NATIONAL ACADEMY OF SCIENCES

# HAROLD DELOS BABCOCK

*1882—1968*

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*A Biographical Memoir by*

IRA S. BOWEN



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Harold D. Babcock.

# HAROLD DELOS BABCOCK

*January 24, 1882–April 8, 1968*

BY IRA S. BOWEN*

HAROLD DELOS BABCOCK came from a family whose members have made many contributions to science. Harold himself was elected to the National Academy of Sciences in 1933; his brother Ernest B., a biologist, was elected in 1946; and his son Horace W., an astronomer, was elected in 1954.

Harold Babcock was born January 24, 1882, in Edgerton, Wisconsin, a town of 2,000 inhabitants, twenty-five miles south of Madison. He was the youngest of seven children of Emilus W. and Mary Eliza (Brown) Babcock. His father's ancestry is traced to James Badcock (later spelled Babcock), who was born in England in 1614 and settled in Rhode Island in 1642. His mother's grandparents, German and English, traveled on a raft down the Ohio River from Pittsburgh to Cincinnati to build a home there, about 1800.

Harold's father owned and operated a general store in Edgerton and a farm nearby. The environment, while isolated, was wholesome. Family life was busy and congenial. The father and mother and an older sister had all been teachers. With their help Harold learned to read before reaching school age, and he acquired a lifelong love of music. From an old

* The Academy is indebted to Horace W. Babcock, son of Harold D. Babcock, for his assistance in the final preparation of this memoir for publication after the death of the author.

book, *Natural Philosophy,* and a copy of S. P. Thompson's *Elementary Lessons in Electricity and Magnesium,* he developed an early interest in these subjects, performing many experiments in static electricity and constructing a simple telegraph. A pinhole camera and a few photographic plates, a reward for obtaining a subscription to the *Youth's Companion,* introduced him to photographic techniques.

Harold's health was never robust, possibly because of an attack of rheumatic fever in early youth. He attended public school and had completed one year of high school when, in 1896, the family, except for the two oldest sons, moved to Los Angeles.

In Los Angeles Harold entered the only high school then operating and continued for four and a half years until February 1901. In addition to the usual mathematics, physics, and chemistry, the extra year and a half spent at the school enabled him to take four years of Latin and a year each of German and Greek, as well as short courses in geometry and astronomy. He engaged in dramatics and was president of the school literary society. At the high school he came under gifted teachers who aroused his interest in physics and chemistry. During these years he carried out at home such experimental work in these subjects and in photography as meager equipment would permit.

Marconi's successes in radio communications impressed young Babcock greatly. In 1900 he used the facilities of the physics laboratory of the Los Angeles High School to demonstrate the transmission of radio signals over a distance of one hundred feet. The discharge of a high-voltage condenser was used to produce the signal, which was received by a "coherer" patterned after Marconi's apparatus. Years later Babcock built his own apparatus for receiving early radio broadcasts and in 1940 received his license as an amateur radio operator. The familiarity with electronics obtained in these early studies proved useful in much later work.

In August 1901 Babcock enrolled in the College of Electrical Engineering at the University of California in Berkeley. He found his chief interest in physics and had an opportunity for unscheduled laboratory study in electrical measurements and spectroscopy under the guidance of Professors W. J. Raymond and E. P. Lewis. The death of Babcock's father and his own illness delayed the completion of the requirements for the B.S. degree until 1906. The degree was conferred in absentia the following year.

Summer vacations during these college years brought diverse experiences. In 1903 Babcock was a member of a party making reconnaissance surveys for new construction by the Pacific Electric Railroad. In 1904 he accompanied Dr. H. M. Hall of the Department of Biology of the university on a five hundred-mile botanical collecting expedition in the southern High Sierra. For two months, in the tradition of John Muir, the party lived in magnificent scenery in regions remote from settlements and often without trails. Several peaks, including Olancha Peak and Mount Whitney, were climbed. The exhilaration of this experience was lasting.

In July 1906 Babcock received an appointment as laboratory assistant at the National Bureau of Standards. At the bureau he and Edward B. Rosa made an extensive study of the instability of laboratory standards of electrical resistance. They found the cause to be fluctuations in atmospheric humidity, a result at first disputed but later confirmed by the corresponding bureaus in England and Germany.

Babcock was united in marriage to Mary G. Henderson in 1907. To this union one son, Horace, was born in 1912.

After a few months of teaching physics at the University of California, in 1908, Babcock was invited by George E. Hale to join the staff of the Mount Wilson Observatory of the Carnegie Institution of Washington; this he did on February 1, 1909. He continued this connection with the observatory for the remainder of his active life.

At Mount Wilson, Babcock's first assignment was the photography of selected star fields at the Newtonian focus of the newly completed sixty-inch telescope as part of Professor J. C. Kapteyn's program for the study of the structure and kinematics of the Galaxy. The plates obtained provided some of the first evidence for interstellar absorption of light. Later Babcock collaborated with Walter S. Adams in a spectroscopic program using the 60-inch telescope. Very high-dispersion spectrograms of seven of the brightest stars and some five hundred spectrograms of fainter stars at lower dispersions were obtained.

In 1896 Zeeman had discovered that spectral lines emitted in a strong magnetic field were split into three or more components, the width of the pattern of lines being proportional to the strength of the field. Twelve years later Hale observed with the sixty-foot solar tower telescope on Mount Wilson the same splitting of the lines coming from sun spots. Obviously, the Zeeman effect provided a powerful tool for the study of magnetism in astronomical bodies. The number of components into which a line is split, however, and the ratio of the width of the pattern to the magnetic field, vary from line to line and from chemical element to chemical element. Extensive laboratory work was obviously required before the method could be applied to astronomical studies. Using newly developed equipment that provided fields of up to 35,000 gauss, Babcock made detailed observations of the Zeeman patterns in vanadium and chromium, two elements whose lines are prominent in the solar spectrum.

With the development of atomic structure theory and, in particular, of the vector model early in the 1920s, it became possible to predict the structures of the complicated Zeeman patterns and their widths as functions of the strength of the magnetic field and certain atomic constants. At that time Babcock returned to the problem and from very precise measures of the width of the Zeeman patterns and of the magnetic fields was able to obtain one of the most accurate values then available for $e/m$ or the ratio of the charge of the electron to its mass.

During the first decades of the present century, spectroscopy experienced a tremendous development. This was especially so in astronomy, since it was realized that spectroscopy held the key to many problems, including chemical compositions, temperatures, pressures, radial velocities, and magnetic fields of astronomical bodies. Progress in most of these problems depended on very precise measurement of wavelengths, and this in turn required accurate and easily reproducible standards for comparison. The publication of Rowland's *Preliminary Table of Solar Spectrum Wavelengths* between 1895 and 1897 provided the first such set of standards. They were used as the basis for both laboratory and astronomical observation of spectra for the next quarter century. However, by the second decade of the present century it became evident that these Rowland wavelengths were not only too large by 0.0036 percent, but had erratic fluctuations of up to 0.03 to 0.04 Å throughout the range from 3000 to 7330 Å.

One of the first problems here was to find a new source, preferably a laboratory source, that produced a large number of lines well distributed through the ordinarily observed spectral range and the wavelengths of whose lines remained constant under all ordinary conditions of operation. The first criterion, a satisfactory distribution of lines throughout the spectrum, was satisfied by an electric arc between iron electrodes. Beginning in 1914, Charles E. St. John of the observatory staff and Babcock carried out an extensive study of the second criterion, the constancy of the wavelength of the light emitted from various points in such an arc under different conditions of operation using the most precise techniques available, namely, a Fabry–Perot interferometer combined with a grating. In general, they found substantial wavelength shifts of many of the lines, depending on operating conditions and the position in the arc from which the light originated. However, by carefully defining the operating conditions and the location of the source of the light, they were able to achieve highly reproducible results. The specifications for the arc that they set up were later adopted officially by the International Astronomical Union for the source of the iron wavelength standards.

Using this standard source, St. John and Babcock proceeded in 1921 to the measurements of the wavelengths of the lines emitted. Later, in 1927, Babcock repeated many of the measurements and measured additional lines. For adoption as an official wavelength standard, the rules of the International Astronomical Union required that at least three independent observers agree on the wavelength of a line within certain very close limits. The values by St. John and Babcock were used as one of these three measures.

Because of the important role that these studies played in the establishment of the basic wavelength standards, Babcock was asked in 1925 and again in 1928 to serve as president of the Commission des Etalons du Longueur d'Onde et des Tables de Spectres Solaires of the International Astronomical Union.

Using the same precision techniques, St. John and Babcock then investigated certain pressure-sensitive lines in the solar spectrum to measure the pressure in the photosphere. They also studied the constancy of the wavelengths of both terrestrial and solar lines in the solar spectrum as a means of detecting motions in the earth's and the sun's atmospheres.

Having established the necessary wavelength standards and investigated the constancy of the wavelengths of the lines in the solar spectrum, St. John and Babcock, with the assistance of

Charlotte E. Moore, Louise M. Ware, and Edward F. Adams, carried out a revision of Rowland's table of solar wavelengths. All wavelengths were related to the new wavelength standards. A large fraction of the lines that had not been classified as to chemical element in Rowland's list were classified on the basis of later laboratory work. Temperature classifications and excitation potentials were added when available. The tables were extended from Rowland's limit in the red at 7730 Å to 10,218 Å on the basis of new observations. A total of some 22,000 solar and terrestrial lines were listed. The volume containing these results was published in 1928 and at once became the basis for many investigations of both the sun and other stars.

In 1947 Babcock and Charlotte Moore published a second volume repeating many of the earlier infrared measurements and extending them to 13,500 Å in the far infrared. The following year Babcock, with Miss Moore and Mary F. Coffeen, extended the observations of the solar spectrum in the ultraviolet to 2935 Å and increased the accuracy and detail of the measurements from 3063 Å to the former limit.

These observations of the solar spectrum included a large number of sharp lines originating in the earth's atmosphere, especially in the red and infrared. Many of these lines were caused by absorption by the oxygen molecule. Observations made when the sun was near the horizon and the light passed through some hundreds of kilometers of air brought out many very faint lines that could not have been observed otherwise. In 1927, G. H. Dieke and Babcock published the wavelengths of these lines and their classification as bands of the oxygen molecule, each of whose atoms was considered to be of mass 16. A little more than a year later Giauque and Johnson of the University of California noted that several of the faint bands could be explained best as arising from an $^{16}O^{18}O$ molecule. Babcock again went over the observational data and listed a number of hitherto unclassified lines. Some of these proved to be missing $^{16}O^{18}O$ lines, while some of the faintest were caused by the $^{16}O^{17}O$ molecule. From measures of the relative intensities of the lines of $^{16}O^{16}O$, $^{16}O^{17}O$, and $^{16}O^{18}O$, Babcock was able to estimate the relative abundances of the $^{16}O$, $^{17}O$, and $^{18}O$ isotopes. Likewise Birge and Babcock were able to fix the relative masses of the $^{16}O$ and $^{18}O$ isotopes from the constants of the band structures. Some twenty years later, Babcock and Louise Herzberg, using new measurements, made new precision determinations of the constants of the $^{16}O^{16}O$, $^{16}O^{17}O$, and $^{16}O^{18}O$ molecules.

This discovery that oxygen had isotopes of mass seventeen and eighteen and that ordinary oxygen was a mixture of these with the predominant isotope of mass sixteen had a fundamental impact on the atomic weight systems as determined from chemical analyses and from mass-spectrograph observations. Because of the procedures used, the chemical system was relative to the average weight of all isotopes of oxygen, while the mass-spectrograph system was relative to the mass of the $^{16}O$ atom alone. Since the basic assumption of both systems was that the atomic weight of oxygen was exactly sixteen, it became necessary to shift one or the other system to a new base to bring them into agreement.

In 1923 Babcock used the interferometer techniques that he had developed to make the first precise measurement of the wavelength of the brightest but as yet unidentified line in the spectrum of the aurora—the well-known "green line." He achieved at least a one hundred-fold increase in accuracy, showing that the line's wavelength was 5577.350 Å and that its width was less than 0.035 Å. This led to its identification as due to a forbidden transition in the oxygen atom.

Starting in 1912, a very large engine for ruling diffraction gratings was designed and constructed at the Mount Wilson Observatory under the direction of J. A. Anderson. Because of the friction and flexure inherent in such a large engine, it never succeeded in ruling the very large gratings for which it was designed. When the 200-inch telescope project was initiated, in 1928, Anderson was made its executive officer, and Babcock was asked to take charge of the ruling of gratings. A careful review of the program indicated that for the ruling of small and moderate size gratings (up to 10 × 7 inches), a smaller engine would have a much larger probability of success. Under Babcock's direction, such an engine was designed and constructed between 1928 and 1932 by Francis G. Pease, Edgar C. Nichols, Clement Jacomini, and Elmer Prall. In the course of this development much attention was given to the selection and the shaping of the ruling diamond in order to control the exact shape of the grooves ruled. With the proper groove shape, it is possible to throw most of the incident light into one order of the spectrum. A still further increase in grating efficiency was achieved by Babcock by shifting from speculum metal (an alloy of tin and copper) to a coat of aluminum evaporated onto glass as a ruling surface. These procedures were so successful that the gratings he produced had a higher efficiency than a prism train of the same dispersive power. Moreover, when ruled on aluminum evaporated onto Pyrex blanks, the gratings had a sensitivity to temperature only about one twenty-fifth of that of prisms. Because of these advantages, all prisms in the spectrographs at Mount Wilson were replaced with Babcock's gratings, and noteworthy improvements were achieved in resolving power, speed, and stability.

On Babcock's retirement from regular duties at the observatory on February 1, 1948, he was asked to continue the supervision of the ruling engine for another year. By the end of that year the ruling engine was in regular production of grating up to 6 × 7.5 inches, which approached closely the capacity of the engine. The gratings produced in this and the following year met the needs of the large spectrographs of the 200-inch Hale telescope.

After Hale's discovery of magnetic fields in sunspots in 1908, Hale and a number of collaborators had attempted for many years to detect and measure the general magnetic field of the sun, but were never able to achieve conclusive results. Babcock began work on the problem in 1938 using a Lummer plate, which provided somewhat higher resolution than had been used in the earlier studies. The photographs obtained, however, failed to yield a definite answer.

Shortly after World War II, Babcock and his son Horace attacked the problem again, using new optical and electronic techniques that had been developed since the earlier studies. The Babcocks achieved not only unambiguous measures of the field, but were able to push the sensitivity to the point that it was possible to scan the sun's surface rapidly and plot the detailed distribution of the intensity of the field over the surface. A program was then set up for producing daily maps of this distribution of the field. In the course of these observations it was found that this general magnetic field of the sun reverses with the eleven-year period of the sunspot cycle.

Babcock participated in the Mount Wilson Observatory expeditions to observe solar eclipses in 1918, 1923, 1930, and 1932.

In World War I Babcock served in the Research Information Service of the National Research Council. Later he engaged in supersonic research that was part of an antisubmarine effort. In World War II he served as consultant on a number of projects and produced special ruled surfaces for the Manhattan District, the U.S. atomic bomb project.

In summary, Harold Babcock's scientific life was devoted to pushing the precision of measurements and of techniques to the furthest possible limits. In spectroscopy this resulted in a set of standards that are basic to most spectroscopic measures in both astronomy and physics. His accurate measurements of the oxygen bands provided the basis for the discovery by Giauque and Johnson of the isotopes of oxygen of mass seventeen and eighteen, which required a major revision of the atomic weight system. His development of precision techniques made possible the final solution of the problem of the general magnetic field of the sun and the ruling of the first large gratings of high efficiency for astronomy.

Harold Babcock's results were never published until they had been carefully considered and were fully established on a sound basis. Underlying this patience and thoroughness was an unusual awareness of nature. As Gerald E. Kron remarked in 1953, when presenting to him the Bruce Medal of the Astronomical Society of the Pacific, Babcock was a person with a high degree of interest in his environment and in people. He sought to understand and appreciate in depth the elements of nature that he encountered, on whatever scale, and he had the ability to transmit this appreciation, especially to younger associates.

Always considerate of his colleagues, he unobtrusively accomplished many kindnesses for them and their families, especially in later years. He died suddenly on April 8, 1968.

Babcock was a member of the American Association for the Advancement of Science and received its Pacific Division Prize in 1929. He was a member of the American Physical Society, the American Astronomical Society, and the Astronomical Society of the Pacific and was an Associate of the Royal Astronomical Society. The University of California conferred the honorary LL.D. degree on him in 1957.

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*KEY TO ABBREVIATIONS*

Astrophys. J. = Astrophysical Journal
Carnegie Inst. Wash. Publ. = Carnegie Institution of Washington Publication
J. Inst. Metals = Journal of the Institute of Metals
J. Opt. Soc. Am. = Journal of the Optical Society of America
Phys. Rev. = Physical Review
Phys. Soc. London Opt. Soc. = Physical Society of London Optical Society
Popular Astron. = Popular Astronomy
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences
Publ. Am. Astron. Soc. = Publications of the American Astronomical Society
Publ. Astron. Soc. Pacific = Publications of the Astronomical Society of the Pacific
Trans. Internat. Astron. Union = Transactions of the International Astronomical Union


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