Men and milestones in optics. VI: The rise of infrared spectroscopy in the U.S.A. to World War II

E. Scott Barr

This survey reviews the rise of ir spectroscopy in the United States from about 1845 to about 1941 in terms of the discoveries and activities of the individuals who contributed importantly to this field. Generally speaking, the emphasis is on molecular, rather than atomic, spectra and on experimentation, rather than theory. The presentation is chronological with respect to the birth dates of the contributors, and a limited amount of biographical material is included for some of them. Some quantitative information about the institutions where ir spectroscopy was carried on, and for the journals in which the results appeared, is appended.

The story of the development of any branch of science must necessarily be incomplete, not only because the ramifications and interrelations are so extensive, but also because much of the activity was never recorded. Despite their importance, atomic spectroscopy in the ir and work with undispersed ir radiation are not treated here, and this survey is concerned chiefly with the experimental aspects of molecular spectroscopy.

Material for this paper was derived chiefly from about 500 papers by American authors, in English, cited in the (incomplete) listings in the Physics Section of *Science Abstracts,* 1898–1941. Each of these original papers was consulted, and about fifty others. A few papers published in German journals by Americans studying in Germany with Rubens and others were included. I realize that I did not find and scan all pertinent papers, but the sample used seems adequate. Fortunately, I was able to add valuable information by personal communications with some of the participants.

After considering various alternatives, I decided to present my findings in a sequence that is chronological with respect to the births of the individuals involved, rather than in terms of annual progress, for my chief incentive in preparing this survey was to give credit and appreciation to the many individuals who collectively established the field. I regret that I can write little or nothing about many other admirable investigators whose contributions, though creditable, were limited, or whose careers were just beginning at the close of the period treated here.

John William Draper (1811–1882)[1] came to this country from England when he was 22 and at 27 became a professor at the University of New York, where he taught for 45 years. His thermal emission studies helped to establish the nature of ir radiation; in 1844 he pointed out the desirability of using reflective optical spectrometer systems, advocated the use of wavelengths (rather than arbitrary letters) to locate spectral positions (and the use of gratings for this reason), and photographed three atmospheric absorption bands in the near ir spectrum of the sun.[2] He became interested in photography—he used his sister as the subject of the first photograph of a person—and used it for scientific purposes. His 8-mm wide grating was ruled by Joseph Sexton, mechanician at the U.S. Mint in Philadelphia. It was ruled on glass backed with tinfoil to make a reflecting grating. He earned his M.D. at the University of Pennsylvania. He organized the NYU medical school in 1841 and headed it from 1850 to 1873. There "laboratory work commenced at seven in the morning and continued uninterruptedly till after midnight." (See page 1726 for an article on Draper by Hyde.)

Lewis Morris Rutherfurd (1816–1892)[3] was an independently wealthy lawyer who retired at 33 and became interested in astrophysics. To facilitate his measurements of the solar spectrum, he began making gratings. He did the ruling at night in his bedroom at his home on the corner of Second Avenue and 11th Street, in New York. His gratings were about 5 cm wide, with up to about 680 l/mm. Their quality was unequaled until Rowland entered the field, and they were shared with others (Langley, for example). (See article by Devons on page 1731.)

The author is retired from the University of Alabama; mailing address is Box 3174, East Side Station, Tuscaloosa, Alabama 35401.

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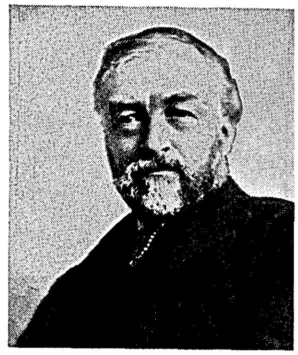
Samuel Pierpont Langley (1834–1906),[4] although probably best known for his aeronautical work and as the third Secretary of the Smithsonian Institution, was the first American to make notable contributions to ir technology. His great interest in the distribution of energy in the solar spectrum[5] made him realize the need for an improved detector. In 1881 he revived and improved the resistance thermometer to make an "actinic balance," now called a bolometer.[6] His threadlike detector, about 1 mm wide, was some 15 times more sensitive and much faster than the best thermocouple then available. He and his noted assistant, Charles Greeley Abbot (1872–1973), used it to make, in 1892, what seems to have been the first recording spectrograph.[7] With this detector he was able, in 1882, to make the first useful measurement of a grating spectrum, using plane gratings ruled by Rutherfurd.[8] In 1881 Langley took his equipment to the top of Mt. Whitney and unexpectedly discovered the existence of radiation beyond 1.8 μm, previously thought to be the limit, thus expanding the known spectral region severalfold.[9] In May 1882 he used a Rowland concave grating to make a monochromator with which he was able to calibrate a flint prism to 2.35 μm (Ref. 10) and one of rock salt to 5.3 μm (9 times the D line wavelength).[11] He observed both water and CO_2 atmospheric bands.

Langley was fortunate in having the help of John Alfred Brashear (1840–1920) to make his rock salt prisms. Brashear became a master optical worker: with his prism the solar D lines could be seen as separate.

Langley was almost entirely self-educated, having only a high school education. Despite this he got a position at the Harvard Observatory, then in 1866 taught mathematics at the newly organized Naval Academy. In 1867 he became director of the Allegheny Observatory and stayed there 20 years before going to the Smithsonian Institution, where he founded its Astrophysical Laboratory.



S. P. Langley
Photo: Smithsonian Institution, courtesy E. S. Barr

He had few close friends and never married. He greatly admired Thomas Carlyle, the essayist, who in turn found Langley's great capacity for silence quite agreeable. Langley seems to have been a shy and rather lonely man, with a love for good literature and a flair for writing. His nontechnical writings are both penetrating and delightful.

Sunspot of 5 March 1873 drawn by S. P. Langley From Langley. *The New Astronomer* (Houghton, Mifflin, Boston, 1889). Photo: AIP Niels Bohr Library.

Henry Augustus Rowland (1848–1901)[12] was the first American university professor to do notable research in optics. From 1876 on he was at Johns Hopkins University where he became famous for his gratings. With the help of Theodore Schneider he completed his first dividing engine in 1881; the screw pitch was 0.8 mm, and wood plugs were used in the nut. With it he could rule 100,000 lines on a 15-cm grating.[13] This engine was later loaned to the University of Michigan, where Barker used it to rule the first of his famous echelette gratings around 1920. Rowland's introduction of the concave grating in 1883[14] was a major advance.

Though associated with a university, Rowland had no great liking for teaching or training graduate students and inspired little personal following (with the exception of J. S. Ames).

Edward Leamington Nichols (1854–1937)[15] graduated from Cornell University in 1875 and studied in Germany until 1879 when he got his Ph.D. at Göttingen. His dissertation was "On the character and intensity of the rays emitted by glowing platinum."[16] In 1887 he joined the Cornell staff and remained there until his retirement at sixty-five in 1919—after which he published 37 more papers, all but five on his own experimental work, before 1936. During his career he published 7 books and 192 papers (in twenty different journals), one of these (on measuring radiant efficiencies[17]) was with his most famous student W. W. Coblentz, in 1903.

During the decades just before and just after 1900, scientific research by university professors was disparaged as a waste of time that should be devoted to instruction, or as a harmless foible of no real importance. Nichols is particularly admirable for his part in winning acceptance of the idea that scientific research is a proper and necessary function of a university. One of his greatest contributions to this end was his founding of the *Physical Review* in 1893. He edited it for 20 years before turning it over to the American Physical Society, which he helped organize 6 years after founding the journal. His chief re-

Photo: Cornell University Archives, courtesy AIP Niels Bohr Library.

search interest was optics, especially luminescence, but not exclusively. Even more important than his own achievements were the training and inspiration he gave to a host of advanced students, among them were W. W. Coblentz, E. F. Nichols, B. W. Snow, and G. W. Stewart. As his colleague, Ernest Merritt, wrote, "At the time of his retirement the heads of departments of physics in 35 colleges, 15 of them state universities, were men who had received their physics training from him. Add to this list the large number of his students who held important posts in government and industrial laboratories or who were college teachers but not department heads, and we get some idea of how great his indirect influence was."

Benjamin Warner Snow (1860–1928)

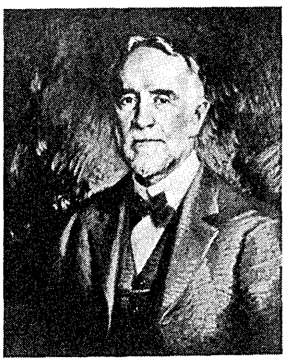


Photo: University of Wisconsin, courtesy AIP Niels Bohr Library.

got his B.S. at Cornell in 1885 and his Ph.D. in Berlin in 1892. He worked on determining indices of refraction for ir prism materials with Rubens and on the ir line spectra of the alkalies with Kundt for his dissertation.[18] He was at the University of Wisconsin from 1893 to 1926, where W. Weniger and L. R. Ingersoll were among his ir students.

Exum Percival Lewis (1883–1926) seems to have been the first (1895) Johns Hopkins University student to have done his Ph.D. research in the ir: "The measurement of some standard wavelengths in the infrared spectra of the elements."[19] His thanks were expressed to J. S. Ames, to E. S. Ferry for help, and to Rowland for the loan of a concave grating. He was born in Washington County, North Carolina. From 1898 to 1900 he studied in Berlin. From 1895 onward he taught at the University of California, where J. W. Ellis was among his students.

Joseph Sweetman Ames (1864–1943)[20]

Photo: AIP Niels Bohr Library

worked under Rowland and—after the customary study period in Germany—got his Ph.D. at Johns Hopkins in 1890. He joined the Johns Hopkins staff in 1891, succeeded Rowland as chairman in 1901, and became president of the University in 1929. While his research record is creditable, he is more to be honored for having made his school a great research center by his own excellence as a teacher, his administrative skill, and his constant emphasis on scholarship as a university's chief concern. Among his students were E. P. Lewis, C. E. Mendenhall, A. H. Pfund, and J. T. Porter.

Ernest George Merritt (1865–1948)[21]

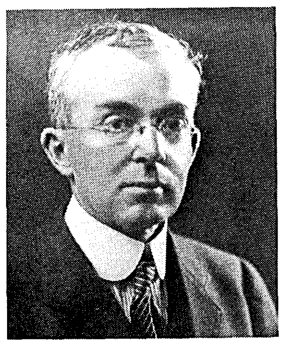


Photo: Cornell University Archives, courtesy AIP Niels Bohr Library

took an M.E. degree at Cornell in 1888, taught there until 1893, then went to Berlin for 2 years. With help from Kundt, he did an ir study of absorption by crystals as dependent upon the plane of polarization,[22] using Snow's apparatus, which had fluorite lenses rather than mirrors. He returned to Cornell where he became department head in 1919 and was dean of the graduate school from 1909 to 1914. He collaborated on twenty-nine papers with E. L. Nichols, chiefly on luminescence, and helped with the graduate program: he supervised the work of W. W. Coblentz and G. W. Stewart. Of significance also are his contributions as co-editor of the *Physical Review* and his work with the American Physical Society[23] as its Secretary (1899–1912) and President (1914–1915).

Photo: E. S. Barr

Frank Lawton Olcott Wadsworth (1867–1936)[24] is famous for his spectrometer designs.[25] He took two engineering degrees and a M.S. at Ohio State University. After 14 years at various observatories and schools he turned, in 1904, to private consulting. He published more than 100 papers and held 250 patents.

Robert Williams Wood (1868–1955)[26] was a truly brilliant experimenter, particularly in optics, and a fascinating individual. His only earned degree was a B.S. in chemistry in 1891 at Harvard, but he studied at Johns Hopkins (1891–1892), the University of Chicago (1892–1894), and in Germany (1894–1897), wavering between chemistry and physics until turned to the latter by Rubens (with whom he worked on the production of long wavelength radiation by the focal isolation method[27]). He taught at the University of Wisconsin from 1897 to 1900, when he went to Johns Hopkins to replace Rowland; he remained there the rest of his life. He became curious about the effect of groove shape on the light diffracted from a grating and realized that using a 40-l/mm grating with 8.6-μm quartz reststrahlen was equivalent to using a 560-l/mm grating with red light. By use of Rowland's first machine and a carborundum crystal, he reshaped (without cutting) a flat plate of soft metal to make a new kind of grating that he named echelette.[28] The same year he and Trowbridge published two other papers[29] concerning the new device (and discovered incidentally that the 4.3-μm CO_2 band was double), but did nothing more with it.

The ruling of gratings at Johns Hopkins languished between 1916 and 1923, when Wood took over the production of gratings. He introduced improvements in the process and trained Wilbur Perry to operate the equipment. A 1937 Ohio State University report commented that the Hopkins-ruled gratings were very good. (See page 1741 for a short article by Strong on R. W. Wood.)

Ernest Fox Nichols (1869–1924)[30] was the author of the paper that appeared on the first page of the first issue of the *Physical Review,* in 1893: "A study of the transmission spectra of certain substances in the infra-red." The study was made using a CS_2 prism, a bismuth–antimony thermopile, and a galvanometer with a 6-sec period, taking three to five readings at each point. Apparently this was his M.S. degree thesis, directed by E. L. Nichols (no relation). It was the first ir spectroscopy paper done by an American, directed by an American, at an American school, and published in an American journal. Other Americans, of course, had done ir work in Germany, and Langley had made notable advances in ir technology in connection with his solar radiation studies, but this paper seems to mark the real beginning of ir spectroscopy as a standard American research field.

E. F. Nichols came to Cornell in 1889 as a result of hearing a talk by E. L. Nichols in Manhattan, Kansas. In 1894 he went to Germany where, at Pringsheim's suggestion, he developed his radiometer[31] based on Crooke's 1876 discovery; it became widely popular as an ir radiation detector. He also collaborated with Rubens in the discovery of reststrahlen.[32]

He returned to Cornell for his 1897 D.S. degree. At one time or another he was on the staffs of nine different schools. Among his students were H. P. Clark, W. S. Day, H. H. Marvin, and E. C. Wente. While presenting a report on his famous research with J. D. Tear on "Joining the infrared and electric wave spectra" before the National Academy of Sciences in Washington, he died suddenly of a heart attack.[33]

Augustus Trowbridge (1870–1934),[34] after studying at Columbia University (1890–1893), went to Berlin to work under Rubens. He also established friendships there with E. F. Nichols and R. W. Wood while doing his 1897 Ph.D. research on the dispersion and absorption of rock salt and sylvine.[35] From 1898 to 1900 he was at the University of Michigan with H. Carhart (then head) and K. E. Guthe "who was largely responsible for bringing Michigan to its position of prominence in physics." In 1900 he went to the University of Wisconsin to replace Wood, who had moved to Johns Hopkins. In 1901 C. E. Mendenhall came there, and the two became good friends. In 1906 he moved permanently to Princeton University, where he was influenced both by the former head, Cyrus Fogg Brackett (1833–1915), and the current head, W. F. Magie. He worked both on the optical properties of metals in the ir and on spectroscopy, devoting much time to trying to improve the apparatus.[36] Brackett's initial efforts to rule gratings were continued by him, and after several years he achieved a good engine.[37] He lent his best gratings to Randall to help establish his Michigan laboratory. He was the senior author on two 1910 grating papers with Wood.

When World War I came, he turned to governmental science and was thereafter continuously involved

Photo: AIP Niels Bohr Library

in administrative work, both abroad and at Princeton. From 1917 to 1925 he was back at Princeton to upgrade the physics program and was dean of the graduate school from 1932 until his death. The activity in ir spectroscopy at Princeton is probably attributable to his influence. Among his students were A. H. Compton, K. T. Compton, C. J. Davisson, G. H. Harnwell, H. D. Smyth, and A. T. Waterman.

Harrison McAllister Randall (1870–1969)[38] and ir at the University of Michigan are almost synonymous. No other American has had anything like his impact on the development of ir spectroscopy and of ir spectroscopists.

Randall's interest in physics began when he read two books by Tyndall when he was 10, but as a student at Michigan he found physics dull, especially the laboratory experiments. He did, however, continue to a M.S. degree in physics before dropping out to teach in a high school for 5 years. He then returned to Michigan (with a new bride and money he had saved) and completed his Ph.D. in 1902—the second Ph.D. granted by the Physics Department—and began his permanent and long connection with the school.

In 1910 he took a sabbatical leave and went to work with Paschen in Germany. In 1953 he wrote: "Until I was 40 I knew no more spectroscopy than would any teacher of elementary physics. Spectroscopically speaking, my life began at 40, since in that year I had my first experience in that phase of spectroscopy which was to become my permanent field of research, namely, infrared spectroscopy." At the outset Paschen simply gave him a room containing a partly completed ir spectrometer and told him to put it into working order. Despite massive difficulties he did so and then used it to study ir atomic spectra,[39] using a Rowland grating. Then, as a reward for building a new spectrometer, Paschen sent the original instrument with Randall to Michigan.

When Randall was made Chairman of the Department in 1917, he began a vigorous development of ir spectroscopy, especially high-resolution work. To support this work he established a first-class instrument shop, under the direction of Herman Roemer after 1922. The addition of a former Russian naval officer, Capt. A. de Khotinsky—then in his late 60's or early 70's, who had built a ruling engine for Michelson—resulted in Michigan's first ruling engine. Paul Weyrick later operated it under E. F. Barker's supervision (and also made thermocouples).

In 1919 Randall and Barker used a borrowed grating (ruled at Johns Hopkins by Anderson) for some ir measurements on atomic spectra,[40] and this turned them to high-resolution molecular spectroscopy. Randall was intrigued by the measurements on HCl that Eva von Bahr made in 1913 in Rubens's laboratory and saw the need to resolve the rotation–vibration band structure as a means of testing quantum theory predictions and to get data for structural determinations. Success came when the measurements made by his student, E. S. Imes, showed the line positions sharply.[41] The spectrometer he used was a modification of Langley's 1880 instrument designed by Randall and built by W. W. Sleator to measure the spectrum of water vapor; it was actually a prism spectrometer serving as a monochromator to illuminate a grating, with a Coblentz thermopile for detector.[42] Thereafter high-resolution molecular spectroscopy became a concerted departmental activity at Michigan.

Spectrometer improvement continued. A self-recording spectrometer was put into service in 1931,[43] a remarkable large-aperture instrument capable of using a 25-cm × 56-cm grating, in 1932,[44] and a recording instrument for the far ir in 1938.[45]

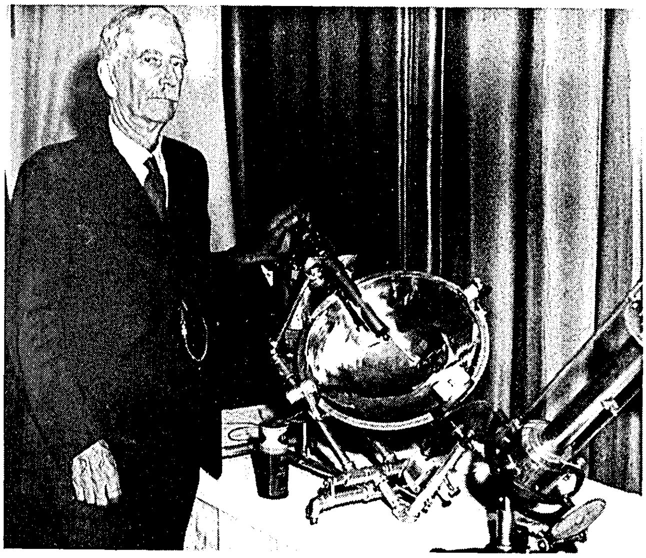
Before 1920 Randall had realized the need for a parallel development of a theoretical staff, but little theoretical work had been done in this country. He brought Oskar Klein to his department for 2 years, 1923–1925, and the success of his stay encouraged Randall to build up a distinguished theoretical staff. By 1927 he had added W. F. Colby and four other capable men, D. M. Dennison, Otto Laporte, Samuel Goudsmit, and George Uhlenbeck. Randall then introduced his summer symposia program in theoretical physics which, during the late 1920's and 1930's, attracted at one time or another just about all the world's most distinguished physicists. The importance of these gatherings to physics in this country can hardly be overestimated. They provided an opportunity for staff and graduate students from many institutions to establish warm friendships and to exchange information and ideas. The summer visitors paid their own expenses, travel aid not being available usually, especially in the case of graduate students. For many students of that era these symposia will remain happy memories.

The men and women who trained at Michigan under Randall and his colleagues—and they should be thought of as a group—form a large and distinguished family. Among them are E. F. Barker, W. Colby, D. M. Dennison, E. H. Eyster, E. S. Imes, R. T. Lagemann, H. H. Nielsen, W. W. Sleator, A. H. Stang, J. D. Strong, and T. Y. Wu. These men, in turn, taught another generation of ir researchers, and so it goes on. Randall's contribution to ir spectroscopy is therefore impossible to assess.

About 1946 Randall became interested in biophysics and was active in that field for the next 20 years despite his retirement in 1950.

To quote Dennison, "What he did was to set the stage so that the rest of us on his staff could do our best work . . . he taught us to work together for the common good of the Department . . . he fought with all his energy to obtain those conditions which we needed for excellence in research and in teaching." The laboratory completed in 1924 was appropriately named the Randall Laboratory; it was 40 years before another physics facility was built.

Photo: AIP Niels Bohr Library



Charles Greeley Abbot (1872–1973)[46] assisted Langley and was his successor at both the Smithsonian Astrophysical Observatory and as Secretary (1928–1944). While his ir work was only for solar spectrum measurements, he contributed importantly to ir technology. His career spanned essentially all the development of ir research in this country. For almost 30 years after retiring he still went frequently to his office.

Charles Elwood Mendenhall (1872–1935) was the son of T. C. Mendenhall, Ohio State University's first physics professor, for whom the laboratory is named. As a boy (6–9) he was with his father in Japan, which led to his lifelong appreciation of Japanese culture. In 1895 he went to Johns Hopkins where he and F. A. Saunders (later at Harvard) worked jointly on a project suggested by H. F. Reid, "with supplementary suggestions from Ames." Their dissertations were published as a joint paper[47] dealing with blackbody radiation dispersed by a spectrometer using rock salt for both prism and lenses.

He went to Wisconsin in 1901 and during his 34 years there did much to develop it as a research center. His own work on the radiating wedge[48] remains important for workers concerned with radiation from hot metal surfaces. He was an excellent teacher, who saw that his students learned to build their own equipment. During his career he directed 35 Ph.D. dissertations. His students, L. R. Ingersoll and B. W. Snow, became members of his staff. Departmental morale remained high, and distinguished visitors were invited there frequently for stays from a week to a year. He was President of the APS from 1923 to 1925.

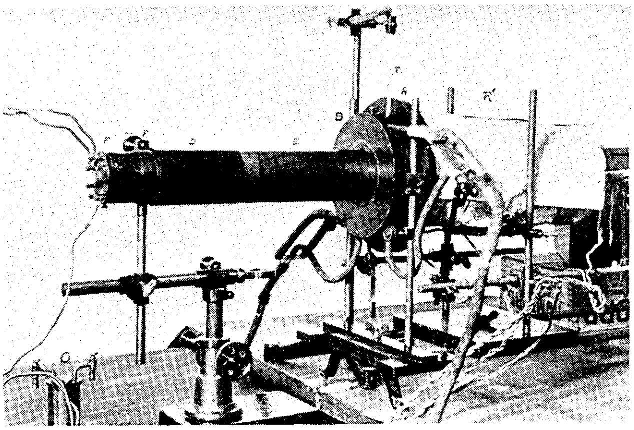
Mendenhall was a man of wide interests: he played the violin well, loved to fish, and played and supported tennis. He married in 1906 (his wife took an M.D. at Johns Hopkins in 1900). Thirteen months after learning that he had an incurable disease, he died. He had told no one about this, but continued to be active in his department until his death.

John Temple Porter (1873–1931) received his 1905 Ph.D. at Johns Hopkins, working under Ames on selective reflection in the ir. After teaching at Williams and at Randolph Macon, he went in 1908 to the University of Tennessee, where he moved from department chairman to Dean of Arts and Sciences. (A. H. Nielsen repeated this pattern at Tennessee and in addition developed his own spectroscopy program there in the late 1930's.)

William Weber Coblentz (1873–1962)[49] was honored in 1954 at the Ohio State University Conference on Molecular Structure and Spectroscopy by the founding of the Coblentz Society, devoted to ir spectroscopy primarily. He was further honored by the award to him of the Ives Medal of the Optical Society of America in 1945 and by the dedication of the November 1963 issue (especially pages 1089–1102) of *Applied Optics* as a Coblentz commemorative issue.

He was born on an Ohio farm and grew up among immigrants who spoke German in preference to English. He overcame great financial difficulties and got a B.S. degree in physics at Case Institute of Technology. He then went to Cornell in 1900, at the age of 27, to study theoretical physics with Merritt. Nichols, however, decided it would be best for him to work on ir absorption spectroscopy, as at that time only a few rough measurements, to about 3 μm, had been made. After unsuccessful efforts to sensitize photographic plates to ir and work on the quenching of phosphorescence by ir, he assisted Nichols by using a CS_2 prism and a radiometer to measure the transmission of asphalt to 2.8 μm. This work and his construction of a small rock salt prism spectrometer earned his his M.S. degree in 1901. His dissertation for his 1903 Ph.D. was on "Optical properties of iodine."[50]

At Nichols's suggestion, he began his study of the ir spectra of pure molecular compounds, for (as Coblentz wrote in 1903) "If we except the investigations of materials suitable for prisms, our knowledge of the selective absorption in the infrared region of the spectrum is rather limited." With Nichols's help he got an appointment as a Research Associate of the Carnegie Institution in Washington, to work 2 years at $1000 a year at Cornell (where he said his living costs were $300 a year). He was made an Honorary Fellow and began his systematic and monumental program of measurements that lasted many years. In 1904 Nichols urged Coblentz to make research his life work and to take the post of Laboratory Assistant (at $900 a year) to S. W. Stratton, the first Director of the newly founded National Bureau of Standards at Washington, located "in the then distant uninhabited suburbs of Washington." His Carnegie Institution studies were published in three Institution reports: 35 (331 pages, 1905); 65 (128 pages, 1906); and 97 (182 pages, 1908). They were republished in 1962 in one volume—a veritable mine of information—by the Coblentz Society and the Perkin-Elmer Corporation.



Coblentz's apparatus used in measuring the total radiant energy from a black body. *Photo:* AIP Niels Bohr Library.

Working conditions at Cornell were far from ideal. Coblentz later wrote, "After all these years I recall with a deep feeling of satisfaction the little laboratory room (one room within another) in the basement of Franklin Hall, next to the storage battery room, with an immense brick pier leading to the room above, and large-sized steam pipes overhead, that provided a warm, elevated transit route for the rats, that sometimes scurried back and forth while I was observing."[51] His radiometer was "so slow and tiring that after observing for 5 hours, I would hold myself to my stool to complete the set of measurements—an all day job." The period of his galvanometer was about 90 sec: circle readings were taken at intervals of from 20″ to 1′ and wavelengths were computed from dispersion data. Absorption cells were made by using natural crystal plates which had to be cut from large crystals and polished.

He began work at the Bureau on 1 May 1905 and for 40 years—with two assistants sometimes, but usually only one—used the same corner room on the ground floor of the South building. His work advanced the early speculations of Abney and Festing in 1881 and of Julius in 1892—that molecular structure could be inferred from spectral measurements—to the status of fact. Absorption bands associated with functional groups in molecules were looked for from about 1908 to 1928, when the Raman effect was discovered. After about 1930 these complementary spectra were routinely used for chemical compound identification.

While Coblentz introduced no new instruments, he did much useful work by improving and comparing existing ones. His thermocouples and thermopiles were widely used in the scientific world for many years.[52] He estimated that in 12 years, working under a reading glass, he had handled about 20,000 tiny bits of metal, chiefly on his own time.

For his measurements he relied entirely upon prism spectrometers, with data taken point by point. (Gratings, he felt, were primarily useful for determining dispersion curves.) He wrote: "This is an age of gadgetry, with automatic recording of everything, including infrared absorption spectra. This is as it should be in the continuous production of an article of manufacture. But if the apparatus is used only occasionally, more time is lost in keeping the automatic recording device in working order than in observing the infrared absorption spectrum of a substance by the old-fashioned 'string-and-shutter' method." [51]

After about 1920 Coblentz devoted most of his efforts to things other than spectroscopy: blackbody radiation constants; radiometric measurements of many kinds; astrophysics; and uv studies. He was seriously interested in psychic phenomena and in 1954 wrote *Man's Place in a Superphysical World.* His autobiography, *From the Life of a Researcher,*[51] is fascinating.

Coblentz was a patient, persevering, energetic, dextrous man. He was sensitive, honest, and loyal: help given him was never forgotten, and help was readily given others. He was also competitive, irascible, and antisocial: he disliked what he called "aimless social life." For many years he worked from 8:30 a.m. to 5 p.m., then went home, where he mulled over the day's observations and worked at writing reports. In some mysterious way, at the age of 51, he managed to marry a charming 27-year-old woman with whom he lived happily, except for the deaths of their two children in infancy. His wife died in 1951, 6 years after he retired, and thereafter he seems to have led a rather lonely life.

Before leaving Coblentz, let us note that his disposition and his situation resulted in his having almost no scientific heirs, in contrast with E. L. Nichols, who sent out a stream of men trained in and dedicated to research.

Herbert Anthony Clark (1875–1944), who got his Ph.D. at Columbia University in 1913, seems to be the first author of an ir paper from that school. His work on selective reflection[53] was directed by E. F. Nichols.

Frederick Albert Saunders (1875–1963),[54]

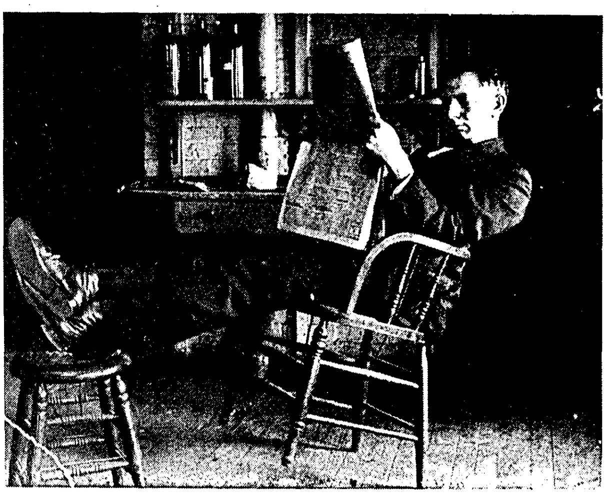
Photo: AIP Niels Bohr Library, Bainbridge Collection a Canadian, worked on blackbody radiation under Rowland and Ames at Johns Hopkins in collaboration with Mendenhall. He received his Ph.D. in 1899. He taught first at Syracuse University (1901–1914), then at Harvard from 1919 until he retired in 1941. His interests were chiefly atomic spectroscopy and acoustics.

George Walter Stewart (1876–1956)[55]

Photo: AIP Niels Bohr Library

followed his older brother, Oscar Milton (who took his Ph.D. in physics in 1897 under Merritt on ir dichroism, but did no more in ir), to Cornell and took his own Ph.D. in 1901. Under the supervision of Nichols and Merritt, he studied the distribution of energy in the acetylene flame.[56] He used a German spectrometer with a fluorite prism (39°, 2.5 × 3 cm) and a Nichols radiometer. He published three other ir papers in 1902–1903, then went to the University of North Dakota and devoted himself to acoustics.

John August Anderson (1876–1959)[57] took his Ph.D. at Johns Hopkins under Ames in 1907 and remained on the staff there until 1915, when he went to the Mt. Wilson Observatory. At Johns Hopkins he was put in charge of the Rowland ruling engines to continue supplying gratings for the scientific community. He rebuilt the engines and operated them from 1909 to 1916. His gratings, particularly the concave ones, were excellent. *Photo: AIP Niels Bohr Library, Meggers Collection*



Reuben Edson Nyswander (1878–1941) took his Ph.D. at Cornell in 1908, under Merritt and Nichols (with help from Coblentz), studying the ir characteristics of calcite and aragonite out to 15 μm.[58] He went to Denver in 1909 and seems to have done no further ir work.

Roswell Clifton Gibbs (1878–1966)

Photo: AIP Niels Bohr Library

received his Ph.D. at Cornell in 1910 and remained on the staff there until he retired in 1946. Among the students who worked with him were J. R. Collins, C. E. Grantham, and K. S. Gibson.

August Herman Pfund (1879–1949)[59] earned his B.S. at the University of Wisconsin in 1901, then went to Johns Hopkins where he worked under Ames for his 1906 Ph.D. He stayed there until 1947 and was chairman of the physics department 1938–1947. During his career he almost single-handedly made Johns Hopkins world-famous in ir. For contributions to ir technology, versatility, and productivity he was truly outstanding.

His dissertation work on "Polarization and selective reflection in the infrared spectrum"[60] was done on J. T. Porter's instrument,[61] using a radiometer. In this same paper Pfund announced both his selenium polarizer and his discovery of the vibration frequency associated with intramolecular radical structures in nonmetallic crystals. [He also discovered a second characteristic (electronic) frequency in the far uv in 1928. Rubens found the third characteristic crystal frequency, that associated with the lattice, in the ir.] The fifth atomic hydrogen series—which bears his name—was observed by him in 1924.[62] His student, F. S. Brackett, discovered the fourth.

Beginning about 1912, Pfund did much to advance the art of making radiation thermocouples.[63] He passed on his techniques[64] to his students, such as J. D. Hardy who in turn passed them on to Paul Weyrich at Michigan. His process involved the melting of Hutchins's alloys[65] in an iron ladle and then violently splashing the molten metal against a glass plate. The thinnest splashes were then cut into tiny strips with a razor blade and used for the elements.[66] In 1913 Pfund made the first measurement of the heat from a star by use of a telescope–thermopile–galvanometer system. It appears, however, that Coblentz's more extensive and more thorough 1914 study was of greater scientific significance. The two men seem to have been great rivals—to the benefit of all concerned with ir radiation detection.

Pfund provided another useful source of ir radiation for spectroscopists by modifying the Wellsbach mantle.[67] His development of powder filters[68] and black coatings for radiation receivers[69] were also important.

His large aperture spectrometer optical system[70] and his universal ir spectrometer[71] greatly influenced spectrometer design.

He attacked the problem of thermocouple drift both by use of duplicate thermocouples connected in opposition (each in turn being exposed to the radiation being measured) and by using radiation pulsed so as to be in resonance with his galvanometer—resonance radiometry.[72] Drift was reduced by a factor of several hundred by his system, but each observation took about 140 s, and the unsteadiness due to Brownian motion was reduced by only about one-third.

Pfund was interested in both pure and applied optics. He conceived an ingenious nondispersive detector arrangement that can be sensitized for detecting or monitoring the concentration of a particular gas,[73] now a standard analytical instrument. He did much industrial consulting work, and his students, J. D. Hardy and R. B. Barnes, pioneered in designing ir spectrometers for industrial research and routine process control.

Even more valuable than his direct contributions to ir technology was his training of men capable of doing excellent ir research. Among them are R. B. Barnes, C. Boeckner, F. S. Brackett, W. G. Fastie, J. D. Hardy, C. E. Leberknight, W. D. Parlin, J. H. Plummer, J. A. Sanderson, and S. Silverman. The admiration, respect, and affection felt for him by those who worked with him is unmistakable; perhaps he was the greatest stimulator and teacher of ir spectroscopists our country has had.

Walter Francis Colby (1880–1970) took his Ph.D. at Michigan in 1909 and became a distinguished member of the staff there, contributing to both theory and experimental programs. He and his students, C. F. Meyer and D. W. Bronk, were among the earliest to utilize the echelette grating. They used one ruled by Barker on the first Rowland engine, 112 l/mm, in their study of gaseous HCl.[74] Theory, however, was his chief activity.

Leonard Rose Ingersoll (1880–1958)

Photo: AIP Niels Bohr Library

seems to have taken the first Ph.D. in ir at the University of Wisconsin, in 1905. C. E. Mendenhall directed his work, and B. W. Snow lent him apparatus.[75] He was on the Wisconsin staff from 1905 to 1950. His research dealt chiefly with rotatory polarization and dispersion studies in the near ir.

Herbert Percival Hollnagel (1882–) went to Berlin after taking his M.S. at the Massachusetts Institute of Technology and worked with Rubens. In 1910 he got his Ph.D. for his study of the interferometric determination of wavelengths for the far ir.[76] Rubens and Wood used this technique to determine the wavelengths of the radiation obtained by the focal isolation method.[27] This approach to wavelength determination was reborn in the 1950's and developed by J. Strong at John Hopkins. Hollnagel went to the Massachusetts Institute of Technology and continued far ir work there until 1919, when he went to work for General Electric.

William Warner Sleator (1883–1956) took his Ph.D. under Randall at Michigan in 1917, carrying out a study of the absorption by water vapor.[42] With Randall's guidance he built an instrument (based upon Langley's 1880 spectrometer used in reverse) where radiation is sent through a rock salt prism before falling on the slit that illuminates the (nonechelette) grating to avoid having more than one order incident on the detector at once. When the Barker echelette gratings became available, Sleator and Phelps reworked the water vapor spectrum in 1925,[77] and in 1931 he and Plyler made a very detailed study of water vapor at high resolution.[78] Soon thereafter he did further work on gases,[79] using the Randall-Strong[43] spectrometer.

Bartholomew John Spence (1883–1972) took his Ph.D. at Princeton in 1909. He taught at North Dakota 1910–1918 and at Northwestern University 1919–1950. Among his students were M. A. Easley and J. G. Moorehead. In a 1923 paper[80] he mentioned that he had been loaned a grating spectrometer by Randall, which he used with his own improved form of Nichols radiometer.

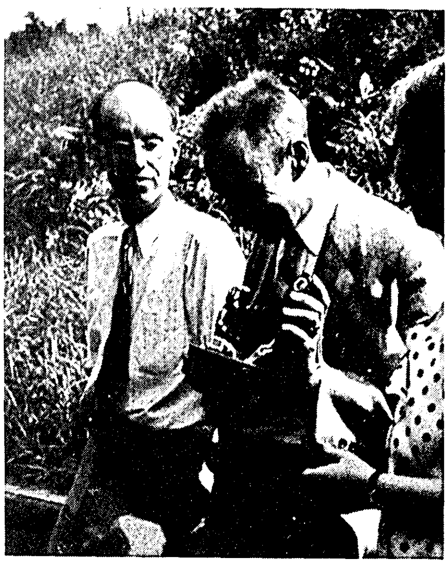
Elmer Samuel Imes (1883–1942) took his Ph.D. at the University of Michigan, working under Randall. His one and only paper, "Measurements on the near infrared absorption of some diatomic gases,"[41] was a milestone both because it opened up high-resolution spectral studies and because it established the half-quantum theory. Using the spectrometer built by Sleator with gratings of 300 l/mm and 800 l/mm (ruled by Anderson at Hopkins), he was able to show clearly the location of the rotational lines for HCl. His curve is probably familiar to all ir spectroscopists. He used a Coblentz thermopile and a shop-made galvanometer; to achieve stability he had to take his data between 1 a.m. and 5 a.m. He was in industrial physics until 1929, when he became professor of physics at Fisk University, now well known for its ir Spectroscopy Institute.[81]

Willebald Weniger (1884–1959) took his Ph.D. at the University of Wisconsin under Mendenhall in 1908. He measured the spectra of forty-one liquids to 10 μm, using Mendenhall's recording spectrometer.[82] He was at Oregon State College 1908–19.

Guy Everett Grantham (1886–1972) was at Cornell from 1915 to 1917 before joining the Signal Corps for 2 years. He returned to Cornell and took his Ph.D. in 1920, at the relatively late age of 34. He worked under Gibbs on the temperature effect on the ir absorption of glass,[83] using an astatic galvanometer with five cylindrical iron shields; the zero was set by use of an external magnet, and work could be done only at night.

Ernest Franklin Barker (1886–1960) was born in Listowal, Ontario, Canada. He received his Ph.D. at the University of Michigan in 1915 and spent his academic career there, becoming departmental chairman in 1941. His success in ruling echelette gratings of high quality on flats up to 25–50 cm, with rulings from 1/mm to 576/mm was a notable factor in making Michigan the international center Randall envisioned. His gratings brought to ir measurements the high resolution needed to get the data essential to theoretical advances and the determination of molecular structure.

While a research fellow he used the echelette grating he had ruled on aluminum on the original Rowland machine loaned by Johns Hopkins for a 1922 study of the absorption of carbon dioxide in the near ir.[84] In 1929 he measured the ammonia spectrum in the 8–14-μm region to provide the data needed for accurate theoretical treatment of that gas.[85] Some of his papers were without collaborators, but he also worked with many others—A. Adel, G. Bosschieter, E. K. Plyler, and W. W. Sleator, as examples. Among his students were J. P. Cooley and E. H. Eyster. His paper with C. F. Meyer on the ir spectrum of gases under high dispersion contains much of interest.[86]



E. F. Barker (left) and John H. and Mrs. Van Vleck. Photo: AIP Niels Bohr Library Goudsmit Collection

Charles Ferdinand Meyer (1887–1969) received his Ph.D. at Johns Hopkins in 1912, but spent his working years at Michigan (1915–1950). In 1927 he worked with D. W. Bronk and A. A. Levin on the spectra of gases at high resolution.[87]

Theodore Willard Case (1888–1944) introduced, in 1920, a new photoelectric detector—the "thalofide" cell—which was the precursor of the many modern high-speed detectors.[88]

Francis Wheeler Loomis (1889–1976), who took his Ph.D. at Harvard in 1917, pointed out that in Imes's curve for the first overtone of the HCl rotation–vibration band isotopic effects for HCl^{35} and HCl^{37} were observable.[89]

F. W. Loomis and R. F. Bacher. *Photo:* AIP Niels Bohr Library, Bainbridge Collection.

Jacob Roland Collins (1891–1948) worked under Gibbs for his 1921 Cornell Ph.D., studying the effect of solutes on the ir absorption spectrum of water.[90] He remained at Cornell, where he continued work on aqueous solutions.

Richard McLean Badger (1896–1974)

Photo: California Institute of Technology, courtesy AIP Niels Bohr Library

received his Ph.D. degree from the California Institute of Technology in 1924. He collaborated with C. H. Cartwright in making the first measurements of the pure rotation lines of ammonia.[91] He was at Caltech from 1929 on, chiefly working in the photographic ir region.

J. W. Ellis and Walther Bothe (1891–1957) in Rome in 1931. In the background are Eduardo Amaldi, George Placzek (1905–1955), and Gian Carlo Wick. *Photo:* AIP Niels Bohr Library, Goudsmit Collection.

Joseph Wesley Ellis (1897–) worked under E. P. Lewis at the University of California (taking his Ph.D. in 1923) on the characteristic frequencies of molecular groups such as C–H, O–H, etc.[92]—a topic largely neglected after Coblentz's 1905 publication. He went to the University of California at Los Angeles where he worked energetically, publishing papers at a rate of better than one a year for 20 years. He designed two recording spectrographs, one in 1925 and another in 1933.[93]

Earle Keith Plyler (1897–1976) took his M.S. at Johns Hopkins, then went to Cornell, where he worked under Collins on a study of the ir absorption of ice[94] for his 1924 Ph.D. He then went to the University of North Carolina and soon made Chapel Hill well known as an ir center. He also participated in the Michigan summer programs, doing three papers with Barker and one with Sleator. Before he left North Carolina in 1941 he had trained many students, including E. S. Barr, T. Burdine, C. J. Craven, W. Gordy, P. E. Shearin, and F. D. Williams. From 1941 to 1945 he was at the University of Michigan, then he went to the National Bureau of Standards, where he remained until 1962. At the Bureau he was made chief of the Radiometry Section in 1952 and of the Infrared Spectroscopy Section in 1960. While he was at the Bureau he published 141 papers. I feel sure Coblentz would have been quite pleased with this productivity, especially so because of the high quality of the studies.

After retiring from the Bureau in 1962 he went to Florida State University as chairman of the physics department and had another distinguished career before retiring finally in 1970. In 1972 his bibliography included 195 items.

Since Plyler concentrated almost exclusively on ir spectroscopy during all his working years, his is probably the most extensive bibliography of any worker in that field. Much of Coblentz's work appeared in his three comprehensive monographs.

Plyler so distinguished himself as a researcher, a teacher, and an administrator that it seems proper to add his name to those of E. L. Nichols, W. W. Coblentz, H. M. Randall, and A. H. Pfund as the men who were chiefly responsible for the rise of ir spectroscopy in this country during this century. In 1974 he received the first Beams Award of the Southeastern Section of the American Physical Society, for distinguished research in that region; his student Walter Gordy received the second in 1975.

Floyd Alburn Firestone (1898–) took his Ph.D. at Michigan in 1931 and was on the staff there until 1945. He deserves mention for his excellent work on thermocouple design[95] and his periodic radiometer for elimination of drift,[96] both done while on the staff at Michigan. Acoustics became his main interest, and from 1939 to 1957 he edited the *Journal of the Acoustical Society of America.*

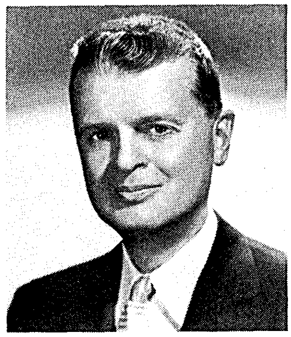


Photo: AIP Niels Bohr Library

David Mathias Dennison (1900–1976), Michigan's distinguished theorist, took his Ph.D. there in 1924, working with O. Klein and W. F. Colby. He remained at Michigan until he retired in 1970. During his 46 years on the Michigan staff he contributed importantly to making that school a distinguished center for theoretical physics. Special mention must be made of his notable papers on the ir spectra of polyatomic molecules in 1931 and 1940.[97] His readily available and effective theoretical assistance to his experimental colleagues at Michigan was a major factor in the department's growth. Among his students were W. H. Bennett, S. L. Gerhard, L. A. Matheson, C. F. Meyer, and H. H. Nielsen. His recent paper[98] on his recollections of physics and physicists in the 1920's makes fascinating reading.

Photo: AIP Niels Bohr Library

Edward Dorris McAlister (1901–) got his Ph.D. at the University of California in 1928. From 1920 to 1941 he was at the Smithsonian Institution, where he developed an ingenious method for using an ir spectrometer to monitor the evolution of CO_2 by plants.[99] During the war years he worked at the Johns Hopkins Applied Physics Laboratory, going to Eastman Kodak in 1945. He collaborated in making two automatic recording spectrographs.[100]

Harald Herborg Nielsen (1903–1973) took his 1929 Ph.D. at Michigan under Dennison; he is probably Dennison's greatest contribution to ir theory through Nielsen's own contributions and those of his students at Ohio State University. He joined the Ohio State staff in 1930 and was its chairman from 1946 to 1967. He created a distinguished ir center there and pioneered in the design of high-resolution spectrographs, particularly those for use in the study of vibration–rotation bands. He initiated the well-known and important Ohio State annual symposium on molecular structure and spectroscopy and in July 1957 established the *Journal of Molecular Spectroscopy.*

He made his laboratory facilities available to many workers from other institutions where needed equipment was lacking. Among those who took advantage of this help to do distinguished work were his able younger brother, Alvin H. Nielsen (who eventually developed his own good ir laboratory at the University of Tennessee), and Walter Gordy.

James Daniel Hardy (1904–) received his Ph.D. in 1930 at Johns Hopkins for his theoretical–experimental study of the resonance radiometer first described by Pfund[101]; he and S. Silverman continued this work in 1931.[102] While a National Research Fellow at Michigan he concentrated on high resolution ir spectroscopy.[103] His interests turned to biophysics, and his great experimental skill (especially in thermocouple construction) enabled him to introduce ir spectroscopy into medical investigations. In passing we may note that a study he made in 1934 of skin reflectance showed that in the ir black skin and white skin reflected about equally well. He designed and built a recording ir spectrophotometer for use at the Russell Sage Institute of Pathology in 1939.[104] After 1941 he was at the Cornell Medical College.

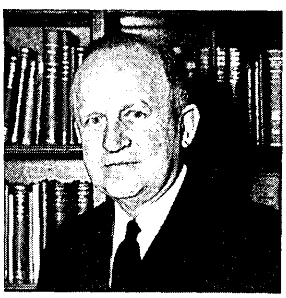


Photo: AIP Niels Bohr Library

John Donovan Strong (1905–) took his 1930 Ph.D. at Michigan, where he made a notable contribution by developing the technique of growing large alkali halide crystals from their molten salts, of a quality suitable for ir optical needs.[105] This work was done at Randall's suggestion, with the help of Paul Weyrich (and was later continued at Michigan by Katherine Chamberlain[106]). He went to the California Institute of Technology as a National Research Fellow and stayed there from 1930 to 1942. While there he worked on reststrahlen in the far ir,[107] spectrometer design,[108] radiation thermopiles,[109] pure rotation spectra,[110] and wrote his comprehensive and remarkably useful book, *Procedures in Experimental Physics* (in 1938) which quickly became a standby for experimental physicists.

Robert Bowling Barnes (1906–) was awarded his Ph.D. at Johns Hopkins in 1929. He worked under Pfund and Wood on a study of high resolution spectra of some organic liquids, 3.1–3.6 μm.[111] Following the Johns Hopkins tradition, he went to Germany and studied with Czerny, working in the far ir,[112] and with Matossi on a photoelectric amplifying relay for galvanometers.[113] He was at Princeton from 1933 to 1936. His first paper there was about work on a Johns Hopkins spectrometer, lent to him by Pfund.[114] During the next four years he published twelve papers, chiefly with R. R. Brattain, W. S. Benedict, and L. G. Bonner—some on spectra and some on Christiansen filters. After leaving Princeton he held various industrial positions, where he worked on applied physics—especially for chemical industries—before establishing his own Barnes Engineering Company.

Photo: AIP Niels Bohr Library

Permission to publish the photographs in this article has been received from Cornell University Archives, Yerkes Observatory and the University of Wisconsin, California Instituite of Technology, all courtesy of AIP Niels Bohr Library, from that Library's Bainbridge, Meggers, and Goudsmit Collections, and from E. S. Barr.

Supplementary Information

I. *The development of academic centers for ir spectroscopic research* (based upon a survey of about 500 papers cited in Science Abstracts, Section A, 1898–1941). For each are given the date of the first published paper, its author, the school, and the total papers from that institution to 1941.

1893	E. F. Nichols	Cornell	39
1893	B. W. Snow	Wisconsin	19
1895	E. P. Lewis	Johns Hopkins	44
1908	B. J. Spence	Princeton	34
1911	H. M. Randall	Michigan	96
1916	E. C. Kemble	Harvard	24
1924	E. F. Lowery	Ohio State	32
1925	J. W. Ellis	UCLA	19
1927	R. M. Badger	Caltech	20
1929	E. K. Plyler	North Carolina	35

II. *Late Starters*—persons publishing their first ir papers in 1930 or later and being either the sole or first author of five or more papers before 1941 (date, name, institution).

1930	C. H. Cartwright	Caltech
1930	J. D. Hardy	Johns Hopkins
1930	J. D. Strong	Michigan
1933	D. C. Stockbarger	MIT
1934	L. G. Bonner	Princeton
1934	W. Gordy	North Carolina
1934	L. Harris	MIT
1934	A. H. Nielsen	Michigan
1936	E. S. Barr	North Carolina
1936	F. D. Williams	North Carolina
1937	A. M. Buswell	Illinois
1938	B. L. Crawford, Jr.	Harvard
1938	R. C. Herman	Johns Hopkins

III. *Distribution by journals for ir spectroscopy papers from* Science Abstracts. (Note: early ir papers in the *American Journal of Science* are not in *Science Abstracts.*)

Phys. Rev. (1893–1941)	217
J. Chem. Phys. (1933–1941)	89
J. Opt. Soc. Am. (1920–1941)	41
Astrophys. J. (1895–1928)	37
J. Am. Chem. Soc. (1925–1941)	36
Rev. Sci. Instrum. (1930–1941)	29
Other journals, including foreign	59

Supplementary Reading

Much more about the rise of ir spectroscopy in the United States is derivable from the following papers (in chronological order), together with extensive technical details.

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My salutations and grateful thanks go to those distinguished physicists who, through private communications, have shared with me their recollections of the men and the activities discussed here—D. W. Bronk, D. M. Dennison, W. G. Fastie, N. Fuson, E. K. Plyler, and J. A. Sanderson.

Despite my efforts to be accurate and objective, it is quite likely that I have made—or propagated—errors. I will be grateful if mistakes and deficiencies are brought to my attention. Finally, I regret that I could not include a number of other productive researchers and many useful accomplishments. My sincere thanks to the University of Alabama for secretarial assistance in preparing the final draft of this paper.

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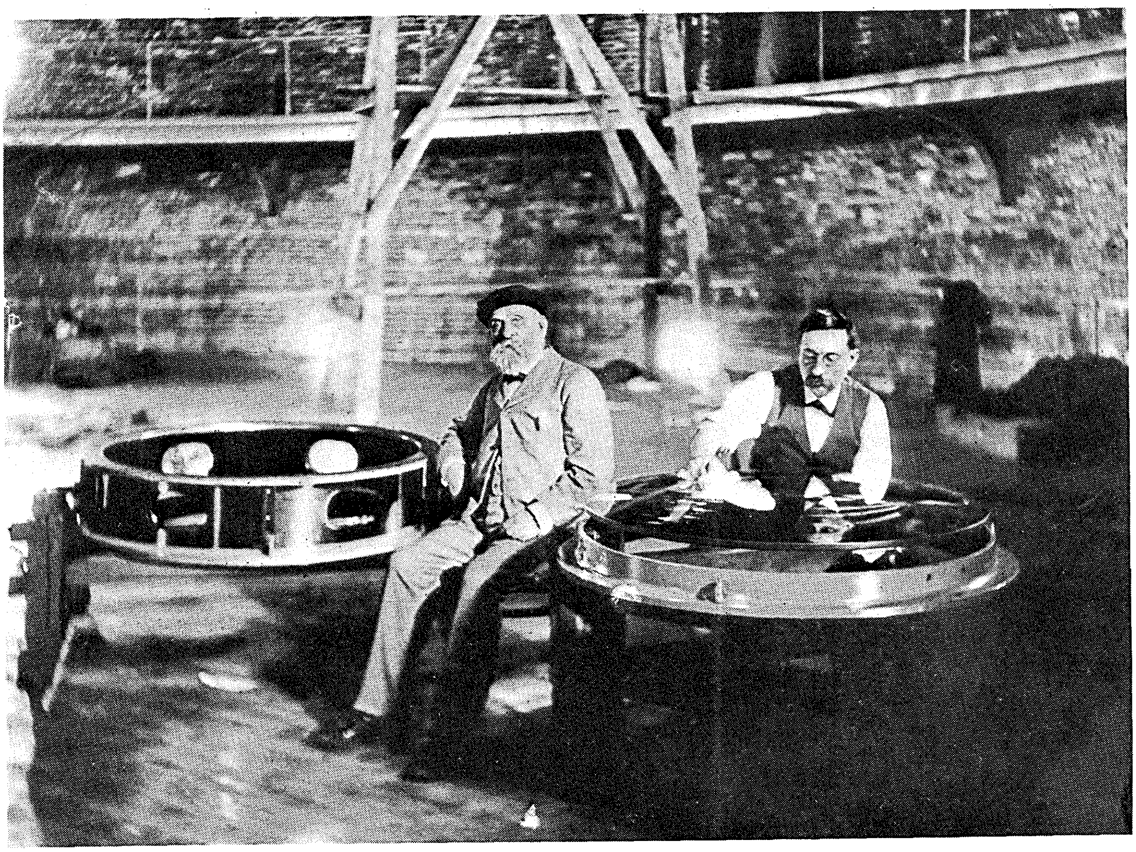

Alvan Graham Clark and Carl Lundin with the Yerkes 40-in. lens. *Photo:* Yerkes Observatory, University of Wisconsin, courtesy AIP Niels Bohr Library. See also page 1698.