RevMexAA (Serie de Conferencias), **12**, 1–7 (2002)

PIONEER NEBULAR THEORISTS FROM ZANSTRA TO SEATON: AND BEYOND

D. E. Osterbrock

UCO/Lick Observatory, UC Santa Cruz, USA

RESUMEN

Se presenta una breve historia sobre los astrónomos estadounidenses que hicieron la teorí sobre las nebulosas gaseosas, enfatizando el conocimiento observacional que es requisito previo de la mayor parte de las teorías. Herman Zanstra e Ira Bowen fueron los más importantes en abrir el campo. Donald Menzel y sus estudiantes, especialmente James Baker, Leo Goldberg y Lawrence Aller, fueron importantes en el desarrollo posterior. Henry Norris Russell puso a andar la astrofísica nebular y varios más, incluyendo a Bengt Strömgren, Lyman Spitzer, Iosif Shklovsky y Michael Seaton, también hicieron contribuciones importantes.

ABSTRACT

A brief history of theoretical nebular astrophysics, particularly in USA, is presented. The importance of observational knowledge of objects that actually exist is emphasized as a prerequisite for most theories. Herman Zanstra and Ira Bowen were the two most important theorists in opening the field. Donald Menzel and his students, especially James Baker, Leo Goldberg, and Lawrence Aller, were quite important in the further development of it. Henry Norris Russell started nebular astrophysics rolling, and several other later theorists, including Bengt Strömgren, Lyman Spitzer, Iosif Shklovsky and Michael Seaton, also made important contributions to it.

Key Words: **ATOMIC PROCESSES — HISTORY AND PHILOSOPHY OF ASTRONOMY — H II REGIONS — PLANETARY NEBULAE — REFLECTION NEBULAE**

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

1. INTRODUCTION

We all have some interest in the past, and especially in our own past, the past of our family, our country, our world, our science, our branch of astronomy, and our observatory or institute. How our predecessors got us to where we are today is interesting to every one of us, and generally speaking, the older we get the more attention we pay to the past. We try to learn and understand our family's history, and our branch of astronomy's history. Hence as Silvia and Manuel are approaching the age of reason (which we seventy-somethings have finally attained), perhaps it is appropriate for me to present a paper on the history of theoretical nebular astrophysics at this Symposium. My aim is to describe how our field developed, particularly in America; who the individuals were, who made early contributions, and what they did; how they were trained or how they taught themselves.

This paper is mostly about "early" nebular theorists, specially Herman Zanstra, born in 1894, 106 years ago; Ira Bowen, born in 1898; Donald Menzel, born in 1901; Lawrence Aller, born in 1913, and Iosif Shklovsky, born in 1916, 84 years ago.

First, however, I will write about observers. It is important to know the objects any theory is to be about. Planetary nebulae, diffuse nebulae, H II regions, and supernova remnants like the Crab nebula were not predicted theoretically, but were first found in the sky. Most of the physical pictures for theoretical research came from pioneering, often qualitative, observational data (Osterbrock 2001).

2. OBSERVERS

Early observers working with small telescopes and visual spectrographs in Europe, especially Angelo Secchi, Johannes Hartmann, and William Huggins, established that some nebulae have emission lines characteristic of a hot gas. They could not measure the wavelengths of the nebular lines very accurately, but except for Hβ, none of them seemed to coincide with known laboratory lines. James E. Keeler was the first astronomer to use the new largest telescope in the world, the Lick Observatory 36-in refractor on Mount Hamilton, California, on gaseous nebulae. He had an excellent undergraduate education in physics at Johns Hopkins University, several years experience working as Samuel P. Langley's assistant at Allegheny Observatory, and a year in Germany as a graduate student at Heidelberg and Berlin. Keeler started working for the Lick Trust in 1886, two years before the telescope was completed, and designed a large visual spectrograph, well matched to it. It could be used with either a Rowland grating or a prism as the light disperser. With this instrument, beginning soon after the Lick refractor went into operation, Keeler measured very accurate wavelengths for the two strong green nebular lines N_1 and N_2, and showed conclusively that they were not known in terrestrial laboratory spectra. This ruled out, among others, a purported identification of one of them with a MgO band, suggested by Huggins. Keeler also measured radial velocities at various points within the Orion nebula, but could not detect any spatial variations. He estimated an upper limit in the bright Huyghenian region of 6 to 8 km s^{-1} to any such differential internal radial velocities. Keeler made all these spectroscopic measurements visually.

In 1891 he left Lick to become director of Allegheny Observatory, succeeding Langley. There, with a little 13-in refractor and a photographic spectrograph he had designed and had built, he continued nebular research. Soon after William Ramsay isolated helium in the laboratory in 1895, Keeler identified several He I emission lines in planetary nebulae and Orion, and in absorption in OB stars. He also noted and investigated observationally the spatial variations in the intensity ratio $(N_1 + N_2)/\mathrm{H}\beta$. Then in 1898 he returned to Lick as its second director, succeeding Edward S. Holden. Keeler took over the Crossley 36-in reflecting telescope, a gift to the observatory which had been considered a white elephant, improved it mechanically, and embarked on a program of direct photography. With it he revealed the true forms of many spiral "nebulae" (actually galaxies), planetary nebulae, and fainter regions in diffuse nebulae as they had never been seen before. The $f/5.7$ Crossley was by far the fastest large telescope that had been used photographically up to then, and with it Keeler proved to many skeptical astronomers that reflectors, not refractors, were to be the important research instruments of the future. Tragically, Keeler died in 1900 at the early age of 42, his promise unfulfilled (Osterbrock 1984).

Edward E. Barnard, who was born and grew up in poverty in the defeated South after the Civil War, had practically no formal education, but became an expert photographer in his youth, and then an outstanding visual observer. He was exactly the same age as Keeler, and they were good friends on the Lick staff, where Barnard started wide-field photography of the Milky Way, using relatively fast commercial lenses. Unable to coexist with Holden, his director at Lick, Barnard left to join the Yerkes Observatory staff in 1895, even before its 40-in refractor was completed. He continued wide-field astronomical photography there with the specially made Bruce camera, relatively fast but with bad astigmatism. Barnard's photographs revealed huge diffuse nebulosities, and dark clouds in the Milky Way which he ultimately realized were due to interstellar extinction. The cloudy, complicated structure which these pictures showed ruled out the idea of a smoothly stratified, homogeneous layer of interstellar matter pervading the Galaxy, although several theorists were slow to grasp that fact (Sheehan 1995).

W. W. Campbell, who had done his undergraduate studies in engineering and astronomy at the University of Michigan and then became an instructor there, worked at Lick as a young volunteer assistant to Keeler in the summer of 1890. He learned spectroscopy on the job, and when Keeler departed for Allegheny Observatory in 1891, Holden hired Campbell to replace him on the Lick staff. He immediately began rebuilding Keeler's visual spectroscope into a photographic instrument; it was clearly the wave of the future. Within a few years Campbell had a better spectrograph built, optimized for radial-velocity observations, which he made his specialty. After Keeler's death, Campbell became the director of Lick, and converted it into a data factory that churned out accurate radial velocity measurements, mostly of stars.

Campbell also measured photographically still more accurate wavelengths of N_1 and N_2. He raced Keeler in identifying more He I lines in nebulae and OB stars. Later, in their huge radial-velocity catalog, Campbell & Moore (1918) included many bright emission-line nebulae, and detected the splitting of the lines in planetary nebulae due to expansion.

William H. Wright had an undergraduate education in mathematics and astronomy at Berkeley, then spent a year as a graduate student with George Ellery Hale at Chicago before Yerkes Observatory was completed. He joined the Lick staff in 1895, where he stayed until he retired fifty years later. At Lick, Wright measured accurate wavelengths of many unidentified nebular emission lines, later understood as "forbidden". He also took slitless spectra of a number of planetary nebulae, producing images which showed the differing stratifications of different lines about the central star, which we now understand in terms of ionization potential (Wright

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

1918). With the newly aluminized Crossley reflector in 1934 (Wright 1934a,b), he obtained ultraviolet spectra of bright planetaries showing the "mutilated multiplets" of O III and N III, now understood as the Bowen resonance-fluorescence lines.

Vesto M. Slipher, who had earned a bachelor's degree in traditional astronomy and mathematics at Indiana University, went to work at Lowell Observatory in 1901. He taught himself spectroscopy, with a little help from Campbell at Lick, and at Lowell showed that the "continuous" spectra of nebulae actually have the same absorption-line spectra as their "exciting" stars, and are thus "reflected" starlight scattered by particles (Slipher 1913, 1916).

Heber D. Curtis studied Greek, Latin, Sanskrit and other ancient languages at the University of Michigan; then with a bachelor's degree taught classics at two little colleges in California. Both had small but good refracting telescopes, and he became interested in astronomy. As a re-entry student with a wife and two small children he earned a Ph. D. in two years at the University of Virginia, and then joined the Lick faculty. There Curtis did every kind of research, but from 1908 on with the Crossley reflector, still further improved since Keeler's time, he photographed planetary and diffuse nebulae, studied their forms, and showed that many of them were similar objects seen in different projections. He found that they all have faint, blue central stars (Curtis 1918).

Edwin Hubble was an undergraduate student at the University of Chicago, then a Rhodes Scholar at Oxford for three years, and then a graduate student back at Yerkes Observatory, where he did his Ph. D. thesis on "nebulae" (most, but not all of them, galaxies). After serving as an officer in the American army during World War I, he joined the Mount Wilson Observatory staff in 1919. There, in his earliest research with the 60-in and 100-in reflectors he studied diffuse nebulae observationally. Hubble (1922a,b) showed that the exciting stars of emission nebulae are very hot OB stars, while reflection nebulae have only later (cooler) B type stars in them.

3. THEORISTS

A continuing problem for nebular theorists was numerical calculating, done in the pioneering days with slide-rules, log tables, or electro-mechanical calculating machines. The earliest theorists tried to find analytic solutions, using very simple interpolation formulae for opacity (in stellar interiors and nebulae), emission coefficients, scattering cross sections, etc. E. A. Milne in England exemplified this approach, which was not very successful for nebular problems. The strongest limitation on theoretical nebular research was generally the need for more computing power, rather than any lack of ideas.

Henry Norris Russell, who had done his undergraduate and graduate work at Princeton University, and then spent two years in England as an assistant at Cambridge, became the outstanding astrophysical theorist and problem solver in America. After World War I he spent parts of most summers in Pasadena. In 1922, knowing of Hubble's results, Russell published a paper in which he concluded that emission nebulae around hot OB stars probably are "excited" either by "etheral" (ultraviolet) or "corpuscular" (fast particles) radiation (Russell 1922).

Herman Zanstra, the Dutch theorist who established photoionization as the mechanism of nebular excitation, studied chemical engineering, not astronomy, as an undergraduate at the Delft Institute of Technology. But he loved theoretical physics, and after graduating in 1917 he taught in a high school, and wrote and published a paper on his own theory of relativity in 1921. This got Zanstra to the University of Minnesota, where he expanded his paper into a Ph. D. thesis in 1923, and then obtained an NRC postdoctoral fellowship. He went to Hamburg to work under Wolfgang Pauli on his own "fundamental" theory linking gravitation and electromagnetism, which was unsuccessful.

But at Hamburg astronomer Walter Baade urged Zanstra to work on Russell's suggestion that ultraviolet radiation from a hot star could "excite" a nebula to emit line radiation. Baade first suggested resonance fluorescence in the Lyman lines might be the mechanism, but when Zanstra did the theory, based on the new quantum mechanics, he found it was insufficient. Baade then suggested photoionization followed by recombination, because Hubble had seen the Balmer recombination continuum in one of his spectra of a nebula. Zanstra showed that this mechanism did work, gave an oral paper on it at an American Physical Society meeting in Stanford in 1926 (he was then a postdoc at Caltech), and published a full paper on it in the ApJ (Zanstra 1926, 1927).

Zanstra then joined the University of Washington faculty in Seattle, where he taught for two years, and worked one summer at the Dominion Astrophysical Observatory in Victoria, B. C. Assisted at its 72-in reflector by H. H. Plaskett, he applied his theory to determine the effective ("Zanstra") temperatures of the central stars of planetary nebulae (Zanstra 1928). He published this work in full in a DAO publication which he completed in 1929, but it did not appear until two years later (Zanstra 1931a). That same year he published two important theoretical papers in Germany, outlining in theoretical terms much of the physical picture of planetary nebulae which we still have today (Zanstra 1931b,c). Among other ideas, he interpreted the observed splitting of lines in planetaries as resulting from expansion.

Zanstra was a shy, gentle, unassertive person, who drifted from one temporary research job to another, and was reduced to teaching physics in a college in South Africa during World War II. At last in 1946 he was appointed professor of astronomy in Amsterdam, where he continued nebular research until he retired in 1959, always applying theoretical ideas and calculations to actual observed nebulae (Zanstra 1961; Plaskett 1974).

Ira ("Ike") Bowen, born in upstate New York but with a strong New England background, studied for three years in a tiny Methodist seminary (where his mother was a teacher) before transferring to Oberlin College, from which he graduated in 1919. Then he went to the University of Chicago, where as a physics graduate student he was Robert A. Millikan's assistant in vacuum spectroscopy. When Millikan moved to Caltech in 1921, Bowen went with him and did all his lab work. The two of them had published 25 joint papers by 1926, when Bowen got his Ph. D. and joined the faculty. He read the astronomy textbook by Russell, Dugan and Stewart, and learned of the unidentified "nebulium" lines, which Russell had suggested must be emitted only under conditions of very low density. Bowen quickly came up with the idea that they were "forbidden" transitions in the very ions of O, N, Ne, S, etc. which he and Millikan had been studying in the lab. From the energy levels they had determined, Bowen could calculate the wavelengths of such lines and found them in excellent agreement with the accurate values Keeler, Campbell, and Wright had measured.

Bowen's paper, published in 1928, explained in clear, physical terms how the excess energy acquired by an electron in a photoionization process would be shared with other electrons, and thus lead to collisional excitation of these lines (Bowen 1928).

Bowen became more and more involved in astronomy. He explained the "mutilated multiplets" of O III and N III that Wright had observed in terms of an accidental coincidence of the excitation energies of a single level of O III and He II Lyα. Bowen had his first observational experience as a research fellow at Lick Observatory in 1938. There with Arthur B. Wyse as his collaborator, he did photographic photometry of several planetaries and applied his theoretical ideas to estimating relative abundances of the observed ions to hydrogen. They used recombination of C, N, O, and other ions as much as they could in this work (Bowen & Wyse 1939). After Bowen returned to Caltech, Wyse, the most theoretically oriented astronomer on the Lick staff, continued this work on ten more nebulae, but he was killed in World War II soon after he published these results (Wyse 1942). Zanstra and Bowen were the two outstanding pioneers of the astrophysical study of gaseous nebulae, the former more a mathematical theorist, the latter more an observational theorist.

Donald Menzel, born in Colorado, earned his undergraduate and master's degrees at the University of Denver before going to Princeton, where he did his Ph. D. thesis with Russell. Menzel did much of the research for it at Harvard, interpreting the spectra of cooler stars in terms of ionization theory. In 1926 he was hired as the first trained astrophysicist on the Lick staff, to reduce and interpret Campbell's solar eclipse data. Like his teacher Russell, Menzel was interested in every branch of astrophysics. He quickly published a long review paper on planetary nebulae, which contains the idea of the "Zanstra method". On this basis Menzel later claimed it should be called the "Menzel-Zanstra" method, but in fact his paper actually concluded that there are not enough ionizing photons, and went on to discuss fast particles as the excitation mechanism (Menzel 1926). He may have seen the abstract of Zanstra's oral paper, published in the Physical Review early in 1926. Years later Menzel (1973) revealed that originally he had written that photoionization did work, and derived temperatures near 40,000 K, but changed his paper before publication at the insistence of Wright and other Lick astronomers, who could not believe such high-temperature stars existed.

In working up the eclipse results, Menzel became very familiar with low-density astrophysics. He was bright and well tied in to the Berkeley physics department, but the Lick astronomers ignored (Wright) or actively resisted (Director Robert G. Aitken) his theoretical ideas. Then, in 1932, Menzel left for a faculty position at Harvard, still doing mainly solar research at first. But in 1935 he began a long series of papers on physical processes in gaseous nebulae, aimed at quantitative results. He and his collaborators, who included Chaim Pekeris, George Shortley, Malcolm Hebb, and Harvard graduate students Leo Goldberg, Lawrence Aller, and James Baker, published 18 papers in all in this series. They had an important impact on the field of nebular astrophysics (Menzel & Pekeris 1935; Menzel 1937; Aller & Menzel 1945).

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

Louis Berman, born in London of immigrant parents from Lithuania, was brought by them to Minnesota, where he grew up and earned his A.B. and A.M. in astronomy, Then as a graduate student at Lick Observatory, Berman did his pioneering Ph. D. thesis on spectrophotometry of nebulae, the first on that subject in an American university. He had heard Zanstra give a colloquium on his work at Berkeley, and thought it was somewhat boring, but Menzel brought the subject alive for him and encouraged him to work on it. Berman took slitless spectra of planetary nebulae at the Crossley reflector, calibrated them (as Wright, who also supervised his thesis, had not done earlier), and discussed them in terms of ionization theory. Berman (1930) derived temperatures, densities and abundances in this early period of nebular research. After receiving his Ph. D. in 1929, he taught at Carleton College for a few years, but he longed to get a research position back in California. Although Berman published several papers, one of them a very important analysis of R CrB, which he correctly described as a high-temperature carbon star (Berman 1935), he could only get a full-time teaching job. He also published an important early paper on the velocity distribution of planetary nebulae and their systematic galactic rotation (Berman 1937). Berman remained in contact with Menzel, the Lick astronomers, and Robert Trumpler at Berkeley, and did what research he could in his "spare" time.

Lawrence Aller was fantastically dedicated to astronomy from childhood. As a young boy growing up near the Oregon-California border he began writing letters to George Ellery Hale, Russell, Zanstra, and Menzel. Aller joined the ASP at age 16 when the $5 dues were a major expense to him. When his father took him out of high school to work in his unsuccessful gold mine, young Lawrence ran away from home and arranged to meet Menzel (who was teaching on the campus in 1931) at Berkeley.

Aller took the exam Menzel was giving in his course and did so well that he was admitted to the University of California as a special student. Armin Leuschner, the department chair, found financial support for Aller (including hiring him to work in his yard). He was an outstanding student, completed a B.S. in 1936, and then had one year as a graduate student at Berkeley before following Menzel to Harvard. Aller worked as a summer assistant for Wyse and Nicholas Mayall at Lick in 1937 and 1938, and started observing there for his thesis on nebular astrophysics with Menzel (Aller 1941). He earned his Ph. D. in 1943, and in his long research career at Harvard, Indiana, Michigan, and UCLA he wrote many papers, mostly on applications of nebular astrophysics to observational data (Aller 1995).

Aller pioneered in using "one-point" models of nebulae, with a mean temperature derived from [O III] ($\lambda 5007/\lambda 4363$) and mean electron density from the Balmer continuum, with an estimate of the distance to get the linear size of the nebula. In data-taking he progressed from photographic spectrograms taken with the ancient Crossley reflector to advanced solid-state-detector spectra obtained with the HST and the Keck I (10-m) telescope at Mauna Kea. Aller (1956) wrote the first graduate textbook on nebular astrophysics in English, Gaseous Nebulae, and as shown by his paper at this symposium in collaboration with Siek Hyung, he is still valiantly producing nebular research results, though confined to a wheelchair or walker and partly physically incapacitated as the result of a stroke.

Iosif Shklovsky was born in Imperial Russia, and educated in the Soviet Union after the Bolshevik Revolution. He was an excellent student, who did his graduate work in astrophysics at Moscow University, which during World War II was evacuated far to the east as the German armies invaded Russia. Shklovsky made many important theoretical contributions in solar physics and astrophysics, especially in radio astronomy, active galaxies, quasars, supernovae and their remnants, and synchrotron radiation in the optical and radio regions (Shklovsky 1991).

In 1956 he published the basic ideas that red-giant stars may evolve into planetary nebulae, and of estimating their distances by assuming that their envelopes all have approximately the same mass and mean electron temperature, and expand with the same constant mean velocity (Shklovsky 1956). From the observed surface brightness in an H I recombination line, usually Hβ, it is then possible to estimate the electron density, using the "known" mass to eliminate the nebular radius. The resulting distance depends only weakly on the assumed mass, electron temperature, and "filling factor" of the gas in the nebular volume. This "Shklovsky method" has been widely used, calibrated by whatever independent distance methods are available for specific nebulae.

4. H II REGIONS

Although Keeler, Curtis, Hubble, and other observers had photographed many of the brightest diffuse nebulae on the blue-sensitive plates available in their time, they were unaware of the numerous fainter objects of this type, especially those behind heavily obscuring (and reddening) dust. Only when Otto Struve and his collaborators at Yerkes and Mc-Donald Observatories set up their "nebular spectrograph", basically a large slit with no collimator, working into a distant prism instrument with a small, fast Schmidt camera using film sensitive to Hα and [N II] $\lambda\lambda$6548, 6583, did the many more faint nebulae become apparent (Struve 1937; Struve, Van Biesbroeck, & Elvey 1938; Struve & Elvey 1939). Bengt Strömgren, the brilliant astrophysicist whose father, an old-time astronomer, had been the director of Copenhagen Observatory, was then on the faculty at Yerkes. Earlier he had made important contributions as a theorist of stellar interiors, stellar atmospheres, and Schmidt cameras; now he quickly worked out his theory of idealized H II regions or "Strömgren spheres" about OB stars in uniform, homogeneous interstellar matter. It included the dependence of the nebular radius on the photon-luminosities of the "exciting stars" beyond the Lyman limit, and analytic solutions for the degree of ionization near the star and near the edge (Strömgren 1939) In a later paper he included treatments of the case of a cloud photoionized by an OB star outside of it, and of density fluctuations within the ionized region (Strömgren 1948). Later the 48-in Palomar Schmidt, working on red-sensitive plates with a red filter, revealed much more detailed structure within these diffuse nebulae, as well as many more of them (Minkowski 1949).

5. LATER THEORISTS

Lyman Spitzer, who did his Ph. D. thesis at Princeton under Russell, made many important contributions to our understanding of the physics of nebular gas. In particular, he showed how the electron temperature is regulated by the equilibrium between the energy input to it by photoionization, and the energy losses in collisional excitation processes, radiated away as forbidden lines. He also pioneered in theoretical studies of dust in nebulae (Spitzer & Ostriker 1997).

Karl Wurm, a Göttingen Ph. D. with excellent training in physics and astronomy, published the first book in German on the astrophysics of planetary nebulae (Wurm 1951). In it he collected, unified, improved, and discussed much of the nebular physics then known, the assumptions, results, contradictions, etc.

Michael Seaton and his students at University College London did very influential research on planetary nebulae, beginning in 1953. At first Seaton specialized in calculating accurate collision strengths for excitation of forbidden (and permitted) nebular lines. His 1960 review on planetary nebulae was highly physical, unified, and quantitative. Its discussion of the "on-the-spot" approximation exemplifies all these quantities (Seaton 1953; 1960). This review stressed the concept of models of nebulae. After it Seaton and his students, beginning with David Hummer, developed the methods for calculating such models through a step-by-step approach, first for pure H nebulae, then H and He nebulae, then with cooling by C^{3+} in the He^{2+} zone (Hummer & Seaton 1963; 1964). These models were calculated with the University of London Mercury Computer of that time, and used many numerical tables, precalculated definite integrals, etc.

Complete nebular models more or less as we know them today, with point-by-point calculations of the local electron temperature and radiation field (though with fewer elements included, and without dust), began with Robert Hjellming (1966), then a graduate student at Yerkes Observatory, He calculated models of H II regions, using an IBM 1620. W. Leon Goodson (1967), a graduate student at Heidelberg working with Karl-Heinz Böhm, did the first similar planetary-nebula model of this general type. Goodson was a U.S. Air Force pilot spending a "sabbatical" at the German university, and he departed for Vietnam soon after completing this thesis. Further planetary-nebula models of this kind were calculated soon after that by J. P. Harrington (1968), David Flower (1969a,b), and for model supernova remnants like the Crab nebula, with a "hard", power-law input photoionizing spectrum, by Robert Williams (1967).

6. GENERALIZATIONS

The earliest nebular observers had very little formal training, usually at most a bachelor's degree, often in mathematics or engineering, but this had changed to most of them earning a Ph. D. by the 1920's. That was about when theoretical nebular astrophysics began, and nearly all the theorists had Ph. D. training, often in physics. They were all keenly interested in physics and astronomy, although the astronomy came late for several of them. Most of them did research in other fields of astrophysics in addition to their nebular work. Many did some research on stars, the most active field in astrophysics up through the 1960's. Others worked particularly in different areas of low-density astrophysics, such as the chromosphere, comets, and interstellar matter.

All the nebular theorists were exceptionally hard working, and most of them were unusually adept at applying whatever were the most advanced forms of computers available in their times. This written paper, presented in condensed form as a poster at the

Symposium, is based in part on an informal talk I gave at the Workshop on Numerical Simulations of Gaseous Nebulae held at the University of Kentucky in Lexington in May 1994. It has been revised, somewhat expanded, and considerably strengthened on the basis of further historical research I have done since then. I am greatly indebted to Gary Ferland, who organized that Workshop, for his continued encouragement to continue that work and to publish it.

REFERENCES

Aller, L. H. 1941, ApJ, 93, 236

———. 1956, Gaseous Nebulae (London: Chapman & Hall)

———. 1995, ARA&A, 33, 1

Aller, L. H., & Menzel, D. H. 1945, ApJ, 102, 239

Berman, L. 1930. Lick Obs. Bull., 15, 86

———. 1935. ApJ, 81, 369

———. 1937. Lick Obs. Bull., 18, 57

Bowen, I. S. 1928. ApJ, 67, 1

Bowen, I. S. & Wyse, A. B. 1939, Lick Obs. Bull, 19, 1

Campbell, W. W., & Moore, J. H. 1918, Publ. Lick Obs., 13, 75

Curtis, H. D. 1918, Publ. Lick Obs., 13, 75

Flower, D. R. 1969a, MNRAS, 146, 171

———. 1969b, MNRAS, 146, 243

Goodson, W. L. 1967, Z. Astrophys., 66, 118

Harrington, P. J. 1968, ApJ, 152, 943

Hjellming, R. 1966, ApJ, 143, 120

Hubble, E. 1922a, ApJ, 56, 162

———. 1922b, ApJ, 56, 400

Hummer, D. G., & Seaton, M. J. 1963, MNRAS, 125, 437

———. 1964, MNRAS, 127, 217

Menzel, D. H. 1926, PASP, 38, 295

———. 1937, ApJ, 85, 330

———. 1973, Mem. Soc. R. Sci. Liège, 5, 491

Menzel, D. H., & Pekeris, C. 1935, MNRAS, 96, 77

Minkowski, R. 1949, PASP, 61, 151

Osterbrock, D. E. 1984, James E. Keeler: Pioneer American Astrophysicist and the Early Development of American Astrophysics (Cambridge: Cambridge University Press)

———. 2001, J. Hist. Astron., 32, 93

Plaskett, H. H. 1974, QJRAS, 15, 59

Russell, H. N. 1922, Proc. Natl. Acad. Sci., 8, 115

Seaton, M. J. 1953, Proc. R. Soc. London A, 218, 400

———. 1960, Rep. Prog. Physics, 23, 313

Sheehan, W. 1995, The Immortal Fire Within: The Life and Work of Edward Emerson Barnard (Cambridge: Cambridge University Press)

Shklovsky, I. 1956, Soviet Astron., 33, 515

———. 1991, Five Billion Vodka Bottles to the Moon (New York: W. W, Norton & Co.)

Slipher, V. M. 1913, Lowell Obs. Bull., 2, 26

———. 1916, Lowell Obs. Bull., 2, 155

Spitzer, L., & Ostriker, J. P. 1997, Dreams, Stars, & Electrons: Selected Writings of Lyman Spitzer, Jr. (Princeton: Princeton University Press)

Strömgren, B. 1939, ApJ, 89, 526

———. 1948, ApJ, 108, 242

Struve, O. 1937 ApJ, 86, 613

Struve, O., & Elvey, C. T. 1939, ApJ, 89, 119

Struve, O., Van Biesbroeck, G., & Elvey, C. T. 1938, ApJ, 87, 559

Williams, R. E. 1967, ApJ, 147, 556

Wright, W. H. 1918, Publ. Lick Obs., 13, 75

———. 1934a, Lick Obs. Bull, 17, 1

———. 1934b, PASP, 46, 280

Wurm, K. 1951, Die planetarischen Nebel (Berlin: Akademie-Verlag)

Wyse, A. B. 1942, ApJ, 95, 356

Zanstra, H. 1926, Phys. Rev., 27, 644

———. 1927, ApJ, 65, 50

———. 1928, Nature, 121, 791

———. 1931a, Publ. Dominion Astrophys. Obs. Victoria, 4, 209

———. 1931b, Z. Astrophys., 2, 1

———. 1931c, Z. Astrophys., 2, 329

———. 1961, QJRAS, 2, 137

D. E. Osterbrock: UCO/Lick Observatory, University of California, Santa Cruz CA 95064, USA (don@ucolick.org).