Critical Density

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Synopsis. *Why are forbidden lines seen easily in the heavens but not in laboratory? It is usually (loosely) stated that forbidden lines are suppressed by high density of lab gases. However this explanation is incorrect. It is the case that permitted lines in the lab are brighter because of higher density. In the heavens, the density is low and so permitted lines do not enjoy a the huge density advantage as they do in the lab. As a result the permitted lines are comparable in strength to forbidden lines.*

Consider a two-level particle. Let n_c be the density of colliding particles (say, electrons) and let n_0 be the density of atoms (or ions) with two states. In equilbrium,

$$n_1 n_c k_{12} = n_2 n_c k_{21} + n_2 A_{21} \tag{1}$$

where n_i is the density of atoms in state i, A_{21} is the A-coefficient and k_{21} is the collisional *de-excitation* rate coefficient (and traditionally quoted in tables). From detailed balance in thermodynamic equilibrium, assuming only collisions, we find

$$k_{12} = \frac{g_2}{g_1} k_{21} \mathrm{e}^{-E/k_B T} \ .$$

Using this relation Equation 1 can be expressed as

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} \frac{\mathrm{e}^{-E/k_B T}}{1 + n_{\rm crit}/n_c}$$

where

$$n_{\rm crit} \equiv A_{21}/k_{21}$$

is the "critical density". Usually we are in the situation where the exponential is much smaller than one. So, we can assume $n_1 \approx n_0$. If so, the rate of radiative decys per atom is

$$l \equiv \frac{n_2}{n_0} A_{21} \approx \frac{g_2}{g_1} \frac{A_{21} \mathrm{e}^{-E/k_B T}}{1 + n_{\rm crit}/n_c} \ .$$

Consider the high density case, $n_c \gg n_{\text{crit}}$. In this case,

$$l = A_{21} \frac{g_2}{g_1} \mathrm{e}^{-E/k_B T} \ .$$

There is a ready availability of excited atoms and the rate of radiation is limited by the A-coefficient. The luminosity per atom is simply set by the Boltzmann equation. In particular, the luminosity does not increase with increasing density of colliding particles. In the opposite case, $n_c \ll n_{\text{crit}}$, the luminosity per atom is

$$l = n_c k_{12} \ . \tag{2}$$

Essentially, every collisional excitation leads to emission and so $l \propto n_c$. The luminosity is independent of the value of A_{21}.

Given similar k_{12}, permitted lines will always be brighter than forbidden lines at *any density*; see Figure 1. In dense gas, forbidden lines are weaker relative to permitted lines because the forbidden line intensity saturates at the Boltzmann value while that of the permitted lines may still be in the low density limit and not yet saturated.

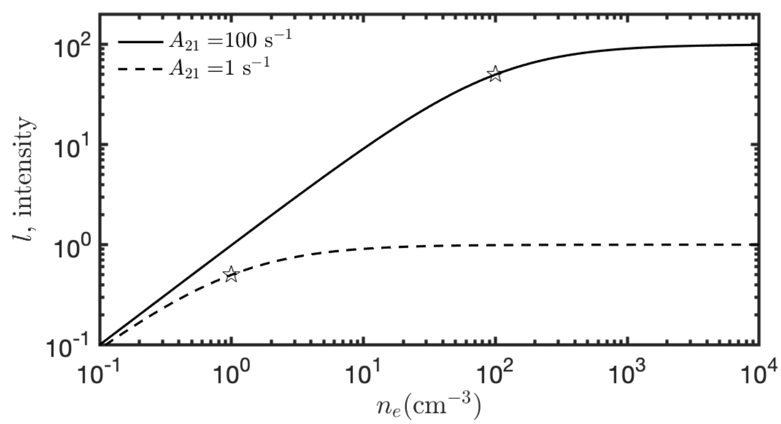


Figure 1: The luminosity per atom as a function of density of colliding particles for permitted and forbidden lines. In this example, k_{21} is fixed to $1\,\mathrm{cm^3\,s^{-1}}$, $g_1 = g_2 = 1$ and the Boltzmann factor is also set to unity. As proxies for permitted and forbidden lines we have set $A_{21} = 1\,\mathrm{s^{-1}}$ for forbidden lines and $A_{21} = 10^2\,\mathrm{s^{-1}}$. The critical density in each case is marked by a pentagram.

A Nebulium

In 1864 astronomer William Huggins discovered strong green emission lines in Cat's Eye, a planetary nebula (NGC 6543). At the turn of the century the prevailing view was that these lines arose from new elements (inspired perhaps by helium being found in the Sun). In 1927 Ira Bowen, Professor of Physics at Caltech, showed that these lines arose as fine structure of O++.

The *Nature* paper in which Bowen identified other "nebulium" lines and a memorial biography of this remarkable physicist, engineer and astronomer are attached.

Letters to the Editor.

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of* NATURE. *No notice is taken of anonymous communications.*]

The Origin of the Nebulium Spectrum.

IN the spectra of the gaseous nebulæ several very strong lines are found which have not been duplicated in any terrestrial source. Many lines of evidence point to the fact that the lines are emitted by an element of low atomic weight. Since the spectra of the light elements, as excited in terrestrial sources, are well known, this leads to the conclusion that there must be some condition, presumably low density, which exists in the nebulæ, that causes additional lines to be emitted.

A type of line, which one would expect to be affected by density in this manner, is that caused by a jump from a metastable state to a lower level. Such a metastable state is usually considered to be one from which jumps are very improbable, that is, one of which the average life is very long. Consequently, under terrestrial conditions, where the time between impacts is a very small fraction of a second, the metastable atom, in general, will be dropped down to a lower state by collisions of the second kind or by impact with the walls long before the return would take place spontaneously with the emission of radiation. Under conditions in the nebulæ, however, the time between impacts is very long, and many of these atoms will have a chance to return to lower states with the emission of radiation corresponding to the difference in energy between these metastable states.

Since the nebulæ are known to emit the well-known spectra of highly ionised nitrogen and oxygen, these ions at once suggest themselves as possible sources of the unknown lines as well.

In a four-electron system such as N_{II} and O_{III} the lowest energy levels are due to the configuration of 2 (2*s*) and 2 (2*p*) electrons. According to the Hund theory, this configuration gives rise to ^3P, ^1D, and ^1S terms. All but the lowest of these are metastable, since any jump between them involves a zero change in the azimuthal quantum number. In a five-electron system such as O_{II}, the normal configuration of 2 (2*s*) and 3 (2*p*) electrons forms ^4S, ^2D, and ^2P terms. These are likewise metastable.

The frequency of lines due to jumps between these terms can be calculated accurately in only two cases, namely, ^1D-^1S of O_{III} and ^2D-^2P of O_{II}. The calculated frequencies, if unresolved, are 22916 and 13646, which correspond to wave-lengths of 4362·54 Å.U. and 7326·2 Å.U. respectively. Two of the strongest nebulium lines are found at 4363·21 Å.U. and 7325 Å.U. These deviations are well within the rather large experimental errors arising from the fact that the values are calculated from the difference in frequency of lines in the 500 Å.U. region.

Another group of which the position can be predicted roughly is ^4S-^2D of O_{II}. Both terms have been calculated from series relationships, but as no intercombinations between quartets and doublets have been found, the predicted frequency is only approximate. The predicted frequencies of the two components are 27157 and 27175, which correspond to wave-lengths of 3681·25 Å.U. and 3678·81 Å.U. respectively. The strongest two nebulium lines in the ultra-violet are at 3728·91 Å.U. and 3726·16 Å.U. The doublet separation checks well and uncertainties in the adjustment of series limits for either the quartets or the doublets can account for the deviation in wave-lengths.

The strongest lines in the whole nebulium spectrum are the pair at 5006·84 Å.U. and 4958·91 Å.U. These have a separation of 193 frequency units, which is in almost exact agreement with the separation of 192 units observed for $^3P_1$-$^3P_2$ in O_{III}. This at once suggests that these two lines are $^3P_2$-$^1D_2$ and $^3P_1$-$^1D_2$ respectively. The relative intensity of these two lines is just what would be expected.

Another strong pair occurs at 6583·6 Å.U. and 6548·1 Å.U., showing a separation of 82·3 frequency units. This agrees very well with the known separation of 82·7 for $^3P_1$-$^3P_2$ in N_{II}. If these lines are identified as $^3P_2$-$^1D_2$ and $^3P_1$-$^1D_2$ of N_{II}, one can calculate at once the term value of $^1D_2$, since those of ^3P are already known. This ^1D term should combine strongly with the ^1P term of the $s^2p{\cdot}s$ configuration and the ^1D term of the $s^2p{\cdot}d$ configuration. The term values of these singlet terms have already been determined accurately by Fowler. The calculated positions of the lines arising from these combinations, obtained with the use of the above nebulium lines, are 746·98 Å.U. and 582·15 Å.U. Strong lines are observed in the nitrogen spectrum at 746·97 Å.U. and 582·16 Å.U. This furnishes almost certain proof of the identification of this pair of nebulium lines.

The other lines to be expected, on the above hypothesis, from N_{II}, N_{III}, O_{II}, and O_{III}, fall outside the range of wave-lengths easily observable in nebulæ. The above identifications account for all but two or three of the strong nebulium lines. It should be noted that in every case where it has been possible to make an exact prediction, a strong nebulium line has been observed at the calculated place. Furthermore, the above identifications are entirely in accord with the behaviour of these lines in the nebulæ as observed by Wright.

The nebulium lines thus far identified are collected in Table I.

TABLE I.

λ.	Source.	Series Designation.
7325·0	O_{II}	^2D -^2P
6583·6	N_{II}	$^3P_2$-^1D
6548·1	N_{II}	$^3P_1$-^1D
5006·84	O_{III}	$^3P_2$-^1D
4958·91	O_{III}	$^3P_1$-^1D
4363·21	O_{III}	^1D -^1S
3728·91	O_{II}	^4S -$^2D_3$
3726·16	O_{II}	^4S -$^2D_2$

I. S. BOWEN.

Norman Bridge Laboratory of Physics,
California Institute of Technology,
Sept. 7.

The Function of Water Vapour in the Photosynthesis of Hydrogen Chloride.

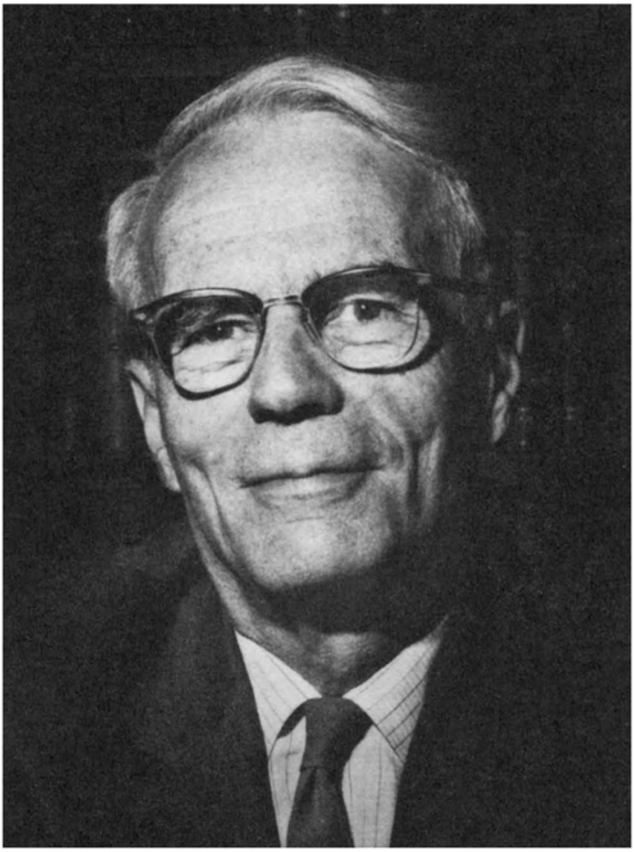
EVIDENCE was presented (B. Lewis and E. K. Rideal, *J. Chem. Soc.*, **129**, 583 and 596; 1926) for the view that the photo-expansion of bromine and other halogens in the presence of water vapour (Budde effect) is due to heat liberated by the recombination of halogen atoms set free by the absorption of light quanta. Although absorption of radiation occurs in the dry gas, no Budde effect is observable (J. W. Mellor, *J. Chem. Soc.*, **81**, 1280; 1902; Lewis and Rideal, *loc. cit.*) even when the gas is subjected to an intense source of ultra-violet radiation (E. B. Ludlam, *Proc. Roy. Soc. Edinburgh*, **44**, 197; 1924). This is interpreted to mean that the halogen does not dissociate in the dry state; that the radiation absorbed

NATIONAL ACADEMY OF SCIENCES

IRA SPRAGUE BOWEN

1898—1973

A Biographical Memoir by
HORACE BABCOCK



Ira S. Bowen

IRA SPRAGUE BOWEN

December 21, 1898–February 6, 1973

BY HORACE W. BABCOCK

IRA SPRAGUE BOWEN was one of the outstanding physicists and astronomers of the twentieth century. He was gifted with exceptional physical insight and with a compelling concern for fundamentals from which he seldom permitted himself to be diverted. As a pioneer in ultraviolet spectroscopy he discovered, with R. A. Millikan, evidence that led to the concept of electron spin in the vector model of the atom. He solved the long-standing mystery of the "nebulium" lines in the spectra of gaseous nebulae, showing that they were "forbidden" lines of ordinary elements. He was a master of applied optics who was responsible for successful completion of the 200-inch Hale Telescope and for many ingenious devices or optical systems that contributed enormously to mankind's observations of the universe.

Bowen was director of the Mount Wilson and Palomar Observatories for eighteen years. Here he took the lead in developing a major organization for research and education while at the same time closely supervising details of observatory operations. On a wider scale, he accomplished much to broaden the opportunities for astronomers generally and to increase the number and efficiency of astronomical facilities.

FAMILY BACKGROUND AND SCHOOLING

The Bowen family traces its beginning in New England to Richard Bowen, who left Wales and settled in Rehoboth, Massachusetts in 1643. During the Revolutionary War some members of the family were Tories and were forced to emigrate to Canada. Later they returned to Washington County, New York. Ira Bowen's great-grandfather, Aaron Bowen, pioneered in Steuben County, in the western part of the state. His grandfather, William H. Bowen, grew up on a farm in this region and married Juliza Cotton, whose family was likewise of New England origin and had pioneered in the same section of the state. After spending his early years on the farm, Ira's father, James H. Bowen, received his education at the local high school and at the Geneseo State Normal. He then became a preacher in the Wesleyan Methodist Church, a small denomination with fundamentalist doctrines and strict codes of conduct. James Bowen married Philinda Sprague, who had grown up in the same rural community of Haskinsville in Steuben County and had completed her education at the Geneseo State Normal.

Ira was born December 21, 1898 at Seneca Falls, New York, where his father was at the time pastor of the local church. Two years later the family, including Ira's older brother, Ward, moved to Millview, a small village in Sullivan County, Pennsylvania. While Ira was quite young, his father became business agent of the Wesleyan Methodist Church; the resulting responsibilities required frequent moves between Houghton and Syracuse, with the result that from 1905 to 1908 Ira did not attend school but was taught at home by his mother, who was a licensed teacher in New York State. Following the death of his father in 1908, the boy's education was continued at Houghton Wesleyan Methodist Seminary, where his mother had obtained a position as a teacher. She later became principal of the high school department.

During his high school years, Ira (or Ike, as he was known to his friends) took considerable interest in popular science as represented by *Popular Mechanics* and *Scientific American*. He also played with lenses, wires, and batteries to the extent permitted by the very limited family finances. He graduated from the high school in 1915 as valedictorian of a class of seventeen.

The first three years of Ike Bowen's college courses were in the junior college that formed part of Houghton Seminary. All of the courses in mathematics, physics, and astronomy were taught by the president, J. S. Luckey, who was a most effective teacher and who was largely responsible for the unusually high scholastic standards at the school. For these three years Bowen had charge of the laboratory of the high school physics course; the income earned in this way was used to pay his tuition.

His early interest in science deepened during Bowen's first college years. It was no doubt stimulated by the ingenuity required to devise suitable experiments with the limited equipment available, as well as by the formal courses. Following a connection established by Luckey, Bowen transferred to Oberlin College for his senior year and received the A.B. degree in June 1919. While at Oberlin he came under the direction of Professor S. R. Williams, whose sympathetic collaboration with his students in research projects was responsible for the continuation of many of these students in advanced study and research. In a project of this sort, Bowen studied the magnetic and magnetomechanical properties of samples of manganese steel supplied by Sir Robert Hadfield, with whom he eventually published the results in the *Proceedings of the Royal Society*. During this year he also assisted in one of the general physics laboratories and gave some time to the Students Army Training Corps, in which he had enlisted before the end of World War I.

In the fall of 1919, having been awarded a scholarship, Bowen took up graduate studies at the University of Chicago. In the two years that he remained there he attended all of the very comprehensive group of courses given by A. A. Michelson on classical physics and R. A. Millikan on modern physics, as well as many other courses in the department. These contacts, and the involvement in a major physics department during a period of extraordinary progress, undoubtedly had a deep and lasting influence. In later life Bowen insisted that research should be aimed incisively at a well-defined, fundamental problem; he was intent on understanding the basic physics and had little patience with mere data-gathering programs, which he characterized as "weather-bureau-type" activity.

RESEARCH AND TEACHING

At about the time of Bowen's arrival at the University of Chicago, Millikan's laboratory assistant, Dr. Ishida, announced his intention of leaving the University and returning to Japan. Bowen immediately accepted the offer of this position, which he took up on January 1, 1920. His first duties were to assist Ishida in the completion of his measurement of the viscosities of several gases by the oil-drop method. Upon Ishida's departure, however, Bowen was transferred to spectroscopic studies in the extreme ultraviolet using the vacuum spectrograph that had been developed by R. A. Sawyer and G. D. Shallenberger under Millikan's direction. At about this time significant improvements were introduced in the methods of ruling diffraction gratings, permitting extension of the shortward limit observable in the laboratory to about 150 angstroms. In the winter of 1920 and 1921 Bowen systematically photographed, in this newly available region, the spectra of most of the first twenty elements of the periodic table. The results were published jointly with Millikan in 1924. Many interesting surprises occurred in this first survey of the new region, such as the discovery that chemically pure aluminum and magnesium electrodes gave practically identical spectra in the region between 300 Å and 1200 Å. At first the investigators even considered attributing this finding to some transmutation of one element into another by the powerful condensed spark that was used. But more reflection and investigation showed that these common lines were due to oxygen, always present on the surface of these easily oxidizable metals. The difference in behavior in the new region and in the spectral regions previously explored results from the presence of all the strong lines of these metals in the older, long wavelength range.

In 1921 George E. Hale persuaded Millikan to move to the California Institute of Technology as chairman of its executive council and director of the Norman Bridge Laboratory of Physics, then nearing completion. Arrangements were made for Bowen also to make the move and to continue as Millikan's assistant in the new physics group at Caltech. One of the inducements offered by Hale was the proximity of the emergent scientific school to the Mount Wilson Observatory of the Carnegie Institution of Washington, where the largest telescopes in the world were being used by an active staff in a variety of investigations in astrophysics and cosmology. More specifically, Hale promised Millikan that diffraction gratings would be provided from the new ruling machine that had just gone into operation at the Pasadena headquarters of the Observatory.

During the first year after the move to Caltech, Bowen taught a course in general physics, using a lecture room in Throop Hall because the Norman Bridge Laboratory was still under construction. He also participated with Millikan in research on cosmic rays. The program involved the design and use of instruments carried to high altitudes by sounding balloons, the actual flights being made from San Antonio, Texas. The researchers obtained the first record from sounding balloons of cosmic rays and found definite evidence for an increase of intensity with altitude. Aerial observations had already been made by Hess and Kolhörster, but because they used manned balloons they were limited to lower altitudes. Bowen also participated with R. M. Otis in measurements of cosmic-ray intensity in the High Sierra of California. They used detectors that were lowered into the waters of mountain lakes at altitudes of some 12,500 feet, such that the water shielded the instruments from local radioactivity of the rocks. A love of the mountains stayed with Bowen all his life, but his principal research interests lay in spectroscopy, to which he soon returned.

With the completion of the physics laboratory, apparatus could be assembled for the continuation of the ultraviolet studies. An exceptionally fine grating was indeed provided by J. A. Anderson of the Mount Wilson Observatory. This grating gave much higher resolution than had hitherto been obtained in this region and made possible the studies of the fine structure of many lines in the extreme ultraviolet that were carried out by Bowen with the vacuum spectrograph in 1923 and 1924.

At about this time, Paschen and R. H. Fowler almost simultaneously made their analyses of highly ionized Al III and Si IV, and Bohr published his discussion of penetrating and nonpenetrating orbits. Applying these results to their new data, Bowen and Millikan found it possible to make an analysis of B III. From further studies made early in 1924 they were able to show that the so-called regular and irregular doublet laws, developed earlier for X-ray spectra, applied equally well to optical spectra when isoelectronic sequences (series of ions of the same electronic structure but differing nuclear charge) were used. This discovery at once made possible a direct correlation between optical and X-ray spectra and therefore between the atomic-structure formalisms developed from these two types of spectra. The results of this correlation constituted part of the evidence that later resulted in the introduction of the important concept of the spinning electron by Uhlenbeck and Goudsmit.

The doublet laws provided a very powerful tool for the analysis of highly ionized atoms. In 1925 and 1926 Bowen and Millikan applied these laws to the analysis of their new data and were able to obtain partial analyses of Be I, Be II, B II, B III, C III, C IV, P III, P IV, P V, S IV, S V, S VI, Cl V, Cl VI, Cl VII, Cl VIII, Y III, and Zr IV. In this research, the heavier part of the load fell on Bowen, who produced and measured the spectrograms and analyzed the data. Millikan was exceedingly busy with the administration of the Institute and of the Norman Bridge Laboratory, as well as with a variety of other research efforts. He would occasionally drop in to keep in touch. When Bowen was ready, he would say to Millikan, "I've got an article. How about coming around tonight?"* Millikan would appear at about nine o'clock in Bowen's office, and the two would work until midnight writing the paper.

For several years after coming to Caltech, Bowen held the title of instructor and research assistant to the director of the Norman Bridge Laboratory of Physics. His teaching assignment was to instruct one of the undergraduate sections of twenty students in physics. In 1924 the practice was initiated of assigning the top men of the sophomore class to section A, the honor section, and Bowen was given this section. Much later he commented that "I never had quite such a run for my money. In the section were Ed McMillan, Robley Evans, and several others who later became heads of departments or university presidents. Keeping ahead of that group took quite some time."†

*Interview with Charles Weiner, Center for the History of Physics, American Institute of Physics.

†*Ibid.*

Bowen continued with undergraduate teaching in physics until 1929, when he took over the teaching of graduate courses in optics and spectroscopy. He became assistant professor of physics in 1926, associate professor in 1928, and professor in 1931.

Under the pressures of research and teaching, Bowen found little time to proceed with the formal requirements for the Ph.D. degree, although he finally received it in 1926, by which time he had already published some twenty articles. Language examinations were required, and partly for this reason he took a month's vacation in the summer of 1925, spending some of the time reading Sommerfeld's *Atombau und Spectrallinien* in German. (He had already passed the French examination.) His thesis, somewhat surprisingly, was on the subject of "The Ratio of Heat Losses by Conduction and by Evaporation from Any Water Surface." This came about because Bowen had been assigned to guide the thesis work of another graduate student, an older man who had been with the weather bureau and who proposed to do a thesis on evaporation but later lost interest. Bowen's interest grew to the extent that he worked out a formula for the ratio of heat lost by evaporation and by conduction to the air, showing that this ratio can be determined uniquely from the temperature of the air, the temperature of the water, and the humidity. This quantity, known as the Bowen ratio, is to be found in the literature of meteorology and has been of use in oceanography. His ratio method is now commonly used to measure the evaporation from plant, soil, and water surfaces. As Bowen said later, "When I got ready to take my degree, that was the paper that was going to press, so it became my thesis."* His subject was undoubtedly a novel one for the faculty pundits—including P. Epstein, R. C. Tolman, and Millikan—who sat on his examining committee.

* *Ibid.*

In the middle 1920's the vector model of the atom to account for complex spectra was developed by Russell, Saunders, Pauli, Hund, and others. Bowen applied this theory to the analysis of the more complex spectra of the elements in the first row of the periodic table, using again the data accumulated from the use of the high-resolution spectrograph. It was thus possible for him in 1926 to fix the low terms of C II, N III, O IV, N II, O III, F IV, O II, F III, F II, and F I. This, as it turned out, was preliminary to his most outstanding discovery, the identification of the so-called "nebulium lines" in the spectra of galactic nebulae. These two bright green lines had been a puzzle to spectroscopists since their discovery by Huggins some sixty years earlier. In parallel with the bright yellow line in the spectrum of the sun's corona, which had been attributed to an unknown element (helium) before the element was discovered on earth, it had been conjectured that nebulium was also an unknown but real element. By 1920, however, spectroscopy in the X-ray region had established the sequence of light elements. It was clear that there was no room here for an unknown, while the very strong nebulium lines could hardly be due to a rare element at the heavy end of the periodic table. Spectroscopists were generally aware of the problem and were alert to any leads that might provide a solution.

H. N. Russell of Princeton was knowledgeable about these matters. In 1927 the text of the classic *Astronomy* by Russell, Dugan, and Stewart appeared, in which Russell made the suggestion that "The nebular lines may be emitted only in a gas of very low density. This would happen, for example, if it took a relatively long time for an atom to get into the right state to emit them, and if a collision with another atom in this interval prevented the completion of the process. In such a case, it might require a great thickness of the very rarefied gas to emit these lines strongly enough to be visible" [p. 838].

NOT TRUE

Bowen bought the two volumes of *Astronomy* and thus became aware of Russell's summary. Later he related that one evening he came home from the laboratory at about nine o'clock and while preparing for bed was thinking about the energy levels of O II and O III and the "forbidden transitions." According to the theory, there was no way for the atom to get from the D or F states to the S (lowest or ground) state except through collisions. In a very rare gas, as in a nebula, the rate of collisions was insignificant. What, then, happens to these atoms? Are they stuck forever in the D and F states? Then it occurred to Bowen that, given enough time, perhaps the atoms can, in fact, make the "forbidden" jumps, although at a low rate.

Bowen quickly dressed and returned to his office. Since all the data on the energy levels were available in his records, it was easy for him to take the differences and to compute the wavelengths of the forbidden lines in a matter of minutes. There they were, correct to a hundredth of an angstrom! "I worked until midnight and had the answer when I went home,"* he said. The "nebulium" lines were in fact due to forbidden transitions between low-lying energy levels of singly and doubly ionized oxygen. The lines were intense because of the immense volume of gas at low pressure in the nebulae. The name "nebulium" could be laid to rest. The solution to the problem was widely acclaimed and brought well-deserved recognition to its author.

[illegible] Bowen continued the work for years,

* Interview with Charles Weiner.

bent on identifying the elements that might provide an explanation of the fainter lines and on solving the larger problem of determining the relative abundance of elements in the gaseous nebulae.

[illegible] The fascinating possibility occurred to him that ultraviolet radiation from helium, in passing through a rarefied gas containing O III, could be expected to selectively populate certain energy levels in O III; this could give rise to peculiar enhancement of specific emission lines of the latter element.

In 1934 Bowen received a letter from W. H. Wright, director of the Lick Observatory, who was one of the chief observers of nebular spectra. New data from the ultraviolet were just becoming available. Wright mentioned that he had new nebular lines in the 3100-3300 Å region and that the intensities of some were quite abnormal. In response to Wright's inquiry about the strange line intensities, Bowen was able to write back with the explanation. He had lacked the data until that time but had the solution in the form of the fluorescence mechanism. It is interesting to note that Wright's new ultraviolet data were made possible by the aluminum coating recently applied to the mirror of the 36-inch Crossley reflector. The great superiority of aluminum compared to silver as a reflective coating for telescope mirrors had resulted in the development by John Strong in Pasadena of the method for evaporative coating in a high vacuum; this development, closely related to the 200-inch telescope project, was quickly adopted for all large telescope mirrors.

Bowen accepted Wright's invitation to spend the summer term of 1938 at the Lick Observatory as a Morrison Associate.

With Arthur B. Wyse, he observed the spectra of gaseous nebulae. This was his first real observational work in astronomy. The work benefited from new, much faster panchromatic photographic emulsions that had just become available from the Eastman Research Laboratories, and the observers were able to discover numerous new emission lines. For many of these lines, Bowen had the identifications from his laboratory studies. The spectrograms made by Bowen and Wyse carried intensity calibrations, so that they were able to obtain quantitative results on line intensities. In this way they showed that the composition of the gaseous nebulae, i.e., the relative abundance of the elements, is about the same as that of the sun and stars. This statement includes the finding that hydrogen is by far the most abundant element, which Russell had already established for the sun.

In later years Bowen carried heavy responsibilities for administration, so he found little time for research. Nevertheless, he continued some work on the spectra of gaseous nebulae. With the large grating spectrograph at the coudé focus of the 200-inch telescope, he made very significant improvements in the precision of the wavelengths of nebular lines, primarily because the resolution and dispersion of this instrument were far superior to those of the laboratory and observatory spectrographs used earlier for the ultraviolet studies from which the term differences were derived. He published this work in 1955, as well as a definitive contribution with L. H. Aller and R. Minkowski on the uniquely rich spectrum (263 lines) of the gaseous nebula NGC 7027.

In the course of his observational work, Bowen was impressed with the very long exposure times often required to obtain direct photographs or spectrograms of faint objects. It was known that the photographic emulsion, generally designed for exposure times of a fraction of a second, does not maintain a reciprocity between light intensity and exposure time for exposures measured in hours. He originated a pre-exposure procedure of baking plates for a specified time at an elevated temperature, showing that for many emulsions this would significantly increase the effective speed for long exposures. Astronomers were quick to adopt the baking technique, which often cuts exposure times to 50 percent or less; it has for years been standard procedure at major observatories.

The "image slicer" is an optical device originated by Bowen to improve efficiency in recording the spectra of stars or nebulae. Because the image of such an object may be large compared to the width of the spectrograph slit, much light may be lost. The image slicer, consisting of an array of several tiny, carefully shaped mirrors, effectively cuts the image into a series of narrow strips that are optically transposed into a single narrow strip that enters the slit with little loss.

THE 200-INCH TELESCOPE PROJECT

Mention has already been made of the activity in astronomy and astrophysics that was so prominent in the scientific life of Pasadena in 1921 when Bowen arrived from Chicago. The Carnegie Institution's 60-inch reflector had been in operation on Mount Wilson for thirteen years, the 100-inch Hooker telescope for three years. The researches of Kapteyn and of Shapley had opened new vistas on the structure of our Galaxy. Using the 100-inch, Hubble was soon to clinch the concept of a universe populated by countless galaxies like our own; the evidence for the expanding universe was on the horizon. Meanwhile, stellar spectroscopy was flourishing. This wave of progress was due in large measure to the quality and size of the Mount Wilson telescopes and to the excellent observing conditions provided by the site. While the optical quality of the mirrors was attributable to the skill of G. W. Ritchey, much of the telescopes' success, and in particular their mechanical design, was due to the Mount Wilson engineer and astronomer Francis G. Pease. It was clear that this sequence of large productive telescopes should not be allowed to end with the 100-inch. Pease went on to promote the design of a 300-inch telescope, for which in 1921 he produced drawings and a scale model introducing the concept of a large "horseshoe" for the main bearing of the polar axle. In 1928 George E. Hale, at that time honorary director of the Mount Wilson Observatory, successfully launched the project to build a 200-inch telescope and obtained from Rockefeller sources the funding for this great optical instrument that was destined to be installed on Palomar Mountain. [illegible]

The design of the 200-inch telescope was conducted at Caltech with the close collaboration of astronomers and engineers of the Carnegie Institution's Mount Wilson Observatory over a period of several years, beginning about 1930. The project was guided by the Observatory Council and by a Policy Committee of which Bowen was a member. His knowledge of optics and his aptitude for instrumentation were invaluable here, and, not surprisingly, his responsibilities rapidly increased as the work progressed. Among the important decisions in which he participated were the choice of the focal ratio of the primary mirror (f/3.3); the specification of a thin-section, ribbed disk of borosilicate glass; and the adoption of the Serrurier truss and of the horseshoe mounting with hydrostatic bearings. His influence was also strong in applications of the Schmidt camera, both for use in spectrographs and for sky-survey instruments such as the 18-inch and 48-inch wide-angle telescopes at Palomar. Indeed, the basic parameters of the 48-inch were due to him. Remarkable success was achieved with this telescope because the aperture, focal length, field size, and correcting-plate material were so specified that three crucial quantities—size of the typical stellar "seeing disk," optical aberrations, and limiting resolution of the emulsion (plate grain)—were equated, each being about 30 microns on the plate.

THE WAR YEARS

The completion of the 200-inch and 48-inch telescopes was delayed by the entry of the United States into World War II; this brought to a halt all work on the Palomar Observatory and resulted in drastic shifts in the activity of all concerned. Bowen accepted responsibility for exterior ballistics on the Caltech ordnance rocket project. This organization, which grew to large size and had an important impact on military operations, was headed by physicist Charles C. Lauritsen, with W. A. Fowler second in command. In close collaboration with military services, it was concerned with all phases of design, development, testing, and production of solid-fuel rockets for immediate use in the war. Bowen organized the photographic section and for nearly four years guided and participated in the field work and analysis needed to provide precise data on acceleration, stability, trajectory, blast effects, and other parameters. Thousands of rocket tests were monitored from the ground and from the air. On other wartime projects not connected with rockets, Bowen contributed to the development of high explosive devices by inventing cameras capable of cinematography at unprecedented rates. He also collaborated in experiments for measuring the transparency of seawater and the penetration of sunlight in the ocean.

In August 1945 Vannevar Bush, who headed the wartime Office of Scientific Research and Development, travelled from Washington to witness the explosion of the first nuclear bomb (the Trinity Test) in New Mexico; he continued on to the West Coast and, in his other capacity as president of the Carnegie Institution, stopped in Pasadena to tell Bowen that he had been appointed director of the Mount Wilson Observatory, to succeed Walter S. Adams on January 1, 1946. Thus began another and very different phase of Bowen's career, in which he effectively completed the transition from physicist to astronomer, and from researcher to director and administrator.

OBSERVATORY ADMINISTRATION

For the Carnegie Institution of Washington and the California Institute of Technology, the end of the war brought urgency to the matter of reorganizing and renewing their peacetime effort in astronomy. Bowen was responsible to the two institutions, and in 1948 he was appointed director of the combined Mount Wilson and Palomar Observatories. Most of the staff members were of an older generation. Hale, Pease, and Sinclair Smith had died in 1938. John A. Anderson, executive officer of the 200-inch telescope project, was in poor health and nearing retirement. The unfinished 200-inch mirror was in the optical shop in Pasadena. To Bowen fell the crucial task of guiding to completion the telescope project and of staffing and commissioning the Palomar Observatory. Further, a graduate school of astronomy had to be established at Caltech. It was necessary to plan and guide the main research programs to utilize to best advantage the new facilities that would soon be available, to encourage the application to astronomy of recent advances in nuclear physics, and to exploit the gains that were being made in technology.

To promote cross-fertilization of the two fields—stellar spectroscopy and nuclear physics—Bowen initiated a series of informal evening gatherings at his home overlooking lower Eaton Canyon. From time to time the group included such physicists as L. Blitzer, L. Davis, W. A. Fowler, R. B. King, C. C. Lauritsen, T. Lauritsen, H. P. Robertson, S. Rubin, and astronomers W. Baade, H. W. Babcock, P. W.

Merrill, R. Minkowski, R. Sanford, and O. C. Wilson. If one can judge from the later contributions of some of the participants, the discussions that developed at these meetings were highly productive.

The main task for the 200-inch telescope was clearly defined: to extend the earlier investigations of the distribution of galaxies in space to the most extreme limits that could be reached and to measure velocities or redshifts in order to refine and extend the velocity-distance relation. The development of more precise methods for the photometry of very faint galaxies was a formidable task, but one that had to be faced. New and better spectrographs had to be provided. The wide-angle, 48-inch Schmidt telescope would be an essential companion instrument for survey purposes and for the study of clusters of galaxies.

To Bowen it was clear that research in stellar astronomy was ready to enter a quantitative phase. Much was known about the classification of spectra, and wavelength measurements could be made accurately, but the measurement of line intensity (equivalent width) was a difficult and generally inexact art. Yet line intensities were the keys to the abundance of the elements in stars, nebulae, and interstellar clouds. It was now evident that great advances were to be made in stellar structure, stellar evolution, and the study of nuclear reactions that produce heavy elements in stars. At many universities and research centers there would be theoreticians and interpreters eagerly demanding quantitative observational data; the instruments at Mount Wilson and at Palomar Mountain must be effectively used to help meet this need.

Bowen himself guided the final stages of polishing and figuring the 200-inch mirror. Such a mirror is extremely sensitive to the functioning of its support system, being subject to flexure that varies as the fourth power of the diameter and inversely as the square of the thickness. Of necessity, testing of the mirror in the optical shop on the Caltech campus had to be done with the mirror on edge. There was concern that upon being placed face up in the telescope, the outer rim of the mirror might sag, giving the figure a turned-down edge. To avoid the possibility of having to refigure the whole mirror, it had been decided to leave an optically high zone some eighteen inches in width around the outer edge; after installation in the telescope, the mirror would be tested on stars, and the outer zone polished down to the extent required. This procedure was indeed followed after the mirror was placed in the telescope in 1948. The rather lengthy process was one of successive approximations. Bowen, using a Hartmann screen in front of the mirror, photographed the Hartmann patterns of bright stars. He then measured the plates in Pasadena and derived the results in terms of high and low areas of the mirror surface. Then the mirror on its support system was lowered to the floor of the dome where Donald O. Hendrix, the optician, carefully polished down the high areas, using a simple mechanism with small tools. After several iterations that required many months, the figure had been brought to a very satisfactory level such that 80 percent of the light of a star was concentrated within a circle 50 microns in diameter. The mirror was then aluminized, and the telescope was placed in regular service for observations at the prime focus and Cassegrain focus, beginning in 1950. The successful completion of the 200-inch Hale Telescope was undoubtedly one of Bowen's major achievements and one in which he inwardly took great and justifiable pride.

Observations at the coudé focus awaited the construction of a large grating spectrograph. For this, the design was evolved by Bowen from the prototype developed by Adams and T. Dunham, Jr., for the 100-inch Hooker telescope on Mount Wilson. Bowen specified a very long focus (30-foot) collimator, to minimize losses at the slit. The resulting

12-inch beam demanded a larger diffraction grating than could be produced on a single blank. He was able to devise a method of mounting and adjusting four identical plane gratings that could be used as a composite. For the four interchangeable Schmidt cameras he introduced the "twice through" correcting plate, to be positioned just in front of the gratings. The spectrograph went into operation most successfully in 1951.

When the 48-inch Schmidt telescope was completed in 1948, the test photographs that were made demonstrated remarkable gains in astronomical photography. On each 14-inch square plate, 6.5 degrees on a side, were recorded vast numbers of stars and galaxies to the faint limiting magnitude of 20.3, with exposure times of only 12 minutes in the blue and 48 minutes in the red. (With more modern plates the limiting magnitude is substantially fainter.) Faint filamentary features such as supernova remnants, gaseous nebulae, and clusters of galaxies formerly beyond reach were now recordable with ease. The Schmidt camera of appropriate size and at a good site had outmoded all earlier sky survey instruments.

Bowen at once came under strong pressure from certain aggressive staff members to let them put the 48-inch to use for their own researches. He was convinced, however, that the telescope should first be used exclusively to complete a survey of the sky for the general good of astronomy. The region from the north pole to declination −30° could be photographed from Palomar Mountain on about 900 plates. With financial assistance from the National Geographic Society, Bowen organized the Palomar Sky Survey. Each of the 900 fields was to be photographed under good conditions on red and blue plates in immediate succession. Glass copies and paper prints produced under close quality control would be made available at cost to other observatories and research centers throughout the world. The Sky Survey was successfully carried through between 1949 and 1957 as a result of Bowen's firm administrative control. R. Minkowski supervised the work and personally approved the plates to be accepted. By 1979, 322 complete sets of prints and twenty glass copies of the Survey had been distributed worldwide.

The Palomar Sky Survey effectively enlarged manyfold the volume of the observed universe and formed the basis for several important catalogs and for almost countless research articles. It led to the optical identification of large numbers of radio sources and to catalogs of planetary nebulae, of supernova remnants, of galaxies, and of clusters of galaxies.

Following World War II the multiplier phototube revolutionized astronomical photometry for individual stars. The next step—the development of image tubes, wherein the high quantum efficiency and other advantages of the photocathode might be applied to the recording and photometry of two-dimensional sky fields—was one that held great promise. Commercial television camera tubes were not suited to the low light levels encountered in astronomy, but if a relatively simple, reliable image tube could be developed, it would have wide application at many observatories. With the enthusiastic support of Bush, Bowen took the initiative in organizing the Carnegie Image Tube Committee, with Merle Tuve as chairman. The Committee, working with industrial laboratories and observatories over an interval of several years, developed a successful sealed, magnetically focused image tube that was produced in some quantity by the Radio Corporation of America; such tubes were widely adopted for use and remain to this day the instrument of choice in several systems. They provide the astronomer with a convenient image-amplifying device having a quantum efficiency of the order of 20 percent as compared to less than 1 percent for the photographic plate.

The ruling engine mentioned earlier had been superseded at Mount Wilson by a newer, more precise machine, and beginning in 1950 this machine began to produce sizeable gratings of a quality not available before. Many of these gratings were put to use at Mount Wilson and Palomar; dozens of others, some of large size and very high quality, were sold at cost or given away to various observatories and physical laboratories on a worldwide basis. This distribution was characteristic of Bowen's policy to broaden opportunities for the advancement of science. Not only were gratings given away to scientific groups, but the complete technology of ruling gratings at the Mount Wilson Observatory was freely disclosed in detail to three scientific companies interested in commercial production.

Bowen faced and solved many challenging problems during his tenure as director of the combined Mount Wilson and Palomar Observatories. The basic pattern for the proposed organization had been sketched years before by officers of Caltech and of the Carnegie Institution, and the plan was understood when Bowen agreed to take the directorship. It remained for him, in consultation with Caltech President Lee DuBridge and Carnegie Institution President Bush, to formalize the agreement for unified operation of the two observatories that was adopted by the trustees of both institutions in 1948. It was not possible for the observatory organization to have a separate corporate existence; ownership of the respective facilities was to be maintained by the two sponsoring institutions, and they required separate budgets. The director would be equally responsible to the two presidents. Research was to be conducted by one integrated scientific staff, together with guest investigators who would be invited to come from outside institutions. There was emphasis on education and on opportunities for young astronomers through research fellowships. Such an organization, with dual sponsorship, is rare, if not unique, in American science. It was no easy task for Bowen, over a period of eighteen years, to maintain a balance between the interests of the two institutions, however harmonious they were at the start.

Working with the Caltech administration, in 1948 Bowen expanded the academic group responsible for instruction in astronomy at Caltech; this group became part of the Division of Physics, Mathematics, and Astronomy, which was administratively separate from the Mount Wilson and Palomar Observatories. J. L. Greenstein accepted an invitation to come from the University of Chicago to join H. P. Robertson and F. Zwicky, with a dual appointment as professor of astronomy and staff member of the Observatories.

One of Bowen's principal aims as director of the Mount Wilson and Palomar Observatories was to ensure that the facilities, and especially the 200-inch telescope, would be administered and used at the highest level of efficiency and productivity. Practically the entire load of administration was carried by him personally, with a very minimum of assistance. He called on staff members for advice but only rarely requested that they perform special tasks, and then after careful consideration. Every effort was made to provide each astronomer with maximum time and freedom for research with support for long-term programs. In return, Bowen took it for granted that others would match his extraordinary capacity for work. Various phases of the rather complex observatory operations were conducted according to policies that he developed and applied uniformly. Some individuals from outside the organization occasionally found it difficult to understand and to adapt to what may have seemed to them rather rigid rules.

An accomplishment, perhaps insufficiently appreciated, resulted from Bowen's efforts to create observation opportunities for astronomers not connected with major observatories. This was particularly important for many in other parts of the United States who lacked not only large instruments but also the good observing conditions that prevailed on parts of the West Coast. The guest investigator program of the Mount Wilson and Palomar Observatories, which Bowen developed and administered with great care, gave substantial opportunities to many, but it fell short of meeting the general needs. This became increasingly evident with the growth of the science during the 1950's, and more so after the opening of the space age. The answer was to promote the construction of more large telescopes at good sites by other organizations or agencies. This became one of Bowen's main interests, and to this cause he gave generously of his time and energy. Even before 1950, for example, he strongly supported the 120-inch telescope project of the University of California. This support included the transfer of much technical and engineering information; he also lent the services of Hendrix, the optician, to the Lick Observatory to oversee and advise on the figuring of the 120-inch primary mirror.

During the formative period of the National Science Foundation and, somewhat later, the creation of the major research facility that became the Kitt Peak National Observatory, Bowen's advice was frequently requested by Bush, Robert R. McMath, and many others. In his service on the National Astronomical Observatory Advisory Panel, he wisely insisted that the several sponsoring universities should be involved in early decisions as to specifications for the basic instrumental facilities of the new observatory.

Bowen's advice was sought by astronomers, telescope engineers, and instrument designers worldwide who visited Mount Wilson and Palomar Mountain for consultation, to inspect the instruments in detail, and to obtain plans and drawings from the engineering group. Many of the innovative features of the 200-inch Hale Telescope are to be found in other large telescopes subsequently constructed: the list includes the 6-meter reflector of the U.S.S.R., the Kitt Peak 84-inch and 150-inch telescopes, the 158-inch telescope of the Cerro Tololo Interamerican Observatory, the 153-inch Anglo-Australian telescope, the 140-inch telescope of the European Southern Observatory, and others too numerous to mention. Complete engineering drawings of the 48-inch Schmidt telescope at Palomar were given to other observatories, so that three or more near-duplicates are now productive in various parts of the world.

Among Bowen's later contributions are authoritative studies of the optical design of large reflectors and of spectrographs. In these articles, he showed that five meters is about the largest single passive primary mirror that can feasibly be constructed and supported, and he emphasized the extreme importance of selecting a site with excellent seeing for any large telescope. He went on to optimize the optical design of three very modern instruments that have been constructed since his retirement as director in 1964. These are the 60-inch reflector at Palomar Mountain (1969), the 40-inch Swope telescope (1970), and the 100-inch (2.5-meter) Irenée du Pont telescope of the Carnegie Institution's Las Campanas Observatory in Chile. The performance of this last instrument is especially noteworthy, for it yields at the Cassegrain focus a field of critically good definition, 2.1 degrees in diameter, with seeing-limited images over the whole of a single glass plate 50 centimeters on a side. Bowen and Vaughan accomplished this by adding a Gascoigne correcting lens to a Ritchey-Chrétien system and by adopting a moderate concave bending of the plate. This highly successful design climaxed Bowen's contributions to the evolution of the wide-field, general-purpose telescope.

The classic treatment on the design of stellar spectrographs for maximum efficiency is to be found in Bowen's 1962 article (see bibliography). He further improved spectrographs by devising several ingenious adaptations of the Schmidt camera, using solid or semisolid camera optics. Typically, only two days before his unexpected death, Ike discussed at lunch with several staff members a new spectrograph that they hoped he could design.

Bowen's work was characterized by penetrating physical insight, thoroughness, and integrity; it was generally held that when he provided the answer to a problem, that answer was right. Associates came to appreciate his inner enthusiasm and his satisfaction with solid results, but these qualities never blossomed into exuberance. Ike could be firm in his insistence on adhering to principles and procedures that had proved to be correct, but he was a most considerate and unselfish individual who held the deep respect and friendship of those who knew him well.

He was elected to the National Academy of Sciences in 1936.

Ira Bowen and Mary Jane Howard were married in 1929; there were no children. Mary Bowen pursued a career as a child psychologist. With her husband, she provided warm hospitality to numerous gatherings at their home in Altadena. Bowen himself read widely in history, especially the history of physics and astronomy, and he was a collector of rare and early editions of scientific books. He also had a substantial collection of ancient coins.

Many honors came to Ira Bowen during his lifetime. In the words of Caryl Haskins, "These were the formal tributes to a life of extraordinary service to science and to scientific organization and administration. But perhaps the most permanent of all will be the living inspiration, both professional and personal, that he brought to three generations of colleagues and students and associates, and their living regard and attachment for him and for his wife Mary."*

THE AUTHOR HAS HAD the benefit of biographical notes provided by the National Academy of Sciences, of a transcript of interviews from the American Institute of Physics, and of articles written by L. H. Aller, J. L. Greenstein, C. P. Haskins, A. McKellar, O. C. Wilson, and A. H. Vaughan.

*Yearbook, American Philosophical Society, 1973: 117.

HONORS AND DISTINCTIONS

DEGREES

A.B., Oberlin College, 1919
Ph.D., California Institute of Technology, 1926
Sc.D. (honorary), Oberlin College, 1948
Ph.D. (honorary), University of Lund, 1950
Sc.D. (honorary), Princeton University, 1953

PROFESSIONAL APPOINTMENTS

Morrison Research Associate, Lick Observatory, 1938–1939
Director, Mount Wilson Observatory, 1946–1948
Director, Mount Wilson and Palomar Observatories, 1948–1964
National Astronomical Observatory Advisory Panel, 1953–1957

PROFESSIONAL AND HONORARY SOCIETIES

National Academy of Sciences, 1936
American Academy of Arts and Sciences, 1939
American Philosophical Society, 1940
Royal Astronomical Society, London (Associate), 1946–1973
Astronomical Society of the Pacific, President, 1948

AWARDS

Draper Medal, National Academy of Sciences, 1942
Potts Medal, Franklin Institute, 1946
Rumford Premium, American Academy of Arts and Sciences, 1949
Ives Medal, Optical Society of America, 1952
Catherine Wolf Bruce Gold Medal, Astronomical Society of the Pacific, 1957
Distinguished Service Staff Member, Carnegie Institution of Washington, 1964–1973
Henry Norris Russell Lecturer, American Astronomical Society, 1964
Gold Medalist and George Darwin Lecturer, Royal Astronomical Society, 1966

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atoms of phosphorus (P III), sulphur (S IV) and chlorine (Cl V). Phys. Rev., 25:600–605.
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With R. A. Millikan. Relations of PP' groups in atoms of the same electronic structure. Phys. Rev., 26:150–64.
With R. A. Millikan. Series spectra of the two-valence-electron atoms of boron (B II) and carbon (C III). Phys. Rev., 26:310–18.

1926

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