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THEODOR LYMAN

1874—1954

A Biographical Memoir by

P. W. BRIDGMAN

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THEODORE LYMAN was born in Boston on November 23, 1874. Most of his life was spent within a few miles of the place of his birth and in the social atmosphere into which he was born. He was still occupying the old ancestral estate in Brookline when he died on October 11, 1954.

The founder of the family in this country was Richard Lyman (1580-1640) of High Onger, Essex, England, who arrived here in 1631. His family eventually settled in Northampton, Massachusetts. The great-great-grandfather of our Theodore Lyman was the Reverend Isaac Lyman (1724-1810), a graduate of Yale, who was a minister in York, Maine, for many years. His great-grandfather, Theodore (1755-1839), "was a successful Boston merchant who accumulated so large a fortune that my branch of the family has never been forced to engage in business since his time." His grandfather, Theodore (1792-1849), was a public-spirited man of letters, who founded the Lyman School for Young Culprits, now the Lyman Reform School. His father, Theodore (1833-1897), was a marine biologist, a student of Louis Agassiz, and was devoted to the interests of Harvard College all his life. The father served a term in Congress, where he was devoted to the cause of civil service reform. His family moved with him to Washington, where they lived from November, 1883, to the spring of 1885.

Lyman's mother, Elizabeth Russell (1835-1911), was the daughter of George Russell, a merchant in the old China trade. Her grandfather, Jonathan Russell, was at one time United States Minister to

Sweden, and was one of the signers of the Treaty of Ghent. This family was connected with the Shaws and Parkmans of Boston.

During the first eight years of Theodore Lyman's life the family spent the winter months at Commonwealth Avenue, Boston, and the summer months in the ancestral house, built by the grandfather, on an estate of many acres in Brookline. The family moved permanently to the Brookline house after their return from Washington, and here Theodore Lyman spent the rest of his life, except for the interruptions of college, vacation trips, and the First World War.

As a boy his health was never robust, with the result that the series of schools in Brookline and Boston at which he received his secondary education were chosen rather for their suitability to his health than because of the excellence of the education they afforded. He entered Harvard in the fall of 1893 from Noble and Greenough, where he had spent the preceding year. He entered with no definite plans for the future, but with tastes leaning toward physical science, as shown by his boyish occupation with a "turning lathe, a windmill, batteries, chemicals, a steam engine, and a dynamo." In his sophomore year he took and passed a course in physics, but without adequate preparation in the fundamentals, something which he says hampered him for a long time. In his junior and senior years he worked hard at electrical engineering, and might have chosen this as a career, if he had not come under the influence of Professor W. C. Sabine in his course on optics. Sabine offered him an assistantship in the elementary course in physics, and suggested that he take up a research problem under his direction and continue for the Ph.D. degree. This suggestion Lyman accepted. Throughout his life he continued to express his admiration and loyalty to Sabine. In his biographical notes he writes: "So it came about that I owe to Professor Sabine not only my interest in the field, but such distinction as I ultimately achieved, for without his constant example before me, and without his constant help and encouragement I should have fallen by the wayside."

He received the A.B. degree, *cum laude,* in 1897 and spent the summer traveling in Europe with his classmates N. P. Hallowell and Joseph Warren. In the fall he started his ascent of the academic ladder with an appointment as one-year assistant, which was twice renewed. In 1900 he received the Ph.D. degree, the title of his thesis being "False Spectra from the Rowland Concave Grating." The winter of 1901-1902 was spent in Cambridge, England, studying under J. J. Thomson, and the summer of 1902 in study at Göttingen. On his return to Harvard he gave a half course on Conduction in Gases, based largely on what he had learned in the Cavendish Laboratory, thus offering the first glimpse of the new world in physics to the Harvard Physics Department, which for many years found it hard to get rid entirely of its traditional conservatism. In the fall of 1902 he resumed his ascent of the academic ladder, first as one-year instructor, then as instructor without limit of time, then as assistant professor for two five-year terms beginning in 1907, then professor with unlimited tenure in 1917, and finally Hollis Professor of Mathematics and Natural Philosophy (the oldest endowed scientific chair in this country and the second oldest endowed chair in Harvard University) in 1921. He held the Hollis professorship for only five years, resigning with the title Emeritus in 1925. It was generally supposed that his resignation fifteen years before the official age of retirement was due to his desire for more complete freedom. After his official retirement he continued to give a course of instruction and to direct graduate students in their work for the Ph.D. degree for many years. During his first term as assistant professor, in 1910, he was given, in addition to his Faculty appointment, the administrative position of Director of the Jefferson Physical Laboratory, a position which he held for thirty-seven years, until 1947. His financial relations to the University appear to have been somewhat irregular. There is a tradition that he was accustomed, during at least part of his tenure, to turn his salary back to the University, as did also a few other professors of wealth. There is a story that President Lowell, on one occasion of a general increase in the level of University salaries, refused to increase Lyman's salary, saying, "Theodore does not need it," and it is known from his own remarks that he never received any salary for his administrative services as Director of the Laboratory.

His last formal course of instruction, a course in optics with which he had been identified for many years, was given in 1937-1938, and the last Ph.D. thesis under his direction was completed in 1942. During his active career he states that his time was divided approximately one fourth to teaching, one fourth to administration, and one half to research.

His scientific work is entirely associated with the spectroscopy of the extreme ultraviolet. The topic was suggested by W. C. Sabine. When Lyman started on his thesis work the spectrum had been recently extended by Victor Schumann to a wave length now known to be about 1,260 A, by several advances in technique, in particular by enclosing the entire spectroscope in an evacuated chamber to eliminate absorption by the air, and using fluorite as the material for windows, lenses, and prisms, fluorite having been found by Schumann to be more transparent in the ultraviolet than any other known substance. Although Schumann obtained a wealth of new spectrum lines beyond 2,000 A, it was a disadvantage of his method that the wave lengths could not be exactly determined in the absence of knowledge of the index of refraction of the fluorite of his prisms. Sabine suggested that Lyman use a concave ruled grating instead of the fluorite prism, thus making it possible to obtain exact wave lengths. It took seven discouraging years before this simple suggestion fructified in the actual measurement of wave lengths in the Schumann region. The difficulties were matters of technique. The most fundamental of these was in producing and maintaining the vacuum. Vacuum pumps were crude, slow, and inefficient; measurements of the vacuum had to be made with the McLeod gauge, and modern improved methods of gasketing the pressure vessel to prevent leak had not been developed. There was always some perceptible leak in all Lyman's early apparatus. Unexpected difficulties arose in connection with the grating; false lines of a new kind were found in the Schumann region due to light in the visible spectrum. The explanation, suggested by Runge and proved by Lyman, involved periodic errors of long period in the ruling of the grating. The establishment of the existence of this kind of false line, now known as Lyman ghosts, was a sufficiently important by-product to provide the subject for his Ph.D. thesis. It is easy to imagine that a less meticulous and conscientious observer would have been deceived by these ghosts and have prematurely announced the attainment of his goal. Lyman's first quantitative measurements in the Schumann region were published in a preliminary paper in 1904, followed in 1906 by measurements to 0.1 A unit of the wave lengths of more than three hundred lines known to be due to hydrogen in the region between 1228 and 1675 A, and some fifty other lines between 1228 and 1030 A, probably due to hydrogen. He established the limit of transparency of fluorite to be 1260 A, thus showing at the same time that Schumann's estimate of his own limit as 1000 A, based on a dispersion formula of Helmholtz and Ketteler, was considerably in error. These measurements incidentally constituted a not inconsiderable extension of the spectrum from 1260 to 1030 A. Measurements of wave length were made and checked by two methods. One was the method of two slits, devised by Lyman, by which the spectrum could be displaced a known distance by utilizing a second slit a known distance from the first. The second method was by comparing the second-order spectrum of known lines of longer wave length with the first-order spectrum of the unknown ultraviolet lines.

His later scientific work was a more or less logical development of the ideas contained in his 1906 paper. There was, in the first place, an exploration of the optical absorption of all likely solids, with the hope of finding something superior to fluorite, but nothing was found. There was an examination of the optical absorption of various gases. Gaseous absorption at first placed serious limitations on the technique. Most gases, with the notable exceptions of hydrogen and helium, are strongly absorptive in the region down to 1,000 A, with the result that the gaseous discharge tube in which the spectrum of the gas is produced must be mechanically separated from the rest of the spectrometer. This demands a window, for which the most transparent material is fluorite, which therefore sets a lower limit to the measurable spectra of such gases at 1230 A. Later, with the development of better vacuum pumps, the fluorite window was dispensed with, the gas diffusing out of the discharge tube being removed by a powerful pump before it could enter the rest of the spectrometer. Gradual improvements were made in the source by employing powerful electric discharges with suitable variations of the capacity or inductance in the circuit, and by bringing the source nearer the slit by modifications in the geometrical design. A source of continuous radiation was devised by producing the discharge in a narrow quartz capillary; the origin of this radiation was traced to the solid particles of quartz torn from the walls of the capillary by the violence of the discharge. The availability of this source was, however, limited by deposition of quartz on the surface of the grating. Much attention was given to the development of a superior photographic plate, but nothing was found better than the original process of Schumann, in which the quantity of gelatine was held to the absolute minimum necessary to hold the grains of silver in place. In some of his later work Lyman used for convenience plates sensitized by dipping in an oil which luminesces under ultraviolet radiation.

During the early years of the century spectroscopic analysis received an enormous impetus because of the discovery of the mathematical regularities shown by many spectra and because of the connection with atomic structure shown by Bohr. Two series for hydrogen had been known—the Paschen series, the frequencies of which are given by the formula $\nu = N\left(\frac{1}{3^2} - \frac{1}{m^2}\right)$, m running through integer values greater than 3, and the Balmer series with the similar formula $\nu = N\left(\frac{1}{2^2} - \frac{1}{m^2}\right)$. In 1914 Lyman announced the discovery of the first three members of the series with the formula $\nu = N\left(\frac{1}{1^2} - \frac{1}{m^2}\right)$, a series now known as the Lyman series. Lyman's caution and meticulousness in assuring himself that this series was really due to hydrogen and not some impurity, and his delay of publication until he was sure, are models of scientific integrity.

By the use of such improvements in technique, but with no changes in the general arrangement, Lyman had by 1915 extended the spectrum to 600 A, and by 1917 to 500 A. In 1917 his work was interrupted by his war service, which will be described in greater detail later. The following quotation is from the biographical notes prepared by Lyman in the files of the Academy. "When I was mustered out of the service in the spring of 1919 I found it impossible to resume my academic work or my research with any enthusiasm. It took some time for me to get back into harness. Meanwhile a number of people had entered the field of vacuum spectroscopy. I had lost the leadership and I never regained it. Moreover, the untimely death of Professor Sabine increased my administrative burdens."

Of the "other people" who entered the field of vacuum spectroscopy the most important was R. A. Millikan, who was able to extend the optical spectrum to 140 A by the use of a new source of much greater efficiency, the "hot spark," first described by R. W. Wood. In his book Lyman was most generous in recognizing the excellence of Millikan's work. In the meantime, workers in other laboratories were extending the spectrum to longer wave lengths from the region of soft X-rays, until finally in 1927 Osgood, working in the laboratory of A. H. Compton, completely closed the gap in the spectrum.

Lyman's first paper after his return from the war contained the announcement of two lines at approximately 1640 and 1215 A in a new spectrum of helium. In his very important paper of 1924 seven lines were tabulated in the principal series of helium, and a rare observation was made of the continuous spectrum beyond the limit of the series due to recapture of free electrons of different kinetic energies. Two lines in the spectrum of doubly ionized helium were observed, of great theoretical significance because the frequencies are four times the frequencies of corresponding lines in the hydrogen spectrum, as predicted by theory. In this paper lines were recorded down to 256 A, using a source similar to Millikan's. Papers followed on the series spectra in the ultraviolet of aluminum, magnesium, and neon, the last with F. A. Saunders. Saunders, whose principal interest at the time was in spectroscopic analysis, had joined the staff of the Laboratory after the war, and there was much fruitful collaboration between Lyman and Saunders.

Lyman's scientific productivity greatly diminished after 1926, because of the press of other activities and the state of his health. His last paper was published in 1935, on the transparency of air between 1100 and 1300 A. He continued for some years working on such topics as the development of a photometric method for measuring the coefficient of absorption of gases below 1,000 A, and methods for improving the sensitivity of plates by oiling, but he obtained nothing satisfying his own meticulous standards, and he published nothing. In this latter period he continued to direct the research of graduate students in ultraviolet spectroscopy, and six Ph.D. theses were published under his direction after 1931, the last two in 1941 and 1942.

Lyman's health was never vigorous and he always had to be careful of it. He found it necessary to keep early hours, something always respected by his colleagues. In this connection there is a story, substantiated by Lyman himself, that Amy Lowell, the poet and a childhood companion, had suggested to Lyman that he call on her and renew childhood memories. After a suave exchange of correspondence the project was abandoned because of the insuperable difficulty that Amy Lowell could never receive anyone before 11 P.M. because she was accustomed to breakfast at 5 P.M., whereas

Lyman invariably retired at 9. During the academic vacations Lyman was accustomed to recuperate the strength lost during the rigors of the academic year by extensive travel, usually in the form of hunting trips. He was an early member of the Travellers' Club, an organization founded in 1902 by the geologist William Morris Davis "to promote intelligent travel and exploration, especially by Harvard men." In the last *Year Book* of the club, issued in 1935, the following entries appear under Lyman's name: Cassiar, British Columbia, 1903, 1905; Korea, 1906; British East Africa, 1908; Highlands of Siberia, 1912; Alaska, 1921, 1925. These are only the more important of Lyman's travels: in Lyman's own notes there is record of summer expeditions every year, except during the war, from 1897 to 1930, many of the trips being to more conventional places in Europe and our own West. He is listed as having talked about his experiences to the Club on seven different occasions. Lyman writes in the twenty-fifth report of his Harvard class: "At first my sole object was amusement, but more recently I have done some collecting for the Museums in Cambridge and Washington." In British East Africa he shot four lions, to his great satisfaction. He was summoned to the White House by Theodore Roosevelt to advise about Roosevelt's prospective African trip, and a second time later, on Roosevelt's return, to hear the account of the trip. It is said that at one time during the second interview Lyman expostulated, "But, Mr. President, I too have been there."

Doubtless his most important trip was in 1912 to the Altai Mountains of Siberia and Mongolia. This trip, financed by Lyman, was participated in by representatives of the U. S. National Museum and of the Harvard Museum of Comparative Zoology for the purpose of collecting fauna in the Altai Mountains, which at that time were virtually unrepresented in American museums. There is an account of this trip in Proc. U. S. Nat. Mus. 45:507-532, 1913, written by N. Hollister, Assistant Curator, Division of Mammals, U. S. National Museum. The expedition required nearly a month from St. Petersburg to reach the Siberian-Mongolian border. Here the expedition divided, the two professionals remaining to collect the smaller mammals, and Lyman pushing on alone into Mongolia for large game hunting. He brought back specimens of sheep, ibex, and gazelle. A gazelle, *Procapra altaica,* was the first recorded specimen of the species. The expedition returned to civilization with numerous specimens for the museums, including thirteen species not previously known. One of these was named after Lyman, Lyman's stoat, or *Mustela lymani.* In his later years Lyman sometimes commented wryly on the inscrutable ways of the taxonomist, who chose the insignificant stoat to receive Lyman's name, rather than the larger gazelle, which Lyman felt would have been more fitting.

A later trip with a scientific tinge was with Dr. Bert Wolbach in 1926 to the Bitterroot Mountains of Idaho and Montana to collect specimens of the tick which infested the mountain goats of that region and were responsible for Rocky Mountain spotted fever. The ticks were successfully collected, but there seems to be no publication by Dr. Wolbach on the subject later than his well-known treatise on Rocky Mountain spotted fever in 1919, so that the precise point at issue is not clear.

In his later years Lyman enjoyed salmon fishing in the Gaspé.

With the outbreak of the First World War in Europe Lyman became interested in General Wood's volunteer training camps, and in the winters of 1915-1916 and 1916-1917 acted as general assistant to the training activities at Harvard. In the spring of 1917 he pretty much gave up his college work, serving as Adjutant of the Harvard Training Corps. He writes: "In this cause I expended a great deal of energy and a good deal of money," and in another place: "I believe the results accomplished were of real value; I look back on my share with considerable satisfaction." In the fall of 1917 he cut loose from the University and went to France as a Captain in the Signal Corps, in company with Professor Augustus Trowbridge of Princeton, to study flash and sound ranging. Of this experience he writes: "Most men of my age who entered the service were occupied with office work generally in back areas. I had the good fortune to see some service in the field. I began in November of 1917 with the British at Neuport near the extreme east of the line. Here the artillery fire was often quite severe. During the winter I conducted a school for Flash and Sound Rangers near Langres. This experience was interesting and often amusing. In the spring, after a short tour of duty in the quiet area in front of Roul I took a flash ranging unit to the very active Chateau Thierry section. This was a most valuable experience; I was to some extent my own master, I was in constant communication not only with the American Divisions in the neighborhood, but with the French artillery intelligence, as well. I saw the German offensive rise to a maximum, I saw fortune turn toward the Allies. I took part in the second St. Mihiel offensive. Thereafter I was attached to the Second Army. I returned home in March '19 in command of a Battalion of over 1000 officers and men." In another place he writes: "My military experience [the details are given in a book, *Harvard's Military Record in the World War,* 1921, p. 600] was one of the most interesting of my whole life."

It would perhaps be natural to expect that Lyman, with his scientific background, would have made technical contributions to the subject of flash and sound ranging. There is, however, little evidence of this, the subject having apparently been so far advanced before our entry into the war by the French and British that Lyman's chief concern was with organizing and directing the men under his command and in securing results with the equipment supplied him. Of his success in doing this his commanding officer, General Roger G. Alexander, writes: "It was not surprising that a man of his eminent scientific attainments would handle the technical problems of ranging with ease and assurance, but we could do nothing but admire and marvel at the way he, without previous military experience, organized and conducted the ranging schools, commanded, disciplined, and trained his officers and men, looked out for them, cared for them, and gained their lasting respect and regard. You can't fool soldiers long, and Lyman's men soon saw through his

New England austerity and recognized the strength, fairness, and unselfishness behind it."

In 1926 the growing inadequacy of the Jefferson Physical Laboratory, built in 1884, became so pressing, an inadequacy emphasized by the numbers of the recently established National Research Fellows in physics attracted to Harvard, that Lyman for several years devoted most of his energy to a campaign to raise money for a new laboratory, and after the money was raised, to overseeing the details of the plans for the new building. Probably only Lyman, with his wide acquaintance among men of wealth, could have been successful at this. As it was, he met with many discouragments and even personal rebuffs. The timing of the enterprise was most fortunate; the various contributions were paid in before the financial crash of 1929, and the contracts for construction were let during the ensuing period of deeply depressed prices. The building, with many conveniences and floor space somewhat greater than the old Jefferson, was begun in August, 1930, and completed in April, 1931. For many years it was known simply as the Research Laboratory of Physics. After its completion Lyman continued as Director of the Jefferson Laboratory and in addition became Director of the new building. In the entry hall of the New building there is a bronze tablet, reading:

RESEARCH LABORATORY OF PHYSICS
BUILT EQUIPPED AND ENDOWED
WITH FUNDS GIVEN FOR THE LARGER PART
BY FIFTY ONE INDIVIDUALS
FRIENDS OF HARVARD UNIVERSITY
AND BY GRANTS FROM
THE GENERAL EDUCATION BOARD AND
THE CARNEGIE CORPORATION
COMPLETED 1931

In 1947, on Lyman's retirement from the directorship, the building was fittingly renamed in his honor, and a bronze tablet installed below the other:

RENAMED IN 1947
LYMAN LABORATORY OF PHYSICS
ON THE OCCASION OF THE RETIREMENT OF
PROFESSOR THEODORE LYMAN
THROUGH WHOSE VISION AND INITIATIVE
THIS LABORATORY WAS BUILT

Among all his contributions to physics the erection of the laboratory must be reckoned as by no means the least. However, the effort was probably beyond his strength, because while crossing the Atlantic in May, 1930, for a summer of recreation in Europe, he suffered a ruptured appendix, had to submit to an emergency operation by the ship's surgeon in a storm at sea, and never completely recovered from the calamity. For months he was hospitalized in England before gathering strength to return, and after his return he had to undergo a second corrective operation. He suffered for years thereafter from a crippling phlebitis in one leg.

In the fall of 1952, on the occasion of the Boston meeting of the Optical Society of America, a testimonial volume of ninety letters from former students and colleagues was presented to him, prepared chiefly at the initiative of his former student Richard Tousey. A reading of these letters gives a fresh appreciation of the range of Lyman's influence. There is a list in these letters of a surprising number of vacuum spectrometers in other institutions, constructed in the shops of the Harvard Laboratory and made available either as outright gifts or on absurdly generous terms. A number of physicists in other institutions acknowledge the dominating influence which Lyman's work had on their own researches. There is mention of the helpful cooperation of Lyman with the project of the Naval Research Laboratory to find the Lyman hydrogen series in solar radiation by exploration of the upper atmosphere with rockets. There is record of his interest in properly preserving and cataloguing the many historical physical instruments at Harvard, an interest attested by the dedication of the book by I. Bernard Cohen entitled *Some Early Tools of American Science,* which reads in part: "This book is respectfully dedicated to Theodore Lyman . . . whose warm personal interest in every aspect of the laboratory, including its old instruments, and whose generous encouragement of the enterprise of cataloguing and preserving the relics of Harvard's early scientific history, are in large measure responsibile for this book and the exhibition which has been the occasion of writing it." There is appreciation of his unobtrusive financial assistance to many a needy graduate student. There is the anecdote of one of his early papers before the Physical Society, at the end of which Lyman pulled out his watch and said, "And now, gentlemen, this story which I have told you in seven minutes represents the work of exactly seven years." And there is the picture of his rather primly efficient enforcement of the newly passed ten-minute restriction on the length of papers before the Physical Society, a duty which devolved upon him as President of the Society.

The last few years of his life were clouded by ill health and physical discomfort. He had an obstinate sore on the back of his hand, an indirect result of excessive exposure to the radiation from the very powerful sparks which he used as sources of the ultraviolet. This sore ultimately yielded to skin grafting. He also suffered from a serious impairment of vision, which he ascribed to overstrain in measuring his spectroscopic plates. His death occurred in the Peter Bent Brigham Hospital, after degenerative illness of many months.

Lyman never married; he was the last representative of a mode of life that will not been seen again in this country, an aristocrat in the best sense. Brought up in great wealth, and always possessed of ample means himself, he looked the part and impressed all who met him, an impression heightened by his erect slender figure and the meticulous correctness and a certain austerity in his dress—for many years he wore a single straight stand-up collar. Before automobiles became plentiful he was accustomed to drive back and forth to the Laboratory from his estate in Brookline, at one time behind a retired race horse, which one day ran away with him. His manner somewhat suggested President Eliot, of whom he was a great admirer, and about whom he had a fund of stories. Along with the courtliness of his manner was a strong sense of *noblesse oblige*—this may have extended even to his scientific work. One of his associates on his sound ranging expedition in the First World War has made the illuminating remark, "It always seemed to me that Lyman felt that he *had* to be good in physics because of his background and advantages." In the Laboratory few could have achieved the harmonious whole that he achieved from naturally discordant elements —in the early days there were on his staff an Orangeman and a Sinn Feiner, both fresh from Ireland. He scolded them and looked after their families and commanded their affection and loyalty much, one imagines, like the squire of an ancestral estate in the old country. It was because of this gift with people that he was urged to retain his post as Director of the Laboratory for years beyond the conventional age of retirement. He felt a personal responsibility for the graduate students and younger members of the teaching staff, particularly the lame ducks, over whom he exercised, on occasion, a fatherly supervision long after severance of their connection with the Laboratory. Outside the University, one kept hearing indirectly of numerous benefactions, in many of which he had raised the money from some ostensibly anonymous source. It was said that he had an understanding with his friends by which he agreed to contribute to their charities if they would contribute to his. For a great many years he was interested in the Peter Bent Brigham Hospital, served on its Board of Trustees, and contributed to its maintenance. He also served on the Board of Trustees of the Brookline Public Library.

He was elected to the National Academy of Sciences in 1917, and was a member of the American Philosophical Society, a fellow of the American Academy of Arts and Sciences, of which he was President (1924-1927), a fellow of the American Physical Society, of which he was President in 1921-1922, and honorary member of the Optical Society of America, an honorary member of the Royal Institution of Great Britain, and a fellow of the Royal Geographical

Society. In addition he was a member of the Harvard Clubs of Boston and New York and of the Somerset Club of Boston.

He received the Rumford Medal of the American Academy of Arts and Sciences in 1918, the Elliott Cresson Medal of the American Philosophical Society in 1930, and the Frederick Ives Medal of the American Optical Society in 1931.

KEY TO ABBREVIATIONS

Astrophys. Jour. = Astrophysical Journal
Jour. Franklin Inst. = Journal of the Franklin Institute
Jour. Opt. Soc. Amer. = Journal of the Optical Society of America
Mem. Amer. Acad. = Memoirs of the American Academy of Arts and Sciences
Phil. Mag. = Philosophical Magazine
Phys. Rev. = Physical Review
Proc. Amer. Acad. = Proceedings of the American Academy of Arts and Sciences
Proc. Nat. Acad. Sci. = Proceedings of the National Academy of Sciences

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