his research at the Kenwood Observatory but was also actively engaged in plans for the larger institution which had taken form as the Yerkes Observatory.

The University of Chicago was at this time in its great period of development under President Harper. A remarkable judge of men, he at once appreciated the abilities of this gifted student and investigator of twenty-four, and Hale became a member of the staff of the University as associate professor of astrophysics in 1892. Together they formed plans for a great observatory; and, both being men of initiative and constructive imagination and enthusiasm, they succeeded in interesting Mr. Yerkes of Chicago, who made the gift for the project in the same year. Hale carried on the detailed plans with characteristic energy, outlining the investigations to be undertaken, designing instruments, and assembling a staff. Barnard, with his wide experience and extraordinary skill in visual observations, came from Mount Hamilton; Burnham, also with Lick Observatory training, from Chicago; Wadsworth, from Michelson's laboratory; Frost, from Dartmouth College; and Ellerman, with his background of years of experience with Hale, from Kenwood. The Yerkes Observatory was completed and dedicated in 1897, with Hale as its first director and professor of astrophysics at the University of which it formed a part. He retained his relationship to the University of Chicago even after he came permanently to California, being nonresident professor from 1905 onward.

The winter of 1903–4, owing to illness in his family, Hale spent in Southern California. His attention had previously been attracted to Mount Wilson by Professor Hussey, who was investigating possible sites for a high-altitude solar observatory in behalf of a committee appointed by the Carnegie Institution of Washington, of which Hale was a member. In June, 1903, accompanied by Dr. W. W. Campbell, Hale made his first visit to Mount Wilson, where Hussey was still continuing his observations. Tests of the solar seeing were made by Hale at this time and during several of the succeeding winter months. They proved so satisfactory that application was made to the Carnegie Institution for a grant to finance an expedition from the Yerkes Observatory and the installation of the Snow horizontal telescope. A group consisting of Ellerman, Ritchey, and Adams came in the spring of 1904, followed somewhat later by F. G. Pease, and formed the nucleus of the staff of the future Mount Wilson Observatory. Throughout 1904, systematic records of both solar and stellar observing conditions were maintained; and, after much careful consideration, Hale recommended to the Carnegie Institution the establishment of an independent observatory. A grant for this purpose was made in December, 1904; the Snow telescope was purchased from the Yerkes Observatory; and the Mount Wilson Solar Observatory, later changed to the Mount Wilson Observatory, as its stellar activities increased, was organized.

This account of the origin of the Mount Wilson Observatory is given somewhat in detail to illustrate the caution and painstaking care which Hale combined with his enthusiasm in the development of his major projects. Probably no observatory was ever established after so thorough an examination of observing conditions and of all the physical considerations entering into its construction, maintenance, and growth. Questions of transportation, water supply, electric power, building materials, and living conditions were all investigated by him personally; and no subject was too small to be given thought and consideration. It was a period in which he enjoyed life enormously. The isolation of the mountain top in these early years made a strong appeal to the pioneering spirit latent in him, and his joy in discoveries of the everchanging beauties of nature about him was second only to that of his discoveries in science.

In 1910, after six years of active and most productive work, the first shadows of physical illness began to fall across Hale's life. After this time he was never completely free from more or less severe attacks of a type of brain congestion which occasionally produced severe pain and almost complete mental exhaustion. He soon learned that such attacks were most apt to occur when his mind was occupied with his scientific work, and with profound courage and at great sacrifice he attempted to adjust himself to the situation. Without completely giving up his research, he devoted more time to writing, to executive work, and to the organization and development of projects he had especially at heart. After the World War broke out, he spent much time in Washington, where, at the request of President Wilson to the National Academy of Sciences, he was mainly responsible for the creation and organization of the National Research Council. He was foreign secretary of the National Academy from 1910 to 1921 and gave much thought to plans for making the Academy a more active force in national and international science. He also visited Europe several times to attend meetings of the International Research Council, afterward the International Council of Scientific Societies, and aided greatly in directing its policies. Many of these interests he maintained to the end of his life.

On his return to the Mount Wilson Observatory, Hale continued his scientific work as his strength permitted, but with increasing difficulty; and in 1923 he resigned the directorship. He was appointed honorary director by the Carnegie Institution; and, with full realization of his physical limitations and with remarkable courage, he faced the problem of how to make the most effective use of such years as remained to him. He solved this problem in two ways. First, he constructed, largely at his own expense, the small, well-equipped solar laboratory which he presented to the Carnegie Institution, and in which he could carry on such research as his health allowed. Second, he undertook the writing of a number of articles planned to bring some of the results of astronomical discovery before the intelligent public. In this purpose he was remarkably successful, his clarity and simplicity of statement forming an admirable setting for the spirit of enthusiasm pervading all his writing.

Two striking, but widely dissimilar, accomplishments mark these later years of Hale's life. The first was the invention of the spectrohelioscope, which supplements in many important respects the spectroheliograph devised by him so many years ago at Kenwood. It is already yielding results of great value at stations all over the world and, through the application of moving-picture attachments, gives promise of proving the most efficient instrument yet designed for the study of rapidly changing phenomena on the sun's surface. The second was the project of the 200-inch telescope. Attracted by his article published in 1928, "The Possibilities of Large Telescopes," and strongly influenced by their personal knowledge of Hale and his contributions to science, the president and trustees of the General Education Board made a grant for the construction of a 200-inch telescope, the instrument being given to the California Institute of Technology on the basis of a plan of co-operation with the Carnegie Institution and the Mount Wilson Observatory. From 1929 until the closing days of his life, problems relating to this great instrument occupied most of Hale's thoughts. He was chairman of the group having the project in charge, and his active mind was fertile in suggestions for the design both of the telescope itself and of the equally important auxiliary instruments. As illness increased and his strength gradually failed, his mind turned constantly to the progress of the telescope and the observatory; and each clear day, as the winter rains during the past winter were delayed, he rejoiced in "one more day for work on Palomar."

The first article published by Hale appeared in 1889 in a small Chicago periodical, *The Beacon*, and was entitled "Stellar Photography." This was written at the age of twenty. Succeeding papers during this period appeared in *The Beacon*, *Astronomische Nachrichten*, *American Journal of Science*, *Sidereal Messenger*, *Publications of the Astronomical Society of the Pacific*, and especially *Astronomy and Astrophysics*, the astrophysical portion of which he edited during the three years of its existence. He had for several years considered the desirability of establishing a journal devoted to spectroscopy and astrophysics and had sought carefully the opinions of scientists from all parts of the world. Assured of their strong support, Hale founded in 1895, in collaboration with James E. Keeler, the *Astrophysical Journal*, the University of Chicago assuming the responsibilities of publication and taking over, through purchase, *Astronomy and Astrophysics*. The new journal was successful from the beginning and was truly international in character, with a board of collaborators whose names were eminent in science throughout the United States and Europe. Many of the classical papers of astrophysics and spectroscopy have first appeared in the *Astrophysical Journal*, and the influence of its founder and first editor has been maintained throughout the period of its existence, now nearly half a century in length.

Nothing illustrates more clearly Hale's breadth of interests than a study of his bibliography. In a list of nearly four hundred and fifty titles there is found a range from spectroscopic observations of solar prominences to an analysis of the intellectual culture of France. Included in it are his two interesting nontechnical books, *Stellar Evolution* and *Ten Years' Work of a Mountain Observatory*, together with compilations, in book form, of his numerous magazine articles of an interpretive character. The longer technical monographs appeared in the publications of the Yerkes Observatory and the Carnegie Institution of Washington, but most of his best-known papers are found in the *Astrophysical Journal*. About 90 per cent of his published articles deal with the results of his scientific researches.

The earliest work which Hale carried on at the Kenwood Observatory consisted of visual observations of solar prominences. From the outset he realized the immense value of photography in affording a complete and permanent record of these objects, and his ingenious mind immediately undertook to accomplish this purpose. The problem was twofold in character. First it was necessary to find a spectral line, other than the hydrogen $H\alpha$ used for visual observations, through which the prominences could be photographed, since the photographic plates of this period had little sensitiveness to red light. Second, an instrument must be devised by means of which the small portion of the image of the prominence or the sun's disk which appeared in the light of the spectral line could be made to build up the complete image. Hale solved the first part of the problem through his investigations of the H and K lines of calcium, already known through the work of C. A. Young, to be always bright in the chromosphere and prominences, as well as over sunspots. These lines, which Hale was the first to identify with spark lines of calcium, were used for most of his work with the spectroheliograph until 1908, when photographic plates more sensitive to red light became available and the $H\alpha$ line could also be used to advantage. It is probable, however, that he never felt inclined to revise his early statement about the H and K lines, "which to my mind form the most interesting group in the solar spectrum."

Two instrumental devices for obtaining photographic records of prominences and other solar phenomena were invented by Hale as early as 1889. In the second of these, which he finally adopted at the Kenwood Observatory, and to which he gave the name of "spectroheliograph," two movable slits were used, driven by a specially designed clepsydra, one across the image of the sun and the other immediately in front of the photographic plate. The instrument was extraordinarily successful from the outset, and for years Hale's publications described the new and remarkable results obtained with it. Although his three attempts to photograph the corona with the spectroheliograph in full sunlight—at Kenwood, Pike's Peak, and Mount Aetna—proved unsuccessful, they form an admirable illustration of his characteristic determination to carry the application of an instrument to its extreme limit, a quality which proved brilliantly successful on so many occasions. Nearly all our existing knowledge regarding the calcium and hydrogen flocculi, the forms and motions of prominences, details in the chromosphere, and the structure of the solar surface around sunspots is due to the spectroheliograph or to some adaptation of its principles.

During this period Hale also carried on some extremely valuable investigations of the spectra of prominences and sunspots, identifying the ultraviolet lines of the Balmer series of hydrogen and numerous lines of other elements in active prominences, measuring distortions of the $H\alpha$ line and studying its behavior relative to H and K, and observing with great care the D_3 line of helium both as a bright line in the spectrum of the chromosphere or prominences and occasionally as an absorption line near active sunspots. The spectrum of sunspots already interested him greatly, and it is quite probable that he would have anticipated some of his later discoveries could his spectroscopic apparatus, necessarily attached to a small refracting telescope, have had sufficient resolution. Theories of sunspots and of the relationship of faculae and flocculi to each other and to spots attracted his attention, and he was greatly influenced by the work of Secchi and Tacchini in Italy and of Faye in France. An interesting summary of many of the results and conclusions of his work at this time was published in October, 1892, in *Astronomy and Astrophysics*.

As Hale moved onward to the wider field of work afforded by the Yerkes Observatory, he saw opportunities for extending his investigations with more powerful apparatus. A large spectroheliograph was one of the first requisites, and the Rumford spectroheliograph, when attached to the 40-inch refractor, has remained one of the most efficient instruments for certain types of solar research ever designed. With it dark hydrogen flocculi were discovered and the dark calcium markings which proved to be prominences seen in projection against the disk. The dispersion of the instrument was sufficient to make it possible to set the second slit upon different portions of the K line, and thus to map the calcium flocculi at different levels throughout the solar atmosphere. A grating spectrograph supplemented the spectroheliograph, and with it Hale made the difficult visual discovery of the presence of the green carbon band in the spectrum of the chromosphere. He became fully aware, at this time, of the possibility of observing the chromospheric and much of the "flash" spectrum without an eclipse, and in future years continued such work at Mount Wilson.

A strangely prophetic remark was made by Hale in an article published at the Yerkes Observatory in 1902: "The remarkable peculiarities of the spectra of sunspots seem to deserve more attention than they have hitherto received from spectroscopists." Widened lines in the spectra of spots had been observed visually by Young in 1872 and were studied systematically by the English astronomers Maunder, Cortie, and Lockyer. Hale made some attempts to photograph the spectrum of sunspots while at the Kenwood Observatory, but his success was only partial because of the small size of the sun's image. With the larger image given by the 40-inch telescope at the Yerkes Observatory much better results were obtained, and not only were the widened lines measured but also many of the lines in a green band discovered by Maunder in 1880. Hale realized that for an adequate investigation of the spot spectrum greater linear scale in the spectrograph and a still larger solar image were needed. Accordingly, he designed for the purpose a large spectrograph used in conjunction with a coelostat and long-focus concave mirror, thus planning to bring into regular astronomical use an instrument which had been relegated almost wholly to eclipse expeditions. This instrument finally took form in the Snow telescope, with which in later years at Mount Wilson the first of the extensive sunspot investigations was begun.

Although Hale's primary interest in life lay in the study of the sun, he always emphasized the fact that the sun is an individual star, so close that it can be studied in detail, but only one object in the vast physical universe about us. For any adequate study of the major problems of astronomy, therefore, he felt it necessary to have both solar and stellar equipment on an extensive scale, supplemented by a physical laboratory to which recourse could be had for the interpretation of astrophysical phenomena. This principle underlay his plans for each of the observatories he established, and so we find great stellar telescopes at Williams Bay, Mount Wilson, and on the summit of Palomar. That he developed this point of view at an early age and at the same time fully appreciated the striking value of that somewhat neglected instrument, the reflecting telescope, is shown by the gift, through his father in 1895, of the 60-inch mirror to the Yerkes Observatory. This is now incorporated into the 60-inch reflector on Mount Wilson.

The 40-inch telescope at the Yerkes Observatory gave Hale his first opportunity to study stellar spectra. The objects selected were the stars of Secchi's Fourth Type (Harvard type N), which heretofore had been observed only visually. The carbon bands and a very few prominent lines had been recognized, but otherwise the spectra were essentially unknown. Observational difficulties were great, since all the stars were faint and red and red-sensitive photographic plates were very much in their infancy. With the active assistance of Ellerman and J. A. Parkhurst, however, Hale obtained a series of photographs remarkably good for this period of instrumental development, and discussed the results in detail. The lines of numerous elements were identified in the spectra, bright lines were observed in several stars, a very significant resemblance to certain features of sunspot spectra was discovered, and the physical condition of the stars and their place in the sequence of stellar development were considered from numerous points of view. With but one or two exceptions the conclusions drawn in this important investigation remain without change to the present time, later studies with more powerful apparatus supplementing, rather than modifying, them in any essential way.

Hale's great interest in laboratory investigations and his constant desire to apply physical tests to astrophysical phenomena led him, while at the Yerkes Observatory, to undertake, in collaboration with N. A. Kent, an extensive research on the spectrum of the iron spark in liquids and compressed gases. At first he thought the discovery of lines consisting of both emission and absorption components might have application to the phenomena of novae, but later he gave up this view. As a physical investigation, however, it was important in its bearing on the separation of lines according to degree of excitation, the displacement of lines under pressure, and the study of selective absorption as a function of wave length.

The establishment of the Mount Wilson Observatory gave Hale, for the first time, the opportunity of building instruments on a large scale to fit the problems to be investigated rather than of finding the problems to be undertaken with an existing instrument. This is the point of view of the physicist and was a principle maintained by Hale throughout his life. The Snow telescope was designed for certain specific purposes, primarily to make possible the use of larger spectrographs and the violet region of the spectrum; the 60-foot tower telescope, to improve seeing conditions on the sun's image and afford convenience of operation and temperature control for very long spectrographs; and the 150-foot tower telescope, to afford a very large solar image for the study of sunspots and details on the sun's surface. The same attitude was taken with reference to the stellar instruments, the 60-inch and 100-inch telescopes being designed for use at three foci, so that the magnification and the auxiliary instruments could be adjusted to the problem in mind. Hale was always greatly interested in the coudé form of the reflecting telescope, appreciating from experience the value of large-scale stellar spectra and the immense advantages of fixed instruments operated under laboratory conditions.

The earliest of Hale's publications from Mount Wilson are largely descriptive, dealing with observing conditions, a subject in which he was intensely interested and to which he devoted many experiments, and with plans for buildings, design of instruments, and a program of solar research. The first major investigation was on the spectrum of sunspots, and was carried on in collaboration with Adams and later with Adams and H. G. Gale in the physical laboratory. The solar equipment used was the Snow telescope and a plane-grating spectrograph with a focal length of 18 feet. The photographs were greatly superior to any obtained previously, and showed a wealth of detail, with many solar lines strengthened or weakened, and a great number of lines either not present or very faint in the solar spectrum. These latter lines were afterward identified as due to bands, those of magnesium hydride by Fowler, and those of titanium oxide and calcium hydride by the Mount Wilson observers. One result of especial interest was that in the spectrum of many elements (such, for example, as iron) some lines were greatly strengthened while others were but slightly affected, if at all. The inquiring mind of Hale determined to learn the cause of this behavior, and for this purpose had recourse to the physical laboratory.

It is difficult at the present time, long after the temperature classification of spectral lines, the development of the ionization theory, and the quantitative analysis of spectra according to energy-levels, to realize the situation that existed when these observations of sunspot spectra were made in 1905. Owing mainly to the researches of Lockyer, the distinction between "enhanced" lines, those which first appear or are greatly strengthened in the spectrum of the spark as compared with the arc, and the normal arc lines was known and its importance recognized; but very little distinction could be made among the arc lines themselves. Experiments had shown that λ 4227 of calcium could be obtained in the spectrum of a flame, and it was sometimes called a "low-temperature line"; but no appreciable amount of work had been carried on in this field.

Hale started with the simple and altogether natural working hypothesis that the differences of intensity between the same lines in spots and on the disk of the sun are due to the lower temperature of spots. Accordingly, an investigation was begun in the laboratory to study the effects of temperature on the spectra of various elements. The arc spectrum of iron was photographed, first with a rotating arc, then in an arc through which currents of widely varying amount could be passed, and finally in the outer flame and in the central core of an arc. The results were decisive in showing a great difference in behavior among the lines, some being relatively strong in the spectrum of the low-current arc and the cooler outer flame, while others were strong only in the hot central core and in the high-current arc. Comparison with the spectrum of sunspots at once showed that the "low-temperature" lines of the laboratory were just those which were greatly strengthened in spots while the "high-temperature" lines were but little affected. The final evidence that the effect was due to temperature was provided by a simple electric furnace, which gave results precisely similar to those found with the arc.

This investigation was of great importance not only because its results explained many of the most important phenomena of sunspots but also because it had far-reaching consequences. The classification of lines according to temperature behavior made at this time, and improved and greatly extended by King with the electric furnace, laid the foundation for much of the analysis of spectra in later years. The discovery of the weakening of the enhanced lines in sunspot spectra and the ensuing laboratory investigations led to the suggestion that low density might be favorable to the production of enhanced lines, a conclusion so fundamental in the theory of ionization. Finally, these results had extremely wide applications to stellar spectra, aiding in determinations of temperature and density, and through successive stages leading to the spectral differentiation of giant and dwarf stars and the discovery of the spectroscopic method of determining parallaxes.

Observations with the spectroheliograph were continued regularly by Hale and Ellerman during these years at Mount Wilson, and some experimental work with this instrument led to results which culminated in Hale's most brilliant discovery. Sufficient progress had been made in sensitizing photographic plates to red light by means of dyes, especially by R. J. Wallace, to permit the use of the spectroheliograph with the α line of hydrogen. Photographs with this line at once showed a variety of detail, both in dark and bright flocculi, which had not been seen previously in observations with the $H\delta$ line. Most important of all, Hale's skilful examination at once detected in the curved form of the flocculi about sunspots evidence of vortical motion. Further observations fully confirmed this opinion, in one case a very long dark flocculus, which showed gradual curvature as it approached a double spot, finally forking and being drawn into the two centers of the vortex. That he foresaw at once the consequences of this discovery is shown by two quotations from his article on solar vortices:

In view of the fact that the distribution of the hydrogen flocculi frequently resembles that of iron filings in a magnetic field, it is interesting to recall the exact correspondence between the analytical relations developed in the theory of vortices and in the theory of electromagnetism.

Double lines, which look like reversals, have recently been photographed in spot spectra with the 30-foot spectrograph of the tower telescope, confirming the visual observations of Young and Mitchell. It should be determined whether the components of these double lines are circularly polarized in opposite directions, or, if not, whether other less obvious indications of a magnetic field are present. I shall attempt the necessary observations as soon as a suitable spot appears on the sun.[1]

On June 25, 1908, Hale obtained a series of photographs with the 30-foot spectrograph, using a Fresnel rhomb and Nicol prism. These

[1] *Contributions from the Mount Wilson Observatory*, No. 26; *Astrophysical Journal*, **28**, 311, 1908.

gave unmistakable evidence of the Zeeman effect and of the presence of a magnetic field in sunspots.

Following this remarkable discovery, Hale devoted considerable time to measurements of the strength of field in spots, comparisons with laboratory results, studies of plane polarization across the lines of force, and experimental work on vortex models. Since the resolution of the components of many of the spot lines was beyond the power of the 30-foot spectrograph, he decided to postpone further extensive investigations until the completion of the 150-foot tower telescope and the 75-foot spectrograph, which were under construction in 1909 and 1910. The decreasing sunspot activity, however, and the scarcity of spots led him at this time to undertake an investigation particularly well suited for sunspot minimum but extraordinarily difficult and exacting because of the smallness of the quantities involved. This was the problem of the existence of a general magnetic field of the sun as shown by the Zeeman effect. Here there could be no question of the separation of lines into components, but, as computation showed, only of minute displacements, when the Nicol prism was rotated, of three or four thousandths of a millimeter even on the great scale of the spectra with the 75-foot spectrograph. A large amount of observational material was required, and the measurements were undertaken by van Maanen and other members of the Observatory staff. Positive results were obtained which were discussed by Hale in an extensive article written in March, 1913; but the problem was rendered even more difficult by the apparent failure of certain lines to show the expected effect. The investigation was continued by Hale up to the end of his life, and he developed several ingenious and effective devices for measuring the minute quantities involved. New series of photographs were obtained near the sunspot minima of 1922 and 1932; and the spectra were measured, but with somewhat inconsistent results. It is very difficult to draw a definite conclusion regarding the outcome of this long research undertaken with such great skill and patience. The presumption for the existence of the general magnetic field seems to be strong, but the definite proof may have to await new methods or improved instruments.

In the autumn of 1918, Hale published, in collaboration with

Ellerman, Nicholson, and Joy, one of the most important of his papers, entitled "The Magnetic Polarity of Sunspots." The discovery of the reversal of polarity of sunspots with the spot cycle, fully confirmed by later results, should be ranked with that of the Zeeman effect in its importance to solar theory. In this article are also found the extremely interesting conclusions that the two members of a bipolar spot group have opposite polarities, and that the polarities of the preceding and following spots in such groups are opposite in the northern and southern solar hemispheres. Seven years later, in 1925, Hale and Nicholson, with more extensive material, discussed the law of sunspot polarity as based on 1735 groups observed between 1908 and 1925, a period covering two maxima and minima. The reversal of polarity with the spot cycle was fully established, with only 41 exceptions in the entire number observed. The full sunspot period, corresponding to the interval between the successive appearances in high latitudes of spots of the same magnetic polarity, is, therefore, twenty-three years. The reversal of polarity was found to be a sudden phenomenon unheralded by any increase of spots of irregular polarity or other exceptional event. It is fitting that a series of communications containing such brilliant discoveries in solar physics should have come to a close with one of such fundamental and far-reaching importance.

The invention of the spectrohelioscope and its numerous applications are described by Hale in a series of four publications between 1929 and 1931. The fascination which changing solar phenomena had constantly held for him from his boyhood at Kenwood was never stronger than during this last period of his active observing. In these articles he gave many results of his own observations, summarized and discussed progress in studies of the sun, and outlined a program for obtaining continuous records of solar activity through a series of stations distributed suitably in longitude throughout the world. These plans he lived to see largely accomplished. Two of the most promising fields for solar study, the relationship of solar eruptions to terrestrial phenomena and the recording of rapidly changing prominences and eruptions through continuous high-speed photography, Hale fully recognized and frequently discussed, and had health permitted, he would doubtless have developed them extensively with the aid of all the powerful resources of modern instruments and technique.

Remarkable as were Hale's personal discoveries in science, his contributions in other ways were no less great. Apart from the accomplishments of the institutions he organized and the co-operative investigations he initiated, his influence through the opportunities he afforded to other scientists to carry on special investigations was of immense value. He brought E. F. Nichols to the Yerkes Observatory to make the first measurement of the heat of a star, and Michelson to Mount Wilson to measure successfully a star's diameter and improve so greatly our knowledge of the velocity of light. He was in constant touch with scientists all over the world, corresponding with them, studying their problems and methods, and often offering facilities for the extension of the work upon which they were engaged. For this reason Kapteyn came to Mount Wilson soon after the completion of the 60-inch telescope, to aid in the formulation of a program of stellar research; Julius, to investigate the effects of anomalous dispersion where observational material was immediately available; and Abbot, to undertake measurements of the solar radiation.

The great contributions made by Hale to science were recognized by learned societies all over the world, and the record of the honors and distinctions conferred upon him is a long and distinguished one. He was a member both of the leading academies and the scientific societies of England, France, Italy, Holland, Sweden, Norway, Belgium, and several other countries, in addition to those of the United States; was elected president of the International Council of Scientific Societies in 1931; and served as a member of the Committee on Intellectual Co-operation of the League of Nations in 1922. His foreign membership in the Royal Society of London dated from 1909, and his associateship in the Institut de France (Académie des Sciences) from 1919. Practically every distinction in the form of medals which scientific societies at home and abroad could award for contributions to astrophysics was bestowed upon Hale, his extensive list of honors culminating in the award of the Copley Medal of the Royal Society in 1932. As a trustee of the California Institute of Technology and of the Huntington Library and Art Gallery, he also exercised a powerful influence upon the intellectual and cultural life of the city in which he lived; and an interesting tribute to his accomplishments in this direction was the award by the city of Pasadena of the Noble Medal for civic service.

To his own colleagues Hale was an unfailing source of help and encouragement. His insight and resourcefulness, his enthusiasm and joy in his own work and that of others, his hopefulness, modesty, and great personal charm, made any association with him a constant delight. So strong was the influence of his personality that even in the later years of his illness, when, of necessity, he had to withdraw from frequent contact with his associates, the sense of his presence and knowledge of his continuing thought of them and their work remained as a permanent influence. Finally, in its breadth of interests in the problems not only of physical science but of those of the imagination and human affairs, Hale's life was a most remarkable one. It is perhaps symbolic of this man of great gifts and wide horizons that he who had devoted his life to the study of the nearest star should find his last deep interest in an instrument destined to reveal the remotest objects of our physical universe.

Carnegie Institution of Washington
Mount Wilson Observatory
March 1938