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OF

CHARLES EDWARD ST. JOHN

1857–1935

BY

WALTER S. ADAMS

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Charles Edward St. John, member of the staff of the Mount Wilson Observatory of the Carnegie Institution of Washington for twenty-two years, died at Pasadena, California, on April 26, 1935. During the last five years of his life he was Research Associate of the Institution and continued active investigation until shortly before his death. He was elected to the National Academy of Sciences in 1924.

St. John was born at Allen, Michigan, on March 15, 1857. He came of an old English family, being descended directly from Matthias St. John who came from England to Massachusetts in 1632. Successive generations lived in New England and New York, but about 1850 St. John's father and mother moved westward to Michigan where the father, Hiram A. St. John, took up the trade of millwright in a new and undeveloped country. The mother, Lois Bacon, was born in central New York. Her mother had lived for many years in Williamstown, Massachusetts, and transmitted to her children many of the intellectual interests which she had developed in this college town. St. John's mother received an exceptionally good education for the period and retained throughout her life a wide interest in reading, public affairs and the changing life of the country. She was the intellectual companion of her children and her influence upon their development must have been great.

Charles St. John was the youngest of a family of four sons and two daughters. One brother of exceptional promise died of a brain lesion at the age of 34. A second after three years' service in the Civil War studied law and developed into one of the leading attorneys of southern Michigan. The two sisters were women of marked intellectual ability: one became a successful and influential teacher and the other a business woman of unusual capacity.

As a boy St. John was not physically strong and his education proved a severe tax upon his constitution. He entered Michigan Normal College in 1873 and was graduated at the age of nineteen, the youngest member of his class. During this period he greatly overtaxed his strength and for the next ten years he was incapacitated for further study. It is probable, however, that these were the years in which he built up the philosophy of life which he followed throughout his career. As his health recovered he undertook an instructorship in physics and chemistry at the Normal College and in 1887, at the age of thirty, received the degree of Bachelor of Science from the Michigan Agricultural College. The need for severe economy at this time obliged him to combine teaching with the continuance of his studies. After two years of graduate work, mainly in electricity and magnetism, at the University of Michigan, he went to Harvard University where he received the degree of Master of Arts in 1893. The award of the John Tyndall Fellowship enabled him to spend a year abroad at the University of Berlin after which he returned to Harvard and obtained the degree of Doctor of Philosophy in 1896 at the age of thirty-nine. The advanced age at which he reached this important stage in his education bears eloquent testimony to the tenacity of his purpose in the face of severe physical and financial handicaps.

The courses at Harvard which St. John followed during his graduate study dealt largely with problems of electrical conduction and self-induction, magnetic permeability and similar subjects which formed an important part of the theoretical and observational physics of that period. His first extensive publication was a paper on the *Wave-Lengths of Electricity on Iron Wires* which appeared in the American Journal of Science in 1894. In Berlin his work had to do mainly with the radiation of black bodies, and a valuable article giving some of his results was published by him in the Annalen der Physik und Chemie in September 1895. At Harvard he studied chiefly under Trowbridge and B. O. Peirce, and the fundamental training he received under these eminent teachers proved of the greatest value to him in his future work. It is clear that even at this time problems connected with radiation held a strong attraction for St. John, an interest which developed with the years which brought him into contact with spectroscopy.

After leaving Harvard, St. John was for one year Instructor in Physics at the University of Michigan and then accepted an appointment as Associate Professor of Physics and Astronomy at Oberlin College. He remained at Oberlin for eleven years, becoming Professor of Physics in 1899 and Dean of the College of Arts and Sciences in 1907. He left Oberlin to become a member of the staff of the Mount Wilson Observatory in the summer of 1908 at the age of fifty-one.

As a teacher at Oberlin, St. John was remarkably successful and held the interest and affection of his students to an unusual degree. Dealing with relatively small classes, he was brought into intimate contact with the individual students by whom his remarkable enthusiasm and love of knowledge in every form were appreciated and respected. Many of these students later went out into careers of teaching or scientific research, and St. John's influence was often a determining factor in their after lives. Perhaps the most striking characteristic in his teaching, apart from his enthusiasm, was his love of accuracy and his intolerance of vagueness and lack of precision, whether in the statement or the solution of a problem. He had an extraordinary capacity for concentration which frequently made him oblivious to his surroundings, both within and without the classroom, and his absent-mindedness was proverbial throughout his life. His chief interest lay in advanced and graduate, rather than elementary, student courses and to these he brought the clearness of exposition and demonstration which characterizes the exceptional teacher.

It is rarely that one who has been engaged in teaching for many years and has taken part in administrative work is desirous at an age of more than fifty of changing his life completely and entering upon pure research. But the research instinct was very strong in St. John's mind, as was clearly indicated by the character of his work while a graduate student at Harvard and Berlin. When a teacher at Oberlin he spent several summers, beginning in 1898, at the Yerkes Observatory where he worked with Dr. E. F. Nichols on the first successful attempts to measure stellar radiation with a radiometer. It was here too that he first met Dr. George E. Hale and others of the staff who later formed a part of the group at Mount Wilson. Accordingly, when Dr. Hale offered him in 1908 a position on the Mount Wilson staff he accepted gladly, partly because of the increasing strain of the administrative responsibilities at Oberlin, but chiefly because of the opportunity afforded him of realizing the desire for research which had been so close to his heart for many years. In July 1908 he arrived at Mount Wilson and began his new work.

At this time the Mount Wilson Observatory was still in an early stage of development. The 60-inch reflector was under construction, but the only telescopes available for use were the two solar instruments, the Snow horizontal telescope and the 60-foot vertical telescope. Both were equipped with powerful spectrographs and spectroheliographs. The spectroscopic laboratory in Pasadena had been completed and the small laboratory on Mount Wilson, where the spectra of arc and spark light-sources could be studied and compared with solar spectra, was still used for investigations not requiring heavy currents. It was natural, accordingly, that St. John should enter the field of solar spectroscopy, a field which at just this period was of exceptional interest. In the summer of 1908 Hale had discovered the vortical character of sun-spots, which was immediately followed by the fundamental discovery of the existence of magnetic fields in spots. Two years previously the photography of sun-spot spectra and comparison with the spectrum of the iron arc at different temperatures (an investigation carried on simultaneously by A. Fowler in England) had provided the first definite evidence for the separation of lines into temperature classes and had explained the principal features of the sun-spot spectrum. The immense importance of this work in its application to the analysis of spectra and to a rational understanding of solar and stellar phenomena was just being recognized. In addition, the important differences between the spectrum of the center and the limb of the sun had just been discovered, and the possibility under fine observing conditions of photographing the flash spectrum without an eclipse had been fully established. In short, the field of solar physics and spectroscopy was filled with problems of great variety and remarkable interest.

Once started upon his investigations, St. John pursued them with extraordinary enthusiasm and energy. In the period between 1909 and 1930 he published eighty papers, either individually or in collaboration with other members of the Mount Wilson staff. Most of these, especially those of greater length, appeared in the Astrophysical Journal as Contributions from the Mount Wilson Observatory. He also prepared several extensive committee reports which were published in the Transactions of the International Astronomical Union. Shorter communications appeared in the Proceedings of the National Academy of Sciences, the Publications of the Astronomical Society of the Pacific, the Physical Review and the publications of numerous scientific societies. The Revision of Rowland's Preliminary Table of Solar Spectrum Wave-Lengths was issued in book form by the Carnegie Institution of Washington.

In a broad way St. John's investigations may be analyzed into six groups all of which are more or less interrelated:

1. Motions and circulation in sun-spots.
2. General circulation and levels in the solar atmosphere.
3. Wave-lengths and displacements of solar and terrestrial lines with application to the theory of generalized relativity.
4. Spectroscopic measurements of the rotation period of the sun.
5. Identification of elements in the solar spectrum.
6. Application of solar results to planetary and stellar spectra.

Beginning with accurate measurements of the wave-lengths of the important H and K lines of ionized calcium, St. John made a detailed quantitative study of their behavior and displacements in sun-spots and adjacent regions on the sun's surface. From this investigation he found that in the great majority of cases calcium vapor is descending over the umbrae of spots with velocities of as much as two km a second. Radial motions inward across the penumbrae and occasional rotary motions were also observed. He concluded that in the case of sun-spots there appears to be a local system in which the emitting vapor rises around the flocculi, flows across the penumbra, and is then drawn downward into the umbra, with or without vortical motion.

The results of this investigation and the discovery by Evershed in the spring of 1909 of the displacement of solar absorption lines in the penumbrae of sun-spots led St. John to undertake a very extensive series of measurements involving some 500 lines of different elements. An analysis of his results, besides affording full confirmation of Evershed's hypothesis that the displacements are due to motion of the solar gases tangential to the sun's surface and radial to the axis of the spot vortex, showed larger displacements for the lines of longer wave-length and systematic differences depending upon the intensities of the lines and upon the elements involved. On the basis of this material St. John built up a diagrammatic representation of the probable mode of circulation of the different gases in a sun-spot vortex which is of great interest and permanent value.

At an early period in his solar investigations St. John discovered the pressing need for accurate measures of wave-length of spectrum lines, both in the sun and in laboratory sources. In 1912 accordingly, commencing with the spectrum of the iron arc, he began those extensive measurements which continued almost to the end of his life and form a collection of material of great value to investigators in spectroscopy. This work appealed to St. John especially on two grounds: first, because of the pleasure he took in quantitative studies of high precision; and second, because of the wide and important applications to problems relating to the solar atmosphere which this material afforded.

The investigation of the iron spectrum was carried out in a most careful and painstaking way. The effect of radiation from near the poles of the arc upon the character and the wave-lengths of the spectrum lines was studied in detail and the type of arc best adapted for accurate measures of wave-length was fixed upon after much examination. The hundreds of lines selected for measurement were classified according to their physical behavior in the arc, and the measures themselves were made, not only on photographs taken with large grating spectrographs, but also through the collaboration of Babcock of the Mount Wilson staff on spectrograms obtained with the Fabry-Perot interferometer. The resulting wave-lengths are among the most accurate ever made in spectroscopy and form an essential part of the list of secondary iron standards of wave-length adopted by the International Astronomical Union.

In 1914 St. John made a study of the effective levels in the solar atmosphere at which absorption lines of different elements originate. For this purpose he compared the results obtained by Mitchell at solar eclipses with his own results derived from measurements of displacements over sun-spots and found an excellent degree of correlation. The gases of the elements with the strongest solar lines extend to the greatest height, and for any one element the effective level is highest for the strongest lines. The enhanced lines (those due to the ionized element) extend to higher levels than the normal (neutral) lines of the same element. The problem of levels in the sun's atmosphere always interested St. John greatly, and although the later development of the theory of ionization by Saha partially modified some of St. John's conclusions, he continued to hold to most of the views he developed at this time.

In this same year St. John commenced his extensive spectroscopic investigation of the rotation of the sun, a research which he carried on throughout the remaining years of his life. Using the 17-inch solar image at the 150-foot tower telescope, he developed an improved method of photographing the spectra of the opposite limbs of the sun and extended his observations to include, not only the region in the green portion of the spectrum which was first undertaken in cooperation with other observatories but also parts of the violet and of the red regions. In the red he utilized atmospheric lines to serve as a check upon the accuracy and adjustment of his apparatus. Especial attention was given during the earlier years to points at high solar latitudes with a view to determining as accurately as possible the peculiar law of the sun's equatorial acceleration.

St. John's first results showed lower values of the radial motion at the solar edge and a longer rotation period than had been found by nearly all previous observers, and it was largely on this account that he decided to extend his observations over at least a full sun-spot cycle. At the end of an even longer period, however, the interpretation of the results still remains inconclusive. The observed velocities at the sun's limb after remaining low for several years, gradually began to increase and in 1934 reached nearly the values which earlier observers had found. But no certain correlation with the sun-spot cycle could be established. St. John recognized that at least a part of the change, which is definitely in evidence upon these photographs of spectra, is probably to be ascribed to scattered light in the apparatus. Whether any remaining difference represents a real variation in the sun's rotation period cannot as yet be decided. An important result of St. John's investigation was his confirmation of the higher angular velocities of rotation given by the lines of highest level in the sun's atmosphere.

The development and announcement of the theory of relativity interested St. John very greatly, and much of his later work was associated with the observational evidence for the validity of the equivalence principle of generalized relativity. In accordance with this principle solar and stellar spectrum lines should be displaced toward the red owing to the difference in gravitational potential between the gravitational field in which the emitting center is located and the terrestrial field where the radiation is received and measured. The displacement in the case of the sun when observed from the earth as calculated by Einstein amounts to 0.010 angstrom at $\lambda 5000$, a quantity well within the possibilities of observation.

St. John's first work on the relativity shift was based upon a group of lines in the so-called "cyanogen" fluting with its head at $\lambda 3883$ in the solar spectrum. These lines were selected because of their freedom from appreciable pressure shifts such as might complicate the problem under investigation. The results of measurement gave no definite evidence of the presence of the displacement required by the relativity theory, but soon afterward considerable doubt was thrown by new laboratory data on band spectra upon the quality and reliability of the lines used in the investigation. Accordingly, St. John undertook a much more extensive and elaborate study of the problem, which required several years and involved repeated measurements of more than 1500 lines. It reached its conclusion with an important paper published in 1928 entitled *Evidence for the Gravitational Displacement of Lines in the Solar Spectrum Predicted by Einstein's Theory.*

In this paper St. John discusses in detail the various causes of displacements of lines in the solar spectrum, including convection currents in the sun's atmosphere, differential scattering affecting the forms of the lines, and the "limb-effect." His final conclusion is that the predicted relativity shift is present in the sun in its full amount but that the effect of level is important. Lines at the center of the sun arising from medium levels give very closely the theoretical value, while those arising from high levels give somewhat more and those from low levels somewhat less than the predicted value. These differences he ascribes chiefly to the existence of radial convection currents near the photosphere the effect of which would, of course, vanish at the sun's limb. Several independent lines of evidence derived from both the sun and the stars add weight to the conclusion that such currents must exist. The important conclusions derived from this investigation, the care and skill in the discussion of the complex factors involved, and the extent of the material studied will doubtless make St. John's work on this problem a fundamental contribution to astrophysical knowledge.

Two interesting investigations on the planet Venus were carried on by St. John in collaboration with S. B. Nicholson in the years 1921-22. The first of these dealt with the problem of a possible "earth-effect" proposed by Evershed and Royds to account for differences observed by them between terrestrial and solar wave-lengths, and pictured as an actual repulsion of the solar gases by the earth but not by other planets. Hence wave-lengths in the light from the earth-facing hemisphere of the sun should differ from those observed from a hemisphere facing, for example, the planet Venus. St. John and Nicholson collected a large amount of observational material when Venus was east and west of the sun and discussed their results both with reference to the angle Venus-Sun-Earth and the altitude of the planet. The measured values agreed in general with those obtained by Evershed and Royds, but the correlation of the displacements with the altitude of Venus seemed to be so definite that their origin was assigned to the conditions under which the observations were made rather than to any repulsive action from the earth.

A further investigation of the spectrum of Venus in the less refrangible region led to the important conclusion that the amount of oxygen in the part of the planet's atmosphere traversed by the reflected sunlight cannot exceed one-thousandth of that over equal areas in the earth's atmosphere. The amount of water vapor in the planet's atmosphere was also found to be very small. These observations have modified very considerably earlier views regarding the nature and composition of the atmosphere of this sister planet to the earth.

St. John's productive capacity during the years 1915-1925 was very high and his interests covered a wide range. In addition to the investigations already noted he made a valuable study of anomalous dispersion in the sun which proved the minor influence of this phenomenon upon solar observations; he undertook a detailed examination of the accuracy of measurement of close pairs of solar spectrum lines; in the physical laboratory he studied the pole effect in the electric arc and developed methods for its elimination; and he applied the results of his solar investigations to stellar spectra with marked success. All of this work was characterized by skill and resourcefulness in observational methods and unusual ability in the treatment and discussion of large quantities of numerical data.

The Revision of Rowland's Preliminary Table of Solar Spectrum Wave-Lengths was completed and published in 1928. In this extensive catalogue St. John, with the collaboration of Miss Moore, Miss Ware, E. F. Adams and H. D. Babcock, supplied one of the most important needs in astrophysics. The original Rowland Table published in 1896 was a work of extraordinary value and the relative wave-lengths of neighboring lines were remarkably accurate. The absolute wave-length of the standard upon which it was based was, however, considerably in error, and the method of coincidences used in the determination of wave-lengths and the adjustments applied to bring the solar and arc wave-lengths into agreement introduced irregularly distributed errors. St. John and his collaborators based their work upon the absolute wave-length of the red cadmium line, the most precise standard known, and a series of secondary and tertiary standards in the iron spectrum, the wave-lengths of which had been adopted by the International Astronomical Union. The wave-lengths of a large number of solar lines observed at the center of the sun and well distributed throughout the spectrum were then measured with reference to these standards, with the aid of both grating spectrographs and an interferometer. The comparison of the wave-lengths of these lines with those of Rowland's Table provided a series of correction curves of high precision by means of which the lines in the Table were corrected.

The Revised Table, in addition to giving accurate wave-lengths upon the International system, contains many corrections and additions to the old Table and much new material. The identification of great numbers of lines has been revised and many new identifications have been added, the behavior of lines in the sun-spot spectrum is noted and the temperature classification and the excitation potential have been listed wherever known. A supplementary table giving the solar lines in the infra-red portion of the spectrum between λ7333, the limit of Rowland's Table, and λ10218, the limit reached at the date of the Revised Table; lists of lines observed in the spectrum of the solar chromosphere and the corona; and catalogues of the strongest unidentified lines and of term designations for the excitation potentials of lines investigated in the laboratory complete this useful volume. Its publication brought together the results and the applications of much of St. John's work over many years and serves as a permanent record of the industry and skill of the author.

In his later years St. John became greatly interested in the broad field of accurate photometry of spectral lines and commenced an extensive program which was but partially completed at the time of his death. This was a natural outgrowth of the years of work upon the Rowland Table of Solar Spectrum Wave-Lengths. Having contributed so greatly to precise measurements of position, he turned his attention to the other fundamental need—that of accurate determinations of intensity. Although he could not carry this work to completion, he published several brief papers dealing with its progress and developed methods of observation which are still in regular use at Mount Wilson.

In his scientific life St. John was a strong advocate of cooperative plans of investigation. He took a prominent part in the work of the International Astronomical Union, attended its meetings frequently, served as president of two of its scientific commissions and was a member of several others. He had a wide acquaintanceship with astronomers and physicists both in the United States and abroad and took great pleasure in the opportunities for discussion afforded by scientific meetings. A notable characteristic of his own scientific work was his desire to obtain the opinions of others and to consider the results of an investigation from as many points of view as possible.

On the personal side St. John had a remarkable ability to make friends and retain them, and some of his most intimate associations had extended over periods of nearly fifty years. His interest in people and in the life of the communities in which he lived was strong and active, and he took a prominent part in the establishment and support of social and cultural agencies of many kinds. Combined with his social instincts, however, were a great fondness for reading and a profound love of nature which made his days of comparative isolation on the mountain top periods of the deepest pleasure and satisfaction. With his friendliness, enthusiasm and intelligent and accurate knowledge of nature he was a delightful companion at all times and under all circumstances. In the last years of his life, with a full knowledge of his physical condition, he faced the end with the same cheerfulness and courage which had characterized his philosophy of life throughout so many active and fruitful years.

BIBLIOGRAPHY

1887-1933

1887

(With William James Beal.) A study of Silphium perfoliatum and Dipsacus laciniatus in regard to insects. Bot. Gaz., vol. 12, 268-270.

1894

Wave-lengths of electricity on iron wires. Amer. Jour. Sci., vol. 48, 311-325.

Wave-lengths of electricity on iron wires. Phil. Mag., vol. 38, 425-441.

1895

Über die Vergleichung des Lichtemissionsvermögens der Körper bei hohen Temperaturen, und über die Auer'schen Brenner. Ann. Phys. Chem., vol. 56, 433-450.

Value of the magnetic permeability for rapid electrical oscillations. Phil. Mag., vol. 39, 297-298.

Wave-lengths of electricity on iron wires. Amer. Acad. Arts and Sci. Proc., vol. 30, 218-246.

1909

Note on the polarizing effect of coelostat mirrors. Astrophys. Jour., vol. 29, 301-304; Mt. Wilson Contr., No. 37.

1910

The absolute wave-lengths of the H and K lines of calcium in some terrestrial sources. Astrophys. Jour., vol. 31, 143-156; Mt. Wilson Contr., No. 44.

The general circulation of the mean and high-level calcium vapor in the solar atmosphere. Astrophys. Jour., vol. 32, 36-82; Mt. Wilson Contr., No. 48.

1911

Motion and condition of calcium vapor over sun-spots and other spectral regions. Astrophys. Jour., vol. 34, 57-78, 131-153; Mt. Wilson Contr., No. 54.

1912

(With L. W. Ware.) Tertiary standards with the plane grating: The testing and selection of standards. First paper. Astrophys. Jour., vol. 36, 14-53; Mt. Wilson Contr., No. 61.

1913

Radial motion in sun-spots. I. The distribution of velocities in the solar vortex. Astrophys. Jour., vol. 37, 322-353; Mt. Wilson Contr., No. 69.

Radial motion in sun-spots. II. The distribution of the elements in the solar atmosphere. Astrophys. Jour., vol. 38, 341-391; Mt. Wilson Contr., No. 74.

Radial motion in sun-spots. Read at 83d meeting B.A.A.S.; Rept. B.A.A.S., p. 392-394; Observatory, vol. 36, 395-397.

Sondage de l'atmosphere solaire par les mesures de vitesses radiales dans les taches. Comptes rendus, vol. 157, 428-430.

1914

The international standards of the second and third orders. Trans. Internat. Union for Cooperation in Solar Research, vol. 4, 74-78.

Radial motions in sun-spots. Trans. Internat. Union for Cooperation in Solar Research, vol. 4, 214-217.

(With L. W. Ware.) Tertiary standards with the plane grating: The testing and selection of standards. Second paper. Astrophys. Jour., vol. 39, 5-28; Mt. Wilson Contr., No. 75.

On the distribution of the elements in the solar atmosphere as given by flash spectra. Astrophys. Jour., vol. 40, 356-376; Mt. Wilson Contr., No. 88.

On pressure in the solar atmosphere. Read at 17th meeting, Amer. Astron. Soc.; Pubs. A.A.S., vol. 3, 95 (1918).

The distribution of the elements in the solar atmosphere from eclipse results. Read at 17th meeting, Amer. Astron. Soc.; Pubs. A.A.S., vol. 3, 94-95 (1918).

(With Harold D. Babcock.) A displacement of arc lines not due to pressure. Read at 72d meeting, Amer. Phys. Soc., Phys. Rev., Ser. 2, vol. 3, 487-488.

1915

Anomalous dispersion in the sun in the light of observations. Astrophys. Jour., vol. 41, 28-41; Mt. Wilson Contr., No. 93.

Critique of the hypothesis of anomalous dispersion in certain solar phenomena. Proc. Nat. Acad. Sci., vol. 1, 21-25; Mt. Wilson Communications, No. 2.

(With Harold D. Babcock). Pole effect in the arc and its relation to other investigations. Read at joint meeting of A.A.A.S. and affiliated societies.

(With Harold D. Babcock.) A study of the pole effect in the iron arc. Astrophys. Jour., vol. 42, 231-262; Mt. Wilson Contr., No. 106.

(With Harold D. Babcock.) Variability of spectrum lines in the iron arc. Proc. Nat. Acad. Sci., vol. 1, 131-136; Mt. Wilson Communications, No. 5.

(With Harold D. Babcock.) On the pole effect in the iron arc. Proc. Nat. Acad. Sci., vol. 1, 295-298; Mt. Wilson Communications, No. 4.

(With W. S. Adams and L. W. Ware.) Solar rotation in 1914-15. Read at 18th meeting. Amer. Astron. Soc.; Pubs. A.A.S., vol. 3, 136-137 (1918).

1916

(With L. W. Ware.) The accuracy obtainable in the measured separation of close solar lines; systematic errors in the Rowland table for such lines. Astrophys. Jour., vol. 44, 15-38; Mt. Wilson Contr., No. 120.

Observational evidence that the relative positions of Fraunhofer lines are not systematically affected by anomalous dispersion. Astrophys. Jour., vol. 44, 311-341; Mt. Wilson Contr., No.123.

The situation in regard to Rowland's preliminary table of solar spectrum wave-lengths. Proc. Nat. Acad. Sci., vol. 2, 226-229; Mt. Wilson Communications, No. 28.

On the suggested mutual repulsion of Fraunhofer lines. Proc. Nat. Acad. Sci., vol. 2, 458-461; Mt. Wilson Communications, No. 30.

The suggested mutual influence of Fraunhofer lines. Read at San Diego meeting, Pac. Div. A.A.A.S.; (Abstract) Pubs. A.S.P., vol. 28, 197.

(With L. W. Ware.) The measurement of close pairs of solar lines. Read at San Diego meeting, Pac. Div. A.A.A.S.; (Abstract) Pubs. A.S.P., vol. 28, 196.

(With L. W. Ware.) Systematic errors in the Rowland table for close pairs of solar spectrum lines. Read at 19th meeting, Amer. Astron. Soc. (1916); Pubs. A.S.P., vol. 3, 218-219 (1918).

On the mutual repulsion of solar spectrum lines. Read at 19th meeting, Amer. Astron. Soc. (1916); Pubs. A.A.S., vol. 3, 219-220 (1918).

Anomalous dispersion in the sun. Observatory, vol. 39, 462-465.

(With W. S. Adams.) The question of diffused light in Mount Wilson solar observations. Jour. R.A.S., Canada, vol. 10, 553.

1917

(With H. D. Babcock.) The elimination of pole effect from the source for secondary standards of wave-length. Astrophys. Jour., vol. 46, 138-166; Mt. Wilson Contr., No. 137.

The principle of generalized relativity and the displacement of Fraunhofer lines toward the red. Astrophys. Jour., vol. 46, 249-265; Mt. Wilson Contr., No. 138.

A search for an Einstein relativity-gravitational effect in the sun. Proc. Nat. Acad. Sci., vol. 3, 450-452; Mt. Wilson Communications, No. 46.

(With H. D. Babcock.) The development of a source for standard wave-lengths and the importance of their fundamental values. Proc. Nat. Acad. Sci., vol. 3, 505-507; Mt. Wilson Communications, No. 48.

(With H. D. Babcock.) Elimination of pole effect from secondary standards of wave-length. Read at Stanford meeting, Amer. Phys. Soc.; (Abstract) Phys. Rev., ser. 2, vol. 9, 577.

1918

(With L. W. Ware.) Notes on solar rotation. Read at 22d meeting, Amer. Astron. Soc. (1918); Pubs. A.A.S., vol. 4, 46-47 (1923).

Our nearest star, the sun. Pubs. A.S.P., vol. 30, 15-28.

The green corona line. Pubs. A.S.P., vol. 30, 250-251.

The present condition of the problem of solar rotation. Pubs. A.S.P., vol. 30, 319-325.

1919

(With H. D. Babcock.) Are the wave-lengths of the atmospheric absorption lines variable? Read at Pasadena meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 31, 178.

(With L. W. Ware). On the source of discordant values for solar rotation. Read at Pasadena meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 31, 186.

1920

The astronomical bearing of the theory of generalized relativity. Seattle meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 32, 191.

The spectroscopic committee of The Division of Physical Sciences of The Research Council. Read at Seattle meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 32, 192.

(With H. D. Babcock.) Concerning tables of solar wave-lengths in the International system. Read at Seattle meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 32, 192.

(With S. B. Nicholson.) Relative wave-lengths of skylight and Venus-reflected sunlight. Read at Seattle meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 32, 194.

(With S. B. Nicholson.) Determination of the solar parallax from spectroscopic observations of Venus. Pubs. A.S.P., vol. 32, 332-334.

Displacement of solar lines and the Einstein effect. Observatory, vol. 43, 158-162.

The displacement of solar spectral lines. Observatory, vol. 43, 260-262.

The spectroscopic committee of the Division of Physical Sciences of the National Research Council. Phys. Rev., vol. 16, 372-374.

1921

(With H. D. Babcock.) Wave-length of lines in the iron arc from grating and interferometer measures, $\lambda 3370$-$\lambda 6750$. Astrophys. Jour., vol. 53, 260-299; Mt. Wilson Contr., No. 202.

(With S. B. Nicholson.) On systematic displacements of lines in spectra of Venus. Astrophys. Jour., vol. 53, 380-391; Mt. Wilson Contr., No. 208.

(With S. B. Nicholson.) On the absence of selective absorption in the atmosphere of Venus. Read at Berkeley meeting, A.S.P.; Pubs. A.S.P., vol. 33, 208-209.

The displacement of solar lines. Nature, vol. 106, 789-790.

(With S. B. Nicholson.) The spectrum of Venus; no oxygen or water-vapor lines present. Read at Swarthmore meeting, Amer. Astron. Soc. (1921); (Abstract) Pop. Astron., vol. 30, 229 (1922); Pubs. A.A.S., vol. 4, 326-327 (1923).

Increased ionization over solar faculae. Read at Swarthmore meeting, Amer. Astron. Soc. (1921); (Abstract) Pop. Astron., vol. 30, 228-229 (1922); Pubs. A.A.S., vol. 4, 326 (1923); Toronto meeting, Amer. Phys. Soc. and A.A.A.S. (1921); (Abstract) Phys. Rev., vol. 19, 390 (1922).

(With S. B. Nicholson.) The physical constituent of the atmosphere of Venus. Toronto meeting, Amer. Phys. Soc. and A.A.A.S. (1921); (Abstract) Phys. Rev., vol. 19, 444 (1922).

1922

(With H. D. Babcock.) An investigation of the constancy in wave-length of the atmospheric and solar lines. Astrophys. Jour., vol. 55, 36-47; Mt. Wilson Contr., No. 223.

(With S. B. Nicholson.) The absence of oxygen and water-vapor lines from the spectrum of Venus. Astrophys. Jour., vol. 56, 380-399; Mt. Wilson Contr., No. 249.

(With S. B. Nicholson.) Further observations on the spectra of Venus. Read at Williams Bay meeting, Amer. Astron. Soc. (1922); (Abstract) Pubs. A.A.S., vol. 4, 385-386; Pop. Astron., vol. 31, 24-25 (1923).

Remarks on testing the Einstein theory by displacements of solar lines. Centenary celebration of R.A.S.; Observatory, vol. 45, 210-212.

Remarks on ionization over faculae. Brit. Astron. Assoc. meeting; Observatory, vol. 45, 214.

On the spectra of Venus and Miller's repetition of the Michelson-Morley experiment. Colloquium at the Istituto Fisico, Rome.

Bemerkung zur Rotverschiebung-Physikalische Zeitschrift, vol. 23, 197.

Solar faculae and ionization. Contr. Jefferson Phys. Lab., vol. 15.

1923

The atmosphere of the sun and relativity. (Abstract) Pubs. Amer. Astron. Soc., 30th meeting, Mt. Wilson, 84-86 (1923); Pop. Astron., vol. 32, 23-25 (1924).

1924

(With Walter S. Adams.) Convection currents in stellar atmospheres. Astrophys. Jour., vol. 60, 43-49; Mt. Wilson Contr., No. 279.

(With Harold D. Babcock.) Pressure and circulation in the reversing-layer of the sun's atmosphere. Astrophys. Jour., vol. 60, 32-42; Mt. Wilson Contr., No. 278.

(With Walter S. Adams.) Convection currents in stellar atmospheres. Proc. Nat. Acad. Sci., vol. 10, 392-394; Mt. Wilson Communications, No. 89.

(With Walter S. Adams and Harold D. Babcock.) On pressure and convection currents in the atmospheres of the sun and stars. (Abstract) Pubs. Amer. Astron. Soc., vol. 5, 32d meeting, Dartmouth, 191; Pop. Astron., vol. 32, 621-622.

(With Harold D. Babcock.) Note on the pressure and currents in the sun's atmosphere. Proc. Nat. Acad. Sci., vol. 10, 389-391; Mt. Wilson Communications, No. 88.

1925

(With Walter S. Adams.) An attempt to detect water-vapor and oxygen lines in the spectrum of Mars with the registering microphotometer. (Abstract) Pubs. A.S.P., vol. 37, 158-159.

Rotation of the sun. (Abstract) Pubs. Amer. Astron. Soc., vol. 5, 34th meeting, Northfield, 290-291; Pop. Astron., vol. 33, 592-593.

Report of the Commission on Solar Physics. Trans. Internat. Astron. Union, vol. 2, 27-39.

1926

The red shift of solar lines and relativity. Proc. Nat. Acad. Sci., vol. 12, 65-68; Mt. Wilson Communications, No. 96.

(With Walter S. Adams.) An attempt to detect water-vapor and oxygen lines in the spectrum of Mars with the registering microphotometer. Astrophys. Jour., vol. 63, 133-137; Mt. Wilson Contr., No. 307.

1927

Revision of Rowland's Preliminary Table of Solar Spectrum Wave-lengths. Proc. Nat. Acad. Sci., vol. 13, 678-683; Mt. Wilson Communications, No. 101.

Revision of Rowland's Preliminary Table of Solar Spectrum Wave-lengths. Read at Reno meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 39, 256-257.

(With Charlotte E. Moore.) As to cadmium in the sun. Pubs. A.S.P., vol. 39, 314-317.

1928

Astrophysical importance of the rare-earth elements. Read at Berkeley meeting, Amer. Phys. Soc.; (Abstract) Phys. Rev., vol. 31, 918-919.

Evidence for the gravitational displacement of lines in the solar spectrum predicted by Einstein's theory. Astrophys. Jour., vol. 67, 195-239; Mt. Wilson Contr., No. 348.

Some results of the revision of the Rowland table. Read at Pomona meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 40, 270-271.

(With Charlotte E. Moore.) On the presence of the rare-earth elements in the sun. Astrophys. Jour., vol. 68, 93-108; Mt. Wilson Contr., No. 364.

(With Charlotte E. Moore, Louise M. Ware, Edward F. Adams, and Harold D. Babcock.) Revision of Rowland's preliminary table of solar spectrum wave-lengths, with an extension to the present limit of the infra-red. Carnegie Inst. Pub. No. 396; Papers of the Mt. Wilson Observatory, vol. 3, pages xxi + 238.

1929

Growth in our knowledge of the sun. Pubs. A.S.P., vol. 41, 133-144.

Report of the Commission de Physique solaire. Trans. Internat. Astron. Union, vol. 3, 5076.

Elements unidentified or doubtful in the sun: suggested observations. Astrophys. Jour., vol. 70, 160-174; Mt. Wilson Contr., No. 385.

The unit character of multiplets. Astrophys. Jour., vol. 70, 312-318; Mt. Wilson Contr., No. 389.

Excitation potential in solar phenomena. Astrophys. Jour., vol. 70, 319-330; Mt. Wilson Contr., No. 390.

Elements in the sun. Proc. Nat. Acad. Sci., vol. 15, 789-793; Mt. Wilson Communications, No. 107.

Elements: Identified and unidentified in the sun. Read at Berkeley meeting A.S.P.; (Abstract) Pubs. A.S.P., vol. 41, 267-269.

1930

The Einsteinian displacement of spectral lines. Read at Eugene meeting, A.S.P.; (Abstract) Pubs. A.S.P., vol. 42, 254.

Growth in our knowledge of the sun. Smithsonian Report for 1930, 177-189 (1931); reprinted from Pubs. A.S.P., vol. 41, 133-144 (1929).

1932

Variability of solar rotation. Third Report of Commission Appointed to Further the Study of Solar and Terrestrial Relationships, 116-122.

Observational basis of general relativity. Pubs. A.S.P., vol. 44, 277-295.

1933

Report of Commission de Physique solaire. Trans. Internat. Astron. Union, vol. 4, 34-57.