

ATOMIC SPECTROSCOPY AND ASTROPHYSICS

In this personal retrospective, the author shows how laboratory work on the interaction between matter and radiation unites physics and astronomy and has frequently led to major discoveries in astrophysics.

Leo Goldberg

Leo Goldberg (1913–87) was Higgins Professor of Astronomy emeritus at Harvard University. This article is based on a plenary talk that he gave in Cambridge, Massachusetts, on 18 May 1987 at a meeting of the APS division of atomic, molecular and optical physics. Alexander Dalgarno, a professor of astronomy at Harvard University, helped prepare this article and select the illustrations.

Most of our knowledge of the universe has come from the study of spectral lines emitted by astronomical objects. The wavelengths of the lines identify unequivocally the elements that are present, their states of ionization and the velocities with which they are moving. Thus the shifts to lower energy of the spectral line wavelengths for distant galaxies—the redshifts—demonstrate that the universe is expanding (see the article by Ralph Alpher and Robert Herman on page 24). The intensities of spectral lines give us information on the densities, temperatures and abundances of the elements in the environment in which the lines are emitted or absorbed. However, to determine these physical quantities we also need to know atomic and molecular parameters such as transition probabilities and oscillator strengths, so it is no accident that much of laboratory spectroscopy has come to be known as laboratory astrophysics. Millions of spectral lines are useful as diagnostic probes, and the assembly of reliable tables of atomic and molecular data is an essential part of astronomical spectroscopy.

Atomic spectroscopy and astronomical spectroscopy have always been closely linked, each depending on the other for support and inspiration. The needs of astrophysics have inspired much of laboratory spectroscopy, and history is full of examples of laboratory experiments that led to major discoveries in astrophysics. Two of the most famous are Ira Bowen's identification of the nebular lines and Bengt Edlén's discovery of the high temperature of the solar corona, both of which derived from the spectroscopy of ionized atoms. More recently, molecular spectroscopy, largely in radioastronomy, has revealed the presence of more than 60 interstellar molecules in massive molecular clouds where stars are born.

Exploring new spectral regions has always led to unexpected discoveries in astronomy. It is also at least plausible that any kind of interaction between matter and radiation that is observed in the laboratory or predicted by theory is occurring somewhere in the universe, although it



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Interstellar matter, consisting of gas and dust. Absorbing material hides background stars in the lower half of this photograph of the Horsehead nebula. The red light is due to hydrogen emission in the visible. The blue light is reflected from dust near hot blue stars. (Photo courtesy of David Malin.)

may be unobservable because it is buried deep within a star or because its electromagnetic signature is too weak to detect.

This article traces the evolution of atomic spectroscopy as a central part of astrophysics. To be sure, laboratory astrophysics is no longer limited to spectroscopy. Atomic and molecular processes play a major role in determining the ionization structure and the thermal balance in astrophysical plasmas. Nuclear physics is vital to understanding stellar and galactic evolution and cosmological nucleosynthesis. The physics of the early universe is particle physics. Solid-state physics is needed to understand the structure of grains and their role in the formation of stars and planetary systems; condensed matter physics determines the behavior of neutron stars. Most of the universe is an ionized plasma. The universe is everywhere in a restless dynamic state whose interpreta-

tion requires a deep knowledge of fluid mechanics in the presence of magnetic fields. Yet in the final analysis, astronomical phenomena, with the important exception of cosmic rays, rely on spectroscopy to carry their messages to Earth.

Beginnings of laboratory astrophysics

The modern era of laboratory astrophysics owes its beginnings to George Ellery Hale, who was the first astronomer to build a physical laboratory as an integral part of an astronomical observatory. When he founded the Mount Wilson Observatory in 1904, Hale set out both to build the largest solar and stellar telescopes in the world and to interpret celestial phenomena by means of laboratory experiments. The work in spectroscopy at Mount Wilson is a good example of what laboratory astrophysics was in the first quarter of the 20th century.

At the outset, research at the observatory centered on the Sun and sunspots. Hale and his associates proved that the differences between absorption line strengths in sunspot spectra and those in the spectrum of the normal solar disk are a result of the lower temperature of sunspots. A byproduct of this research was the discovery in sunspot spectra of bands due to molecular compounds such as TiO, MgH, CN and CaH. Hale's discovery in 1909 of strong magnetic fields in sunspots prompted a major laboratory investigation of the Zeeman effect by Harold D. Babcock and others. A byproduct was a measurement of e/m , the charge-to-mass ratio of the electron, that was found to be in excellent agreement with values derived by other methods.

During the next ten years, the Mount Wilson laboratory provided an experimental basis for the theory of excitation and ionization and for the analysis of spectra by "terms" (later known as energy levels), which was just beginning. Arthur S. King embarked on a long-range program of temperature classification of lines in the spectra of metals in electric furnaces and in spark discharges. He assigned each spectral line a temperature class according to whether it was strengthened, weakened or left unchanged by temperature variations. Other experiments demonstrated that the degree of ionization decreases with increasing pressure; this is especially important in distinguishing between giant and dwarf stars based on their spectra alone.

By the early 1920s, the development of quantum theory and the derivation of the Saha ionization equation led to the discovery, by Ralph H. Fowler and Edward A. Milne in England and Cecilia H. Payne at Harvard, that the progressive changes in stellar spectra along the spectral classification sequence could be explained in the first approximation by a monotonic decrease in temperature. A new era of quantitative stellar spectroscopy had begun.

At Mount Wilson, major efforts were devoted to precision wavelength measurements and the establishment of standards in the visible and the near infrared. Henry A. Rowland's great table listing the wavelengths of some 20 000 lines in the solar spectrum, published over the years 1895-97, suffered from large random and systematic errors. These were a serious hindrance to identifications of elements and required a wholesale revision. The *Revision of Rowland's Table of Solar Spectrum Wavelengths and Intensities*, which appeared in 1928, was the product of two decades of astronomical and laboratory spectroscopy at the Mount Wilson Observatory. The new wavelengths had a 0.001-Å accuracy, which was needed for several solar programs, notably for determining the redshifts of spectral lines predicted by the general theory of relativity and for measuring solar rotation and circulation and the flow of matter in the neighborhood of sunspots. The revised table also included excitation potentials, temperature classifications and eye estimates of intensities, all data of great value for the analysis of solar and stellar spectra.

Also in 1928, Bowen, a Caltech physicist, having been made aware of the problem by the Mount Wilson astronomers, identified some of the strongest emission lines in the spectra of gaseous nebulae, the so-called nebular lines, as due to forbidden transitions from low-lying metastable levels with p-electron configurations. This discovery drew attention to the astronomical importance of forbidden lines, which became the principal means of measuring temperature and density in gaseous nebulae. The forbidden lines were not observed in the laboratory, but their wavelengths could be computed from differences in the wavenumbers of permitted lines ob-

served in the far ultraviolet. Together with Herman Zanstra's proof that the hydrogen emission spectra of gaseous nebulae are due to fluorescence induced by ultraviolet radiation from nearby hot stars, Bowen's identifications of the nebular lines provided a conceptual model for the physical study of the nebulae.

Birth of theoretical astrophysics

Space research enthusiasts often claim that we have learned more about the universe in the last 20 years than in all of the preceding 400 years. I do not know how discovery can be so quantified, but by any standard it would be hard to match the progress made in the decade of the 1920s. Apart from the discovery of external galaxies and the expanding universe, theoretical astrophysics emerged as a subdiscipline of astronomy around 1920, building on Niels Bohr's atom, Arthur Stanley Eddington's stellar interiors and Meghnad Saha's ionization equation. The physical modeling of astronomical objects created an enormous demand for spectroscopic data, as illustrated by the problem of the chemical composition of the Sun and the stars.

Eddington's modeling of stellar interiors had led him to his famous relationship between the masses M and the luminosities L of stars,

$$L \propto \frac{M^{5.5}}{\kappa_0 R^{0.5}} \mu^{7.5}$$

which agreed beautifully with observation. Here R is the stellar radius, μ the mean molecular weight and κ_0 a physical constant proportional to the opacity.

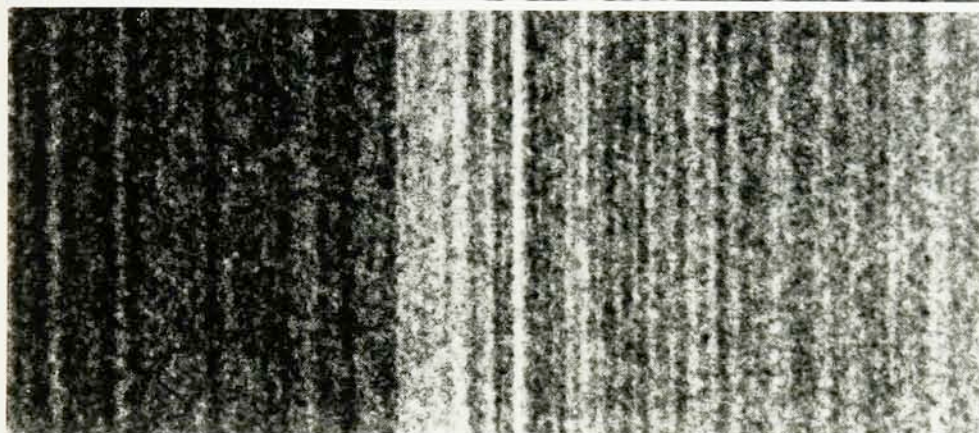
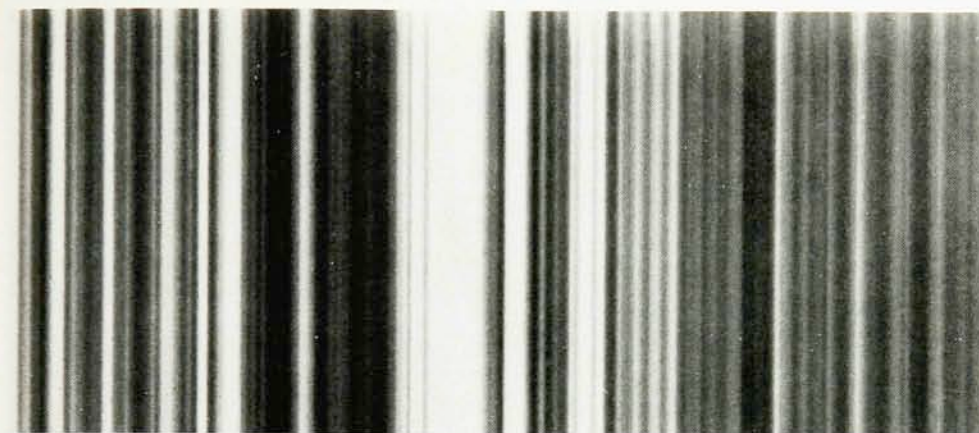
The theory had two unknown parameters: the mean opacity and mean molecular weight of stellar material. For fully ionized hydrogen, which consists of a proton and an electron, the mean molecular weight μ is 0.5, whereas for ionized heavy elements such as iron it is about 2. Eddington chose the larger value, perhaps because of the prevailing view that the abundance ratio of hydrogen to other elements in stars must be similar to that in the Earth's crust. Henry Norris Russell had reached this conclusion back in 1914, when he used the combined intensity of the lines of each element in the solar spectrum as an estimate of relative abundance. The resulting mean molecular weight, together with the observed luminosity, mass and radius for the Sun (a normal dwarf star) and Capella (a giant star), indicated that the required opacity was about 20 times larger than the value given by Hendrik Kramers's law, which was derived from classical theory. Eddington assumed that Kramers's law must be wrong, because the alternative would have been an unbelievably large abundance for hydrogen.

On the other hand, the extraordinary persistence of hydrogen lines over a wide range of spectral classes of stars, especially the very hottest ones, suggested that hydrogen might be enormously abundant in stellar atmospheres. Payne, in her thesis at Harvard, used Saha's new ionization theory, together with what Fowler and Milne called the marginal appearances of absorption lines, to estimate the abundances of elements from stellar spectra. To her surprise, she found that helium and hydrogen were three and five orders of magnitude more abundant, respectively, than all the other elements combined. Russell was asked to judge the thesis. I am indebted to Owen Gingerich for calling my attention to Russell's 14 January 1925 letter to Payne, in which he comments:

There remains one very much more serious discrepancy, namely that for hydrogen, helium and oxygen. Here I am convinced that there is something seriously wrong with the present theory. It is clearly impossi-

1790 Å

1800 Å



1792.6 Å

Solar and laboratory spectra aligned for comparison.

Top: Spectrum of the Sun in the ultraviolet recorded by Richard Tousey (*Q. J. R. Astron. Soc.* **5**, 123, 1964). Bottom: Laboratory spectrum of carbon monoxide at 6000 K taken by Leo Goldberg, William H. Parkinson and Edmond M. Reeves (*Astrophys. J. Lett.* **141**, L1293, 1965). The comparison demonstrates that carbon monoxide is present in the solar atmosphere, where it is an important source of opacity in the ultraviolet region of the spectrum.

ble that hydrogen should be a million times more abundant than the metals, and I have no doubt that the number of hydrogen atoms in the two-quantum state is enormously greater than is indicated by the theory of Fowler and Milne. Compton and I sent a little note to *Nature* about metastable states, which may help to explain the difficulty.

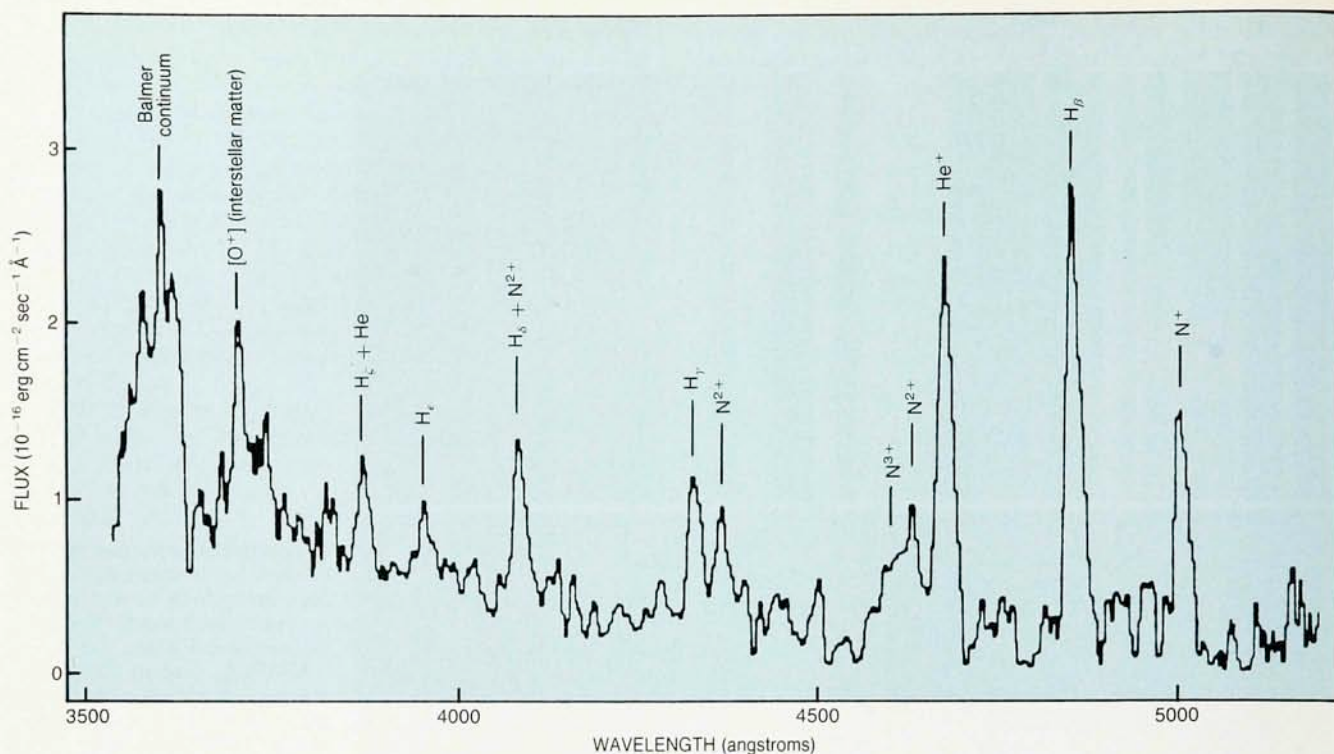
The established view that the compositions of the Sun and the Earth's crust were similar was not easy to dislodge. The hydrogen abundance problem could be solved only by quantitative analysis of the solar spectrum. A number of difficulties stood in the way, the primary one being the absence of transition probabilities. In 1925 Russell and, independently, R. de L. Kronig and Arnold Sommerfeld in Europe made use of the correspondence principle to derive formulas for the relative strengths of lines in multiplets for the case of *LS* coupling—the case in which the interaction between the total orbital angular momentum *L* and the total spin angular momentum *S* is weak. Russell prophesied that his theory might “open the way to a quantitative determination of the relative numbers of absorbing atoms in the solar atmosphere which are involved in the production of Fraunhofer [absorption] lines of different intensities”—and so it did.

The next step was for Russell and his collaborators to use the relative strengths of lines in multiplets to calibrate Rowland's eye estimates of solar line intensities and to determine thereby the relative numbers of absorbing atoms. Then, in 1929, Russell completed the first comprehensive survey of the composition of the Sun's atmosphere, confirming the overwhelming predominance of hydrogen Payne had found earlier. Remarkably, for most

of the approximately 16 elements common to the two investigations, the average difference in the relative abundances was only 0.44 in the logarithm. It is ironic that because of uncertainty in the Boltzmann factor, Russell's value for the abundance of hydrogen was only an order-of-magnitude estimate and hardly more accurate than the value he had earlier persuaded Payne to abandon.

There was still a discrepancy between the abundance of hydrogen found in the solar atmosphere and that derived by Eddington for the interior, but this was soon removed by one of the earliest applications of quantum mechanics to astronomy, when Y. Sugiura computed absorption coefficients for bound-free transitions in hydrogen-like ions. Bengt Strömgren then showed the resulting opacities to be in good agreement with Kramers's law, which meant that one could reconcile the observed and calculated stellar luminosities if stellar interiors were about 98 percent hydrogen and helium, with all the heavy elements making up only 2 percent of the mass.

Still undetermined were the relative proportions of hydrogen and helium. These could not be determined spectroscopically because of uncertainties in the Boltzmann factors of high excitation lines, nor could they be determined from the interior models without a physical theory of hydrogen “burning.” Both problems were soon solved. In 1938 Rupert Wildt discovered the negative hydrogen ion to be the source of continuous opacity in the visible and near-infrared spectra of the Sun and other cool stars. As Strömgren showed soon after, one can use the depth of an absorption line relative to the continuous spectrum to measure the abundance of an element relative



Nova spectrum. Robert E. Williams took this visible-light spectrum of the extended shell around Nova Puppis 1942 (*Astrophys. J.* **261**, 170, 1982). The star has lost material from the outer layers of its atmosphere. This and other spectra show that the jettisoned gas is slowly cooling and deionizing as it moves away from the star.

to hydrogen. Hans Bethe's discovery of the mechanism of hydrogen burning in the same year led to the calculation of the hydrogen-to-helium ratio and to the currently accepted values of 73 percent, 25 percent and 1.7 percent for the proportions of hydrogen, helium and the heavy elements, respectively.

Improving accuracy

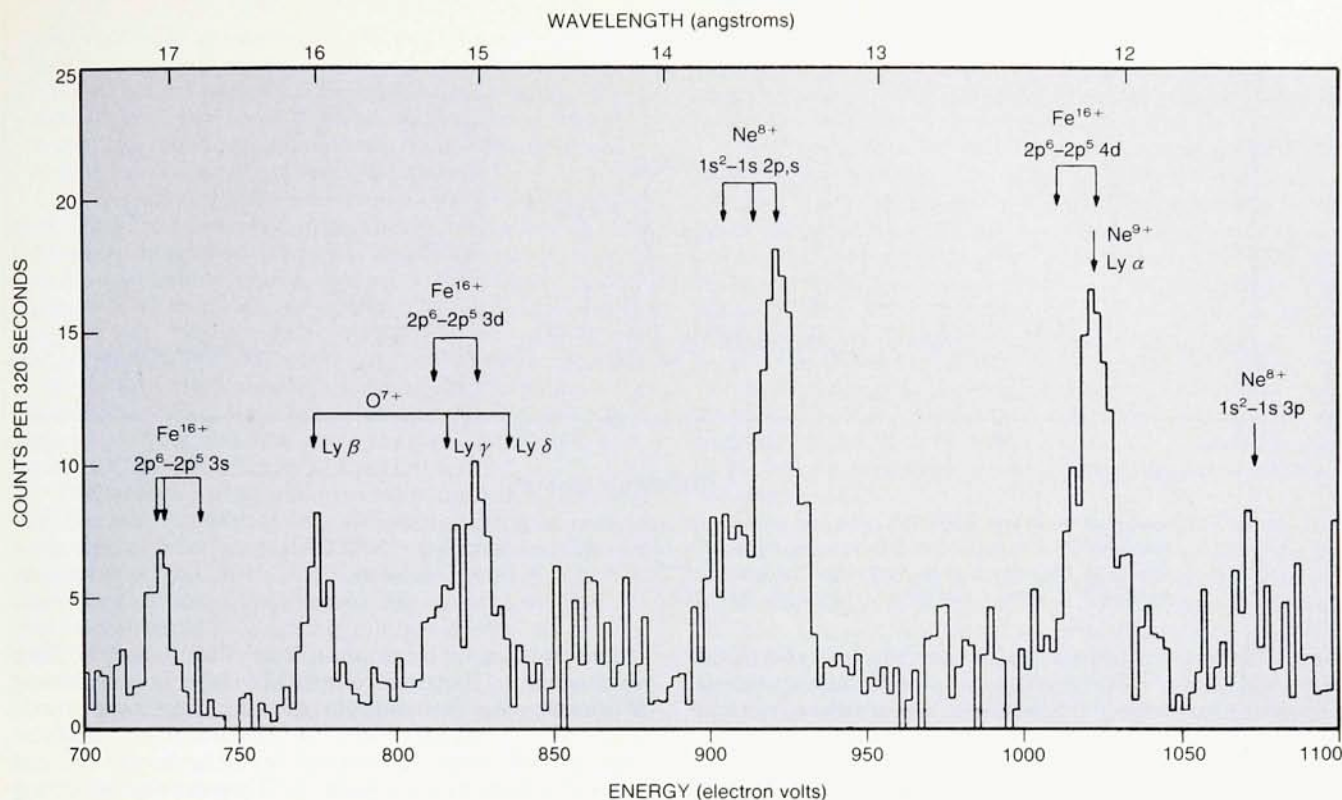
The success of the early models of stellar interiors in the mid-1930s made it important to improve the accuracy of estimates of the Sun's composition and to extend the analyses to other stars. In 1934 Clabon W. Allen in Australia published extensive measurements of the widths of solar lines. This work, together with the identification of hydrogen ions as the source of opacity in the atmospheres of cool stars, laid the basis for realistic theories of the formation of absorption lines. The catch was that apart from hydrogen and a few transitions involving ground state energy levels of heavy elements, transition probabilities were simply unknown. From the theoretical side, quantum mechanics had recently provided a formal solution to the problem, but theoretical physicists by and large did not consider numerical solutions of the wave equation to be of much interest. Likewise, laboratory measurements offered little challenge to experimenters, who were attracted by the emerging field of nuclear physics. And most astronomers were intimidated by the mathematical complexities of the new theory.

Donald H. Menzel was the first American astronomer to promote the large-scale application of quantum mechanics to theoretical astrophysics. Menzel's interest in stellar abundances had been aroused by Russell, his professor at Princeton, and was further stimulated by his association with Payne while he was working on his thesis at the Harvard Observatory in the early 1920s. His passion for theoretical astrophysics had been somewhat

dampened during six years at Lick Observatory, where he was engaged in applying the latest developments in atomic physics to the analysis of William Wallace Campbell's magnificent collection of eclipse spectra. His finding that the density gradient in the solar chromosphere is consistent with a mean molecular weight of $\frac{1}{2}$ was an important factor in persuading Russell of the high abundance of hydrogen. However, the intellectual climate at Lick Observatory in those days was not supportive of theoretical work, and on one occasion the director admonished Menzel to stick to the "facts" and "let the poor benighted British astronomers do the theory, if they so choose."

After Menzel moved to Harvard University in 1932, all restraints on his theoretical activity were lifted. Some of the best physicists in the country were at MIT and Harvard, and Menzel lost no time in meeting with them and directing their attention to interesting problems in astrophysics. First on his agenda was the composition of the solar atmosphere, where the most pressing need was for transition probabilities spanning a wide range of excitation potentials and wavelengths.

As a Harvard undergraduate enamored of astrophysics in 1933-34, I was persuaded by Menzel to fulfill this need by embarking on an extensive program of calculations of relative multiplet strengths in transition arrays. To get me started, he called my attention to a just-published paper by Edward Condon and Charles Ufford giving a generalized method for calculating relative line strengths in *LS* coupling. The paper was rather heavy going for an astronomy student (and for his professor as well). Fortunately Condon, who was then at Princeton, was able to refer me to his former student and collaborator, George H. Shortley, who was spending the year 1933-34 as a National Research Council fellow at MIT. Under Shortley's tutelage, I gained the expertise to calculate relative multiplet strengths for essentially all transition arrays of astrophysical interest. The tables of line



Soft x-ray spectrum of the supernova remnant Puppis A, showing emission lines of hydrogen-like neon and oxygen, in which all electrons but one have been removed, and helium-like neon, in which all but two have been removed. Lines from iron with six electrons removed are also present. The lines carry information on pressure and temperature and on the abundances of elements in the gas. (From P. F. Winkler, C. R. Canizares, G. W. Clark, T. H. Markert, K. Kalaba, H. W. Schopper, *Astrophys. J. Lett.* **246**, L27, 1981.)

strengths, which I published in the *Astrophysical Journal* in 1935, were widely used in solar and stellar abundance calculations until well into the 1950s, when they were superseded by laboratory measurements.

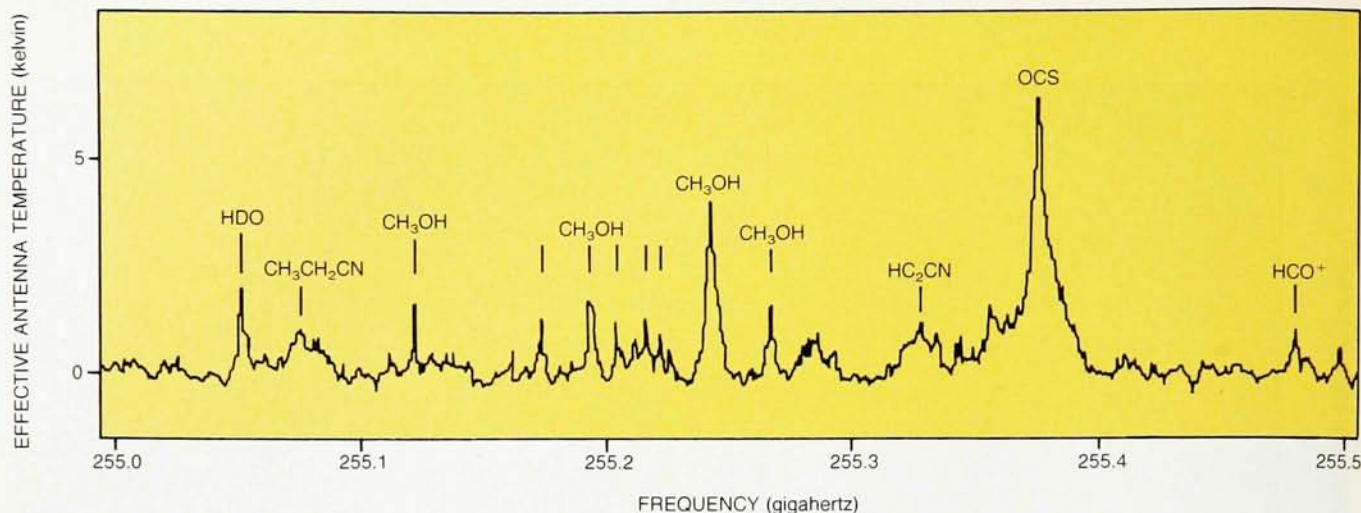
One of the interesting byproducts of my work on multiplet strengths was that my colleagues and I learned how to use the concept of fractional parentage for the calculation of line strengths. A difficulty with the Condon-Ufford method was its inability to distinguish between two or more terms of the same kind occurring in a configuration of equivalent electrons. Menzel and I overcame this difficulty in certain cases by making use of Robert Bacher and Samuel Goudsmit's discovery that one can express the energy levels of the atom arising from shells of equivalent electrons as a linear combination of the energy levels of the ion; the expression involves what are known as coefficients of fractional parentage. Our method, derived entirely by intuition, was valid for all arrays involving equivalent s and p electrons and not more than three equivalent d electrons. In 1952 H. Horie provided a rigorous proof of the method using Giulio Racah's algebra and generalized it for all configurations.

There was still the problem of putting the multiplet strengths on an absolute scale, which required evaluation of the radial wavefunctions for the upper and lower configurations of each transition array. In the 1930s this was a formidable computation with an old-fashioned desk calculator, even for a two-electron atom, to say nothing of the group of atoms between potassium and zinc, which are of special interest to astrophysicists. Nevertheless I had grandiose ideas about making such calculations for the entire series of iron group atoms as a doctoral thesis. John

C. Slater of MIT, whom I consulted, acquainted me with reality by introducing me to M. F. Manning, who had begun a Hartree self-consistent-field calculation for the ground configuration of neutral Fe as a test of Slater's theory of ferromagnetism. He welcomed me as a collaborator, and I labored for two years to complete the project before retreating to the more realistic thesis topic of transition probabilities for the helium atom, in which I was tutored by Philip Morse at MIT.

Redefining 'real' astronomy

My contacts with Shortley helped to arouse his interest in astrophysics, and after his departure for Ohio State University, Menzel and I continued to consult him by correspondence. In April 1937 he wrote describing a colloquium he had given to the astronomers at Ohio State on the physical meaning of dipole and quadrupole radiation. Electric dipole transitions are allowed, but magnetic dipole and electric quadrupole transitions are forbidden and therefore are much weaker. The letter contained some very simple formulas for the magnetic dipole strengths in *LS* coupling, which he had derived from the theory that he and Condon developed in their famous book. He had calculated lifetimes of 2.9 and 16 hours, respectively, for the $J = 2$ and $J = 1$ levels in the ground term of O^{2+} , and he asked "whether this sort of mean life can be of any possible interest in connection with excitation conditions etc. in the nebulae or anywhere. The formulae are so nice but there is no use in printing them ... if they are of no direct use. They do of course simplify a calculation such as Condon's." Shortley went on to say that he was seriously tempted to learn more astrophys-



Molecular cloud spectrum. This spectrum of the molecular cloud Orion A at frequencies between 255.0 and 255.5 GHz shows the presence of the molecules indicated. The HCO^+ line arises from the species containing the isotope O^{18} . (From G. A. Blake, E. C. Sutton, C. R. Masson, T. G. Phillips, *Astrophys. J. Suppl.* **60**, 357, 1986.)

ics: "There seem to be so many interesting problems in that direction." He decided to attend the school at Harvard Observatory that summer, when courses were to be offered by H. P. Robertson on relativity, by Edlén on highly ionized atoms, by Menzel on the solar chromosphere and by Slater on quantum mechanics.

At Harvard that summer, Shortley learned that his calculations of the lifetimes of metastable levels were indeed of utmost importance to astrophysics, where many processes are radiation dominated, not collision dominated as in laboratory experiments. As a result Shortley became an active collaborator in Menzel's series of fundamental papers on "Physical Processes in Gaseous Nebulae." Just before coming to Harvard, Shortley had collaborated with H. A. Robinson in a paper on the mixing of electron configurations, work that also soon proved to have important applications to astrophysics. The paper gave theoretical expressions for the energies of metastable, or long-lived, levels, in a form that made it possible to extrapolate observed ratios of energy level separations along sequences of isoelectronic species to large values of the nuclear charge. From this paper Edlén was able to calculate the wavelengths of forbidden lines arising from p-electron configurations in highly ionized atoms and to identify them with most of the solar coronal lines. The implied temperature of a million degrees came as a great shock to astronomers.

One physicist who was not surprised was Walter Grotrian, who had been convinced for some time, by the appearance of coronal lines in the spectra of certain novae, that the corona must be at a high temperature. His suspicion was confirmed when he found that wavenumber differences between levels in the ground terms of Fe^{9+} and Fe^{10+} , which Edlén had analyzed in the laboratory, coincided with the wavenumbers of two coronal lines. He communicated his findings to Edlén, who proposed identifications for most of the remaining 23 lines and presented overwhelming evidence for their correctness.

Until the end of World War II, astronomers by and large did not regard the calculation or measurement of transition probabilities as "real" astronomy. The International Astronomical Union, for example, at its last prewar general assembly in 1938, limited discussion of spectroscopic data to wavelength and temperature classifications. In 1946, however, the IAU expanded its commission on tables of wavelengths to include a sub-

commission on tables of intensities, with Robert B. King as chairman. King had joined his father at the Mount Wilson physical laboratory in 1934 to begin a systematic program of measurement of the relative oscillator strengths of neutral Ti, to be followed by neutral Fe and other elements in the Fe group. This was the beginning of modern measurements of transition probabilities for astrophysical purposes.

After World War II

With the ending of World War II, astronomers could begin to reach beyond the visible region to the full range of the electromagnetic spectrum. Radioastronomy had already added several new octaves to the observable astronomical spectrum, and soon the placement of astronomical telescopes into Earth orbit and the development of new detectors would extend spectroscopic observations to a vast range of wavelengths: radio, submillimeter, infrared, ultraviolet, x ray and gamma ray.

The first steps, which were the extensions of the solar spectrum to the rocket ultraviolet and out to 2.5 microns in the infrared, lent new importance to the *Tables of Atomic Energy Levels* published by the National Bureau of Standards. In the infrared, for example, we observed the solar spectrum with a lead sulfide detector at the McMath-Hulbert Observatory well before such detectors were used in the laboratory. We used predicted wavelengths both to establish a wavelength scale and to make preliminary identifications. New compilations of atomic energy levels by Charlotte Moore-Sitterly and NBS were issued in 1952, and these, together with the *Revised Rowland Table* and Moore-Sitterly's earlier *Tables of Multiplets of Astrophysical Interest*, were the foundation on which quantitative astronomical spectroscopy was built in the mid-20th century.

Russell was a frequent visitor to NBS, where he continued his active interest in spectroscopy after his retirement from Princeton. The following excerpt from a letter he sent me in May 1947 reflects the excitement generated among astronomers by the latest developments in spectroscopy. Referring to Richard Tousey's recent successful rocket flight above the ozone layer, he wrote:

My job at the Bureau was going over the manuscript of the first portion of the new tables of atomic energy levels which is going to the press very shortly. Mrs. Sitterly is working with her usual excellent judgment

and with very great energy. Menzel dropped in for a few minutes while I was there and we all had a chat. These rocket spectra are certainly fascinating. My first look at one gives me a sense that I was seeing something that no astronomer could expect to see unless he was good and went to heaven!

In the early 1950s astronomers were well supplied with tables of wavelengths and energy levels, but quantitative data on transition probabilities were still extremely meager and inhomogeneous. Just at that time, astronomers were launching a major effort to analyze astronomical spectra. The availability of electronic computers meant that they could replace approximate analytic methods with relatively exact numerical techniques for attacking such problems as stellar atmospheric structure, departures from local thermodynamic equilibrium and, especially, the abundances of the elements.

The local thermodynamic equilibrium approximation, in particular, was seen to be invalid not only in gaseous nebulae but also in giant stars with extended, low-density atmospheres and in the chromospheres and coronas of stars like the Sun. In such cases, the energy level and ion populations could be calculated only with the aid of rate coefficients for collisional and radiative excitation and ionization processes. By itself, the need for these data greatly broadened the scope of laboratory astrophysics.

Whereas in the 1920s the emphasis had been on showing that elemental abundances in the universe were everywhere the same, abundances in the stars were now seen as the end products of nucleosynthesis. In 1957 Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle, motivated by the steady-state theory of cosmology, published their landmark *Reviews of Modern Physics* paper describing nucleosynthesis in stars. Young stars were expected to show a higher ratio of metal to hydrogen than older stars—the metal abundance of a star was an indicator of its age. Moreover, certain stars were found to have abnormally large amounts of such elements as carbon, barium and technetium. There was a rush to assay the chemical compositions of stars as clues to their evolution.

Several years elapsed before laboratory astrophysics caught up with these developments. In the meantime astronomers did the best they could, first by making use of whatever measurements were available, second by using theoretical values and third by deriving empirical oscillator strengths from astrophysical observations. The Sun, for example, could be treated as a laboratory source from which oscillator strengths could be extracted and used to derive stellar abundances. Differential abundances were a means for exploring different classes of stars.

The launching of satellite observatories brought with it another jump in the demand for atomic data. Astronomers now had to interpret phenomena in a wide range of environments: the solar plasma, dark interstellar clouds, novae, supernovae, stellar winds, white dwarfs, neutron stars, black holes in binary systems, nuclei of galaxies, quasars and so on. X-ray astronomers demanded accurate data on collisional excitation and ionization rates, on transition probabilities for highly stripped atoms and on dielectronic recombination and Auger ionization processes. Infrared and submillimeter spectroscopy opened cold interstellar clouds to study, as this required cross sections for the excitation of neutral and ionized atomic and molecular systems by collisions with atomic and molecular hydrogen. These exciting developments in astrophysics helped draw physicists in significant numbers back to atomic and molecular physics.

Compared with the situation 10 or 20 years ago, basic

data are now provided on a relatively large scale. NBS puts out massive compilations and critical evaluations of energy levels, wavelengths and transition probabilities for spectra of astrophysical interest.

But the task is far from over. Support for laboratory astrophysics has been less than adequate in years past, and as a result there are important gaps that need to be filled. In the new wavelength regions accessible to space astronomy, large numbers of lines remain unidentified. Solar opacities that were known well enough to meet the needs of the 1950s are too uncertain to predict such phenomena as neutrino emission and solar oscillations. It is good news, however, that Michael J. Seaton of University College, London, David G. Hummer of the Joint Institute for Laboratory Astrophysics and Dimitri Mihalas of the University of Illinois at Urbana-Champaign have undertaken a major new program of opacity computations.

When I visit the Harvard-Smithsonian Center for Astrophysics and see what goes on within the division of theoretical astrophysics and the division of atomic and molecular physics, I marvel at how far astronomy has come in the last half-century. The beginnings of these divisions date back to 1932, when Menzel arrived at the Harvard Observatory. At that time most astronomers in the United States did not consider quantum mechanical calculations a legitimate subject for astronomical research. I discovered in my files a memo I had received from Harlow Shapley dated 19 February 1935, halfway through my first year as a graduate student:

I am very glad to hear of this new success in the multiplet intensity racket. . . . The work is, of course, still physics, which leads me to inquire if you have thought into the future enough to know whether you should go pure or go astrophysical—explicitly, how about next year? If your study is going more strongly into physical spectroscopy, practical and theoretical, even though the subject matter might be allied to a solar spectrum, should you not consider the possibility of affiliation with Jefferson [Laboratory at Harvard] or the MIT spectroscopic laboratories? I do not know whether it could be managed or not, but now is the time to think and act. . . .

It was not that Shapley had no appreciation for the importance of atomic physics to astronomy. After all, it was he who had brought Menzel to Harvard. He did worry that I would have a problem finding employment in a university astronomy department, which was a legitimate concern. Although theoretical astrophysics was well established as a subdiscipline in Europe, in the United States it was barely tolerated and its accuracy was derided as “equaling zero in the first significant figure.” It was even less respectable to engage in calculations that seemed to have no direct relevance to astronomy other than to provide data in support of theoretical astrophysics. Astronomers usually do not venture into the world of new techniques until their importance to astronomy has been firmly established. Menzel was a rare exception, and his example helped the speedy acceptance of quantum mechanics as a necessary tool of astrophysics.

Bibliography

- L. H. Aller, *Atoms, Stars, and Nebulae*, Harvard U. P., Cambridge, Mass. (1971).
- G. B. Rybicki, A. P. Lightman, *Radiative Processes in Astrophysics*, Wiley, New York (1979).
- D. Mihalas, *Stellar Atmospheres*, W. H. Freeman, San Francisco (1978).