

Diffraction gratings at the Mount Wilson Observatory

'Engines' capable of ruling hundreds of thousands of straight, parallel, equally spaced grooves within tolerances of only a few angstroms have led to advances in fields as different as quantum mechanics and astrophysics.

Horace W. Babcock

The past century has seen major advances in diffraction gratings, motivated by pressure for new and better data in two rather distinct fields: laboratory spectroscopy—aimed at understanding atomic structure and testing quantum theory—and astrophysical spectroscopy—aimed at understanding objects ranging from the Sun and stars to faint sources at the limit of detection. In this historical account I trace some of the hard-won gains in the technology of the ruling machines that produce the gratings, and I touch on the role that larger and higher-quality gratings have played in scientific advances. I focus on the work at the Mount Wilson Observatory, where I directed the diffraction-grating laboratory from 1948 to 1963, but I do so with full recognition of the important contributions made at numerous other laboratories, especially those at The Johns Hopkins University, the Massachusetts Institute of Technology and the Bausch & Lomb Optical Company.

Discontinuous progress

In the 1890s Henry A. Rowland at Johns Hopkins completed his landmark advances in diffraction gratings, building on the contributions of such pioneers as the German physicist Joseph von Fraunhofer and the New

York lawyer Lewis M. Rutherfurd. Rowland not only invented the concave grating, but also constructed three ruling engines and produced a number of plane and concave gratings with widths up to about 12 cm. He used his gratings to produce¹ his "Preliminary table of solar spectrum wave lengths" in 1897.

Equally important were the applications of Rowland's gratings by others. Here one thinks of George Ellery Hale's 1889 spectroheliograph and 1907 discovery of the magnetic field of sunspots at Mount Wilson. In both constructing the instrument and making the discovery, Hale used a plane grating obtained from Rowland's laboratory; this grating came to be known as the "Kenwood grating" because Hale used it at his Kenwood Observatory near Chicago.

As in most fields, progress in diffraction gratings was discontinuous. After Rowland's retirement his best ruling engine was severely damaged by fire, and other misfortunes occurred. Then John A. Anderson, a young faculty member at Johns Hopkins, undertook a serious study of the problems of ruling engines and rebuilt one of Rowland's machines, improving it at the same time. With this engine he ruled several useful gratings, beginning about 1910.

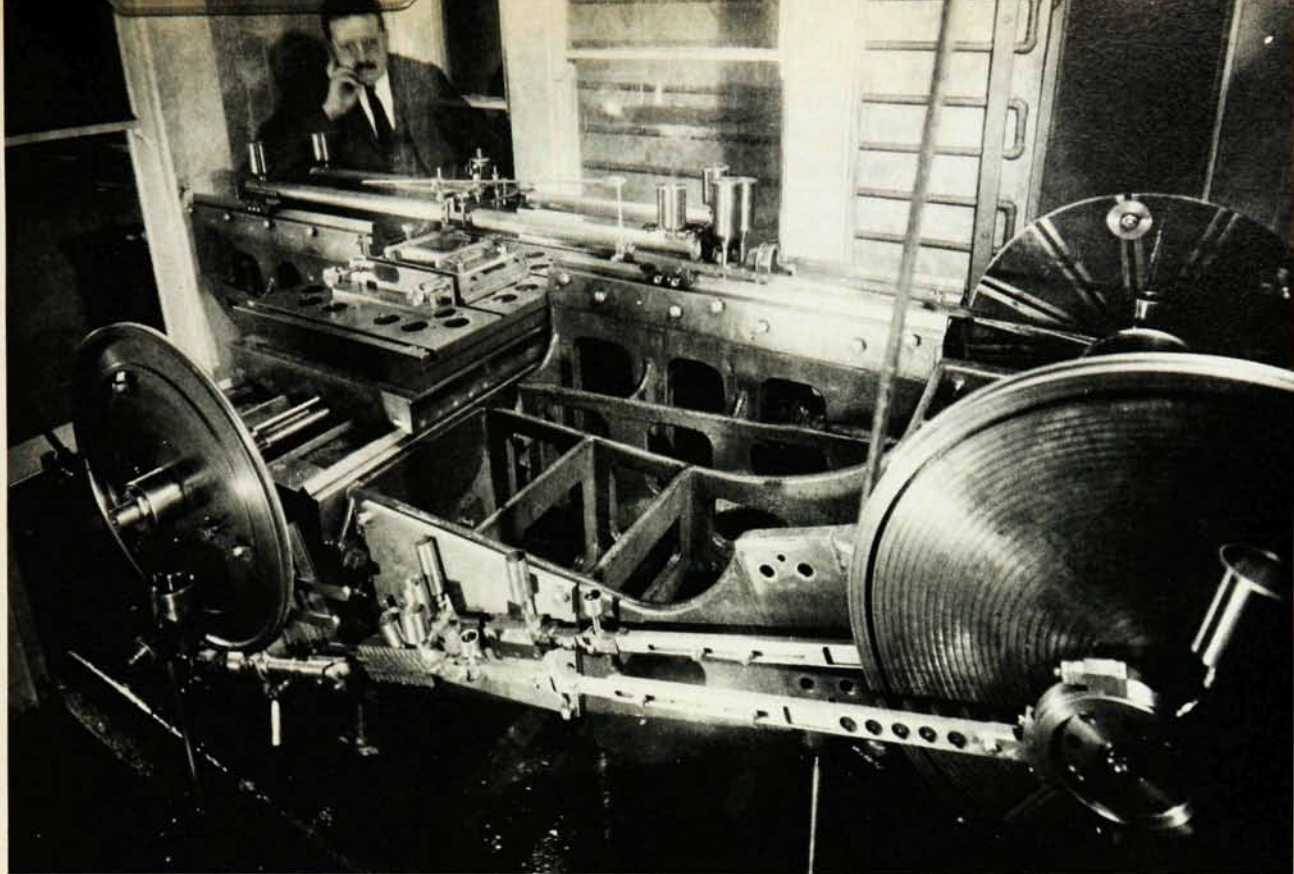
A challenge

The superiority of gratings over prisms—or at least their potential su-

periority—was by this time widely recognized. Prisms suffer losses due to reflections at surfaces and to absorption, especially in the violet and ultraviolet; prisms may have inhomogeneities in the index of refraction and in dispersion; prisms are sensitive to temperature; and finally, the variation of dispersion with wavelength in glass causes serious inconvenience when one makes measurements with prisms. However, gratings in the early 20th century were far from perfect. They had limited resolving power, they often scattered 10–20% of the incident light, and they offered a low luminous efficiency (the ratio of diffracted radiation to incident radiation at a given wavelength). Gratings were also afflicted by strong ghosts, the most common of which are known as "Rowland ghosts." These ghosts are seen most readily in emission-line spectra, as false lines, and are due to periodic errors in the spacing of the grooves on the grating. While some gratings were unsurpassed for their own special purposes, they all fell far short of the theoretical limit on performance. Ruling engines were incapable of generating with the needed precision the many tens or hundreds of thousands of straight, parallel, equally spaced grooves on a highly reflecting surface of the desired area.

It is clear in retrospect that such foresighted individuals as Hale and Albert A. Michelson appreciated the role that better gratings could play in

Horace W. Babcock is the former director of the Mount Wilson and Palomar Observatories, in Pasadena, California.



the advancement of both astrophysics and laboratory physics. In 1904 Hale founded the Mount Wilson Observatory, with plans for solar and stellar telescopes equipped with grating spectrographs of unprecedented power. Michelson must have seen clearly both the need for gratings in the active physics department of the University of Chicago and the technological challenge of the ruling engine. It is noteworthy that the Carnegie Institution of Washington operated the Mount Wilson Observatory as one of its research departments and at the same time sponsored a project, advanced by Michelson, to construct a ruling engine that would begin producing gratings at the University of Chicago in 1908.

According to his daughter,² Michelson approached the project rather lightheartedly, expecting to complete the machine in four or five months. He constructed an engine large enough to rule gratings 35 cm wide, recognizing that the result would be imperfect. He then analyzed and calibrated two of the principal errors: periodic errors that repeat with each turn of the lead screw, and error of run due to variations in the pitch of the screw along its length. This calibration he accomplished, naturally enough, with a Michelson interferometer, but lacking a good monochromatic light source he was restricted to quite short optical-path differences. Michelson therefore had to count fringes, using etalons in step-

wise fashion. Having laboriously measured the errors, he built two compensating cams. Unfortunately, however, such periodic errors as are due to the thrust bearing of the lead screw are difficult to hold constant for long, and accidental errors commonly arise from other sources.

Michelson produced a number of gratings, but his engine did not reach the anticipated level of performance. According to one of his students, Ira S. Bowen, Michelson was personally satisfied with only one of his larger gratings, and he had the misfortune to drop that grating on a concrete floor after giving it a preliminary appraisal. Michelson is said to have remarked in reference to his ruling machine that he regretted "ever having got this bear by the tail."

By 1912 it was clear to Hale that if adequate gratings were to be available for research with the new Mount Wilson telescopes, the observatory would have to produce them by building and operating its own ruling engine. To launch the project, Hale arranged for Anderson to visit Pasadena at intervals in the years 1912-15; Anderson was to supervise the design of a large ruling engine, later known as the "A" machine. In 1916 Anderson moved permanently to Pasadena. Clement Jacomini, a prominent instrument maker, was brought from Italy to head the observatory shop where the machine was to be constructed. A small foundry

Ruling engine for making diffraction gratings, around 1922. Standing with the Mount Wilson Observatory "A" machine is Clement Jacomini, a prominent Italian instrument maker who came to the United States to head the observatory shop where the machine was constructed. The lead screw advanced the grating blank 2 mm for each complete rotation of a large, 1200-tooth gear attached to its end. In early years this machine was driven by a water motor, as electric power was too unreliable.

Figure 1

was set up to cast grating blanks in an alloy of copper and tin known as speculum; the optical shop undertook the finishing of the blanks in preparation for ruling.

The diffraction-grating laboratory continued its work for 50 years. Anderson, assisted by Jacomini, was in charge from 1912 to 1928. My father, Harold D. Babcock, supervised the activity there from 1929 to 1947. For most of this time Elmer D. Prall assisted him as technician and instrument maker. I headed the laboratory from 1948 to 1963. The Carnegie Institution of Washington supported all of this work by allocating to it a modest fraction of the operating budget of the observatory. The work of the diffraction-grating laboratory occupied no more than one-third of the time of the scientist in charge, about one-half the time of an optician and all the time of the assistant; the observatory's design

Distribution of gratings*

- McDonald Observatory, Texas, 82-inch telescope, prime-focus spectrograph
- Palomar Observatory, 200-inch telescope, coudé spectrograph and prime-focus spectrograph
- Mount Wilson Observatory, 100-inch telescope, coudé spectrograph; 60-foot solar tower, pit spectrograph and spectroheliograph; 60-inch telescope, Cassegrain spectrograph; Snow Telescope; 150-foot solar tower, pit spectrograph
- McMath-Hulbert Observatory, University of Michigan, solar spectrograph
- Blindern, Norway
- High Altitude Observatory, Colorado
- Dominion Astrophysical Observatory, Victoria, BC, Canada, 48-inch telescope, coudé spectrograph
- US National Bureau of Standards
- University of Göttingen, Germany
- Hale Solar Laboratory, California, 24-meter pit spectrograph
- Astronomical Observatory, Utrecht, The Netherlands
- Oxford University, solar spectrograph
- Cambridge University, solar spectrograph
- Big Bear Solar Observatory, California
- Ernst Keil, Pasadena, California, for replicas
- University of Wisconsin
- University of London
- Perkin-Elmer Corporation
- Institut d'Astrophysique, University of Liège, Liège, Belgium
- The Observatory, Uppsala, Sweden
- Perkins Observatory, Ohio State University
- Swiss Federal Observatory, Zurich
- Lick Observatory, University of California, 120-inch telescope, coudé spectrograph
- Mount Stromlo Observatory, Australian National University, 74-inch telescope, coudé spectrograph
- Institut pour la Recherche Scientifique en Afrique Centrale, Belgian Congo
- Fysiska Institutionen, Lund, Sweden
- Astrophysical Observatory, Kodaikanal, India
- Stockholms Observatorium, Saltsjöbaden, Sweden
- Sacramento Peak Observatory, New Mexico, solar spectrograph
- Osservatorio Astrofisico di Arcetri, Italy
- David Dunlap Observatory, University of Toronto, Canada
- Kitt Peak National Observatory, Arizona, solar spectrograph

* These gratings were all produced by the Mount Wilson B ruling engine. Some observatories received more than one grating.

department and main machine shop also contributed significantly.

The 'A' ruling engine

Figure 1 shows Jacomini with the Mount Wilson Observatory A machine. The extraordinary size of the machine, which was capable of ruling an area of 40×60 cm², reflected Hale's ambition to match very large spectrographs to the telescopes that he was building for the observatory. The general design

followed that of Rowland, but with two obvious differences. One was the addition of mercury flotation to the heavy grating carriage to reduce the thrust load on the lead screw. The other was the replacement of the pawl-and-ratchet spacing device of Rowland with a cylindrical, one-turn cam rotated intermittently by the crankshaft. The cam, through small change gears, turned a steel worm in mesh with the 1200-tooth gear on the end of the lead screw.

On this machine Anderson and Jacomini ruled several concave gratings that were state of the art for 1920; the ruled areas of some were as large as 10×12 cm². Hale gave one of these gratings to Robert A. Millikan at Caltech, where Bowen used it in the vacuum spectrograph of the just-completed Norman Bridge Laboratory of Physics. This grating, made in 1922, contributed to the success of Millikan and Bowen's far-ultraviolet vacuum spectroscopy of a variety of atomic species, and through this work to important advances in knowledge of atomic energy levels and to the concept of electron spin as formulated by George Uhlenbeck and Samuel Goudsmit. Hale's promise to provide such a grating (in advance of its production) had been instrumental in persuading Millikan and Bowen to make the move from Chicago to Pasadena in 1921, thus greatly elevating Caltech's standing as a scientific institution.

Arthur S. King, a physicist and a staff member of the Mount Wilson Observatory, used other Anderson gratings in the observatory's physical laboratory to conduct a monumental study of the wavelengths and classification of emission and absorption lines of

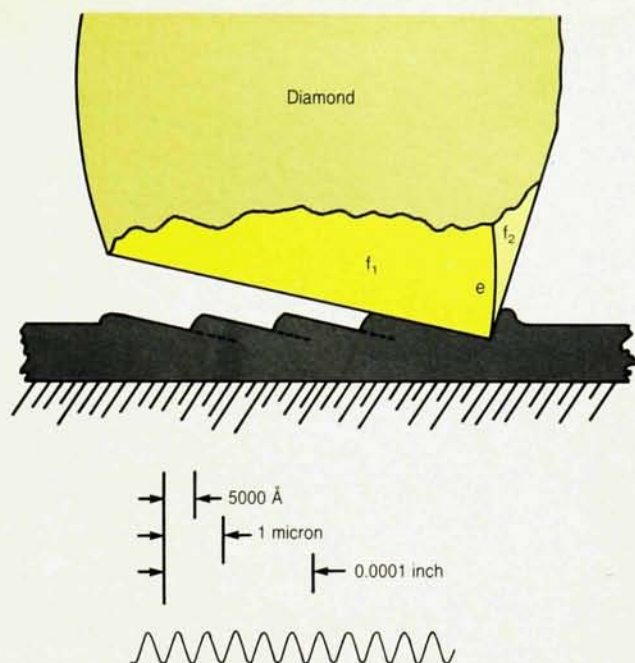
a wide variety of atomic species. In the same laboratory in the early 1920s, Harold Babcock used Anderson gratings to investigate the Zeeman effect in such elements as iron, chromium and vanadium. The data on the magnetic splitting of the spectral lines were basic to understanding the magnetic properties of atoms, and were sought by those developing the formalisms of atomic structure and quantum theory.

Similar gratings figured in a major project that Charles E. St. John and Harold Babcock carried out to revise³ Rowland's preliminary table of solar-spectrum wavelengths. The primary wavelength standard was the red cadmium line at 6438.4696 Å as determined by interferometry. St. John and Babcock established secondary and tertiary standards and used the long-focus grating spectrographs on Mount Wilson to derive revised wavelengths for the solar spectrum from 2975 to 10 218 Å. This reference work has since served as a basic wavelength standard for astrophysical spectroscopy.

Using an Anderson grating at the Snow Telescope on Mount Wilson in 1928-29, Harold Babcock determined⁴ with a precision of one part in 5 000 000 the wavelengths of lines in the bands of molecular oxygen in Earth's atmosphere. He found weak companion bands and with colleagues determined that these represented molecules containing the theretofore undiscovered oxygen isotopes O¹⁷ and O¹⁸. He estimated the abundance of these isotopes relative to that of O¹⁶. His precise data on wavelengths permitted calculation of the relative masses of the isotopes. This was a matter of much interest because it gave information on the

Ruling-diamond geometry. The diamond tool moves away from the viewer, leaving a burnished groove in the thin layer of metal on the thick substrate. The two conical surfaces of the diamond, f_1 and f_2 , have been cut and polished; they intersect at the curved edge e . The original surface of the blank is eventually completely reworked by plastic flow of the metal. The sine wave in the lower part of the figure represents wavelengths of green light. These wavelengths and the distance scales give an indication of the closeness of the grooves.

Figure 2



"packing effect"—the freeing of energy when light atoms fuse to form heavier ones. The discovery of the isotopes of oxygen required revision of the table of atomic weights; it also stimulated others to use band spectra to discover isotopes of additional elements: C^{13} , N^{15} and Be^8 .

Technological advances

In the early years of the Mount Wilson Observatory grating project, Anderson introduced the curved-edge diamond tool for ruling the individual closely spaced grooves on the surface of the blank. Before that time, most such diamond tools had been given a chisel edge formed by the intersection of two plane surfaces produced by cutting and polishing. In ruling, the edge, slightly inclined to the horizontal, is drawn parallel to itself along the surface. Anderson's new tool was formed by the intersection of two smooth, convex, conical surfaces having a prescribed included angle usually in the range 90° – 120° . The curved-edge diamond proved to be more durable and more predictable in performance than those of simpler shape. It was also well adapted for concentrating most of the diffracted radiation into a desired order and wavelength region of the spectrum, a characteristic that was later termed "blazing."

The diamond tool, under a carefully determined load, deforms the plane surface of the grating blank by causing plastic flow of the metal, as figure 2 indicates. The result is a groove that is typically three wavelengths wide, with flat, burnished, highly reflecting walls at the prescribed angles. Successive grooves convert⁵ all of the original flat

surface.

In all, the A machine ruled some 85 concave and plane gratings, mostly between 1920 and 1934. That figure includes about 20 small plane gratings that went to spectrohelioscopes around the world in the late 1920s, and a few coarse gratings as large as $25 \times 25 \text{ cm}^2$ that were ruled as recently as 1950 for use in the infrared or for special purposes.

Before the A engine was ten years old, it became evident that the machine was not capable of producing the much desired new generation of large plane gratings with clean line profiles and resolving power near the theoretical limit. The base frame was not sufficiently stable and rigid. The heavy diamond carriage had serious faults and the ways were showing the effects of wear. The increase in size over earlier engines had been too great. Future requirements were becoming more obvious, for in 1928 the construction of the 200-inch telescope became assured, presenting a clear need for grating spectrographs ranging from large coude instruments to the small, ultra-efficient, low-dispersion devices required for obtaining redshifts of the faintest galaxies. In that year the director, Walter S. Adams, decided that a new, smaller and more precise ruling engine had to be designed and constructed.

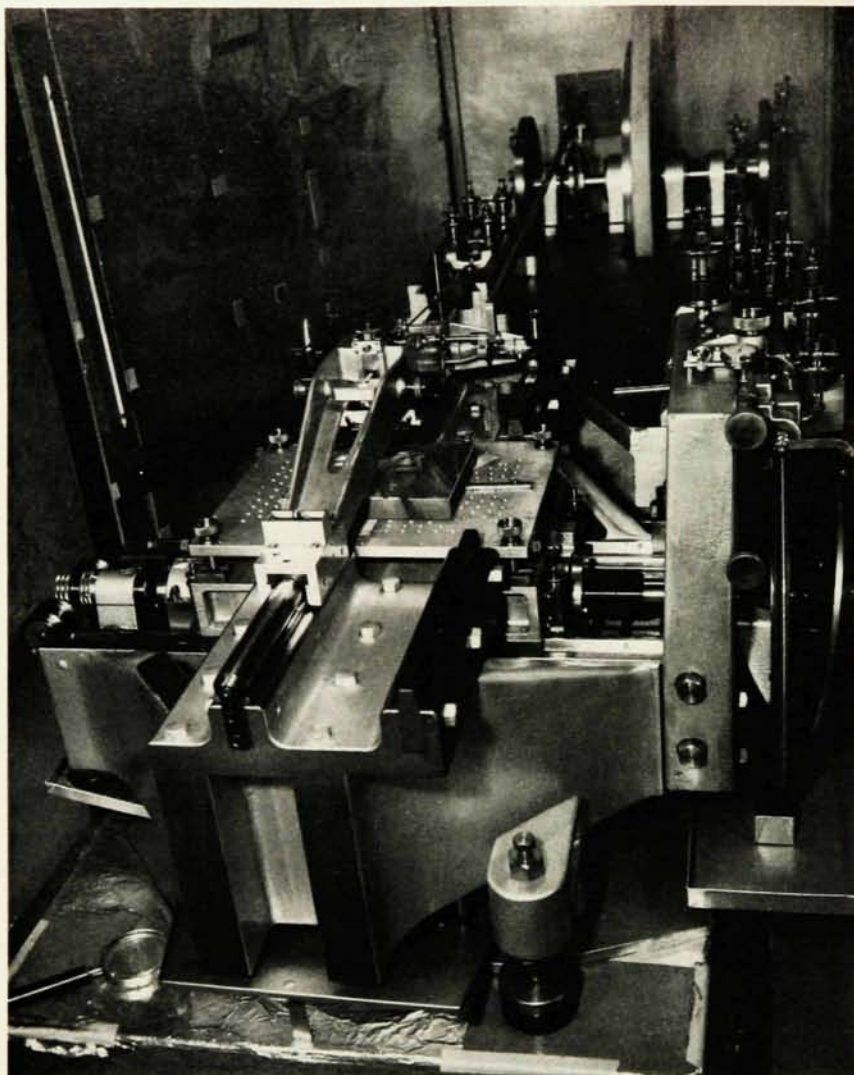
A major advance in grating technology arrived with the introduction of blanks coated with a thin film of aluminum in a vacuum, a process developed in the early 1930s by John Strong. Having successfully introduced⁶ a method for aluminizing telescope mirrors, Strong turned to thicker

evaporated films for producing gratings. Previously, makers of reflection gratings had used polished plates of speculum metal, a material that is so hard as to dull the diamond tool rather rapidly. Speculum is also inferior to aluminum in reflectance, especially in the violet. Speculum surfaces were soon superseded by the new evaporated films.

The 'B' ruling engine

Throughout the design and construction of the new machine in the years 1929–34, workers were careful to use the best materials and the latest techniques for heat treatment and the relief of stress. Prall, the talented toolroom specialist, applied his skills to machining, finishing and fitting. The engine, which operated until 1962, has many innovative features, a few of which I shall mention here; our 1951 paper⁷ has further details.

In figure 3 one can see the engine's stiff and stable base, a single casting of high-grade cast iron that rests on three supports. The main base casting was thermally cycled for two years to promote stability. The ways, the spacing worm and the support bearings in which the lead screw rotates were all made from a special steel known as Nitralloy. This material offers convenience in producing precision parts that are surface hardened and stress free. The final step is lapping, in which one uses a fine abrasive to improve the precision of the surface, leaving it hard, smooth, wear resistant and stress free. A sintered graphite compound with a low coefficient of friction was used for the bearing shoes that slide on the Nitralloy ways.



Improved ruling engine. A cylindrical monorail for the diamond carriage is visible in this photograph of the Mount Wilson Observatory "B" machine. On the right end of the lead screw is a 900-tooth spacing gear. This photograph was made before installation of an anti-creep device and an interferometric control system.

Figure 3

A ruling carriage must maintain a very high standard of performance if accidental errors in groove position are to be avoided. The tool should move in a repeatable straight line for hundreds of thousands of grooves with a tolerance of only a few angstroms. Before the B machine was completed, designers modified it so that it uses a monorail for the ruling carriage, with the diamond tool moving in a gap on the axis of the rail. An outrigger prevents rotation. The second phase of this improvement was completed in 1951 with conversion of the monorail from a flat-topped, flat-sided way to a smooth cylindrical bar of Nitralloy steel. The inverted-V sliding shoes, one on each end of the carriage, are self-centering on the rail.

Another improvement was in the rocker that allows the ruling tool to rise slightly from the grating blank during the return stroke of the carriage. Older designs made use of jeweled bearings or miniature ball bearings for the rocker axis. They were superseded (for plane gratings) by Cardan hinges in

the form of a pair of thin steel strips, crossed at 90°, at each end of the axis. Flexure of the strips provides for easy rise and fall of the diamond.

Because of elastic stresses in the lead screw, nut and associated parts, the grating carriage tends to creep forward slightly at the conclusion of each advance. A gated decoupler between the main nut and the grating carriage eliminates this creep, as figure 4 indicates.

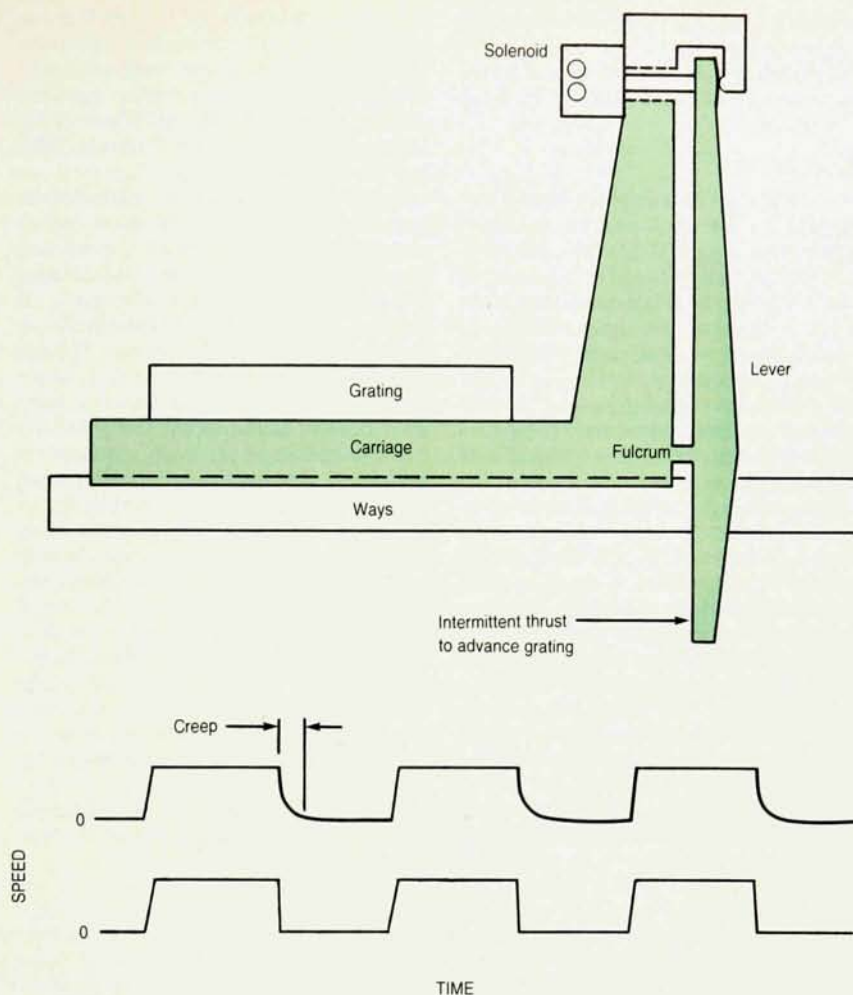
The monorail diamond carriage, the Cardan hinges for the diamond rocker and the anticreep device together reduce accidental errors in ruling to insignificant levels. It is such random small errors in groove placement that can produce false satellites, localized scattering and inferior resolving power. Periodic errors, on the other hand, which produce Rowland ghosts, are traceable to imperfections in the end-thrust bearing of the lead screw—the bearing at the end of the lead screw that prevents it from moving axially as it turns—or in other parts of the spacing mechanism.

Pral's achievement in the precise cutting and lapping of the lead screw is probably unique in the toolmaker's art. Careful study of large gratings ruled later on this machine revealed no errors that could be attributed to imperfections of the lead screw. Error of run was not detectable in a test made in a 7-m Littrow spectroscope: All spectrum orders from the sixth on one side of the normal to the sixth on the opposite side yielded the same focal setting within 3 mm.

In the B machine the end-thrust bearing is a diamond or sapphire mounted on the end of the lead screw and having a plane surface optically adjusted to be perpendicular to the axis of the screw. The fixed element on which this diamond or sapphire bears is made of silver, other soft metal or sintered graphite compound and is about 2.5 mm in diameter with relief at its center. With careful adjustment of the end-thrust bearing or by the use of an error-compensating cam such as Michelson used, errors due to longitudinal movement of the lead screw in a

Creep eliminator. At the conclusion of each advance, the grating carriage tends to creep forward a fraction of a fringe due to elastic stress in the lead screw, nut and associated parts. The device diagrammed here eliminates this creep. Relaxing the solenoid after each advance decouples the thrusting mechanism that advances the carriage. The plots at the bottom of the figure illustrate the motion of the grating before and after installation of the device.

Figure 4



ruling engine may be reduced to inconsequential levels. However, this may involve time-consuming cross-ruling tests, and the low error may be difficult to retain for long. Another remedy is to fit the machine with interferometric control, which we did in fact do for the B machine in 1959.

Interferometric control

The use of an interferometer to control the operation of a ruling engine had to await the availability of a good monochromatic light source. Such a source did not appear until the 1950s, when William Meggers developed his mercury-isotope lamp. George R. Harrison of MIT was the first to achieve⁸ actual interferometric control of a ruling engine. He used the rejuvenated Michelson engine, which had been brought to MIT from the University of Chicago. Harrison converted the machine so that it advanced the grating carriage continuously at uniform speed. To avoid excessive curvature of the grooves due to the motion of the grating carriage, he found it necessary

to devise a mechanism for moving the diamond carriage at nearly constant speed while ruling, rather than with the usual simple harmonic motion. This maintained a more uniform speed during the stroke. Harrison's machine required the use of two interferometric systems: one to control the groove spacing, and one to prevent yawing of the grating carriage.

Our interferometric control in the B machine at the Mount Wilson Observatory was designed⁹ for simplicity and to retain intermittent spacing. Thus it yields strictly straight grooves while accommodating the simple harmonic motion of the diamond carriage. Another advantage of intermittent spacing over continuous movement of the grating blank is that the photoelectric system looking at the fringes has nearly 50% of the operating cycle to sense any positional error; it can therefore produce a better signal-to-noise ratio. Finally, intermittent spacing is more nearly immune to vibration and microseisms.

The interferometric control system

was designed to compensate for residual periodic errors in the spacing mechanism. It was not necessary for the system to count fringes: It needed only to detect and measure any decentering of the n th fringe, where n is a small integer, typically in the range 6–12, that depends upon the change gears selected. For the 117:119 gear ratio indicated in figure 5, n is 6 when the green mercury line is used.

The B engine uses a Michelson interferometer with the moving mirror on the end of the grating carriage, as figure 5 indicates. The usual compensating plate is mounted on a flat strip of spring steel and equipped with a loud-speaker voice coil so that it can be made to nutate continuously with small amplitude at 60 Hz. At the same time, a computer-controlled direct current applied to that coil introduces a variable deflection of the compensating plate to correct for changes in the index of refraction of the air due to changes in barometric pressure. The field modulation, amounting to about $1/5$ fringe, together with the use of a synchronous

detector, permits the system to respond to errors as small as a few millifringes. The resulting small correction is introduced into the system during the next spacing cycle.

Status in 1948

By 1948 the B machine, while not completely free of problems, was performing fairly well. Harold Babcock and Prall had produced a number of useful gratings and had developed laboratory apparatus for rapid visual appraisal of test rulings and completed gratings. Demand for plane gratings had increased greatly owing to the growing number of research problems in astrophysics and to improvements in spectrograph design.

Plane gratings of the highest efficiency were needed for small spectrographs to be used in measuring redshifts of faint galaxies or other sources near the limit of the telescope. Because the Schmidt cameras have a short focus of a few centimeters, other specifications for these gratings were easy to meet. One of the first prime-focus spectrographs of this type was built in 1940 for the 82-inch telescope at the McDonald Observatory in Texas. It was equipped with a blazed grating ruled on the B machine; a novel feature

was a central hole in the grating to eliminate one reflection. Several other blazed gratings were subsequently ruled for the new "nebular spectrographs" used on the Mount Wilson 100-inch telescope and the Palomar 200-inch telescope.

Early experiments with high-dispersion stellar spectrographs were begun around 1910 by Adams at the Mount Wilson 60-inch telescope, and continued in the 1930s with the work of Adams and Theodore Dunham Jr at the coude focus of the Mount Wilson 100-inch telescope. Discarding large prisms as hopelessly inadequate, they were able to demonstrate the possibilities of large plane gratings. As figure 6 indicates, the collimated beam, after dispersal by the grating, could be fed to a Schmidt camera to provide a long spectral range of nearly uniform dispersion with critically good definition. Large gratings would permit the use of a long-focus collimator and wide slit, thereby preventing serious loss of light. By 1946, in fact, the 100-inch coude grating spectrograph, using a collimator only 7.5 cm in diameter, was already producing unprecedented results.

In 1948 the Mount Wilson grating laboratory's first priority was to pro-

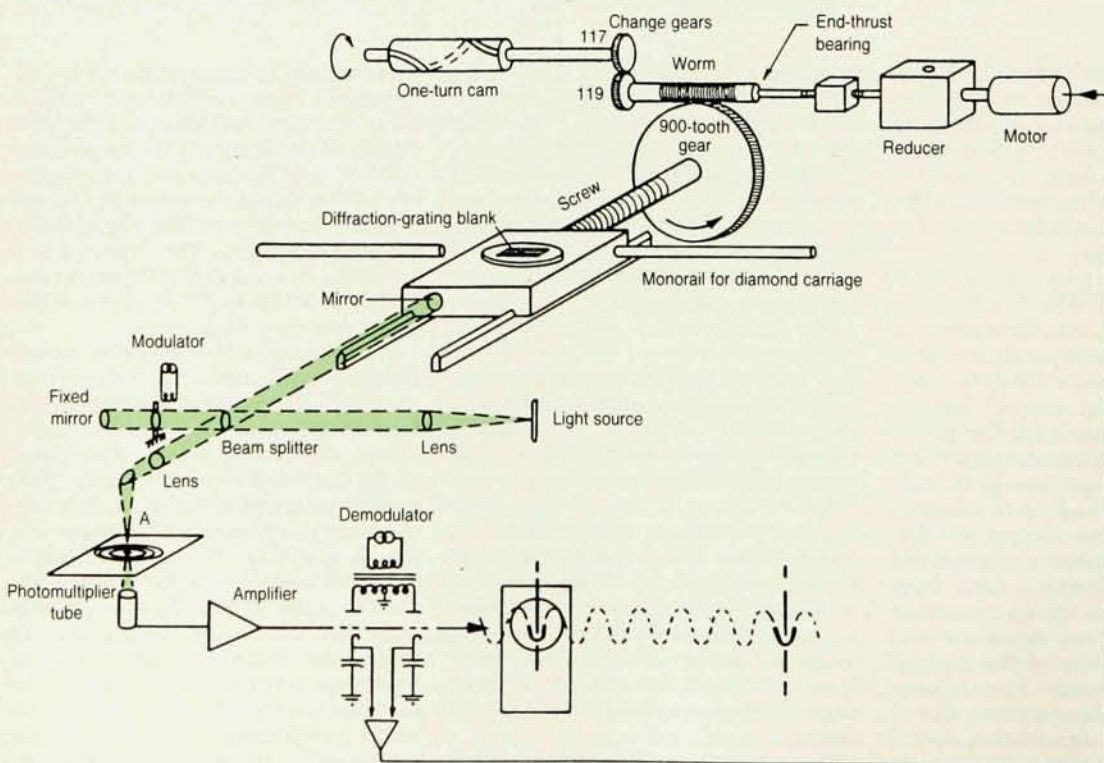
duce two or more interchangeable plane gratings about $15 \times 20 \text{ cm}^2$ in size, blazed in particular regions of the second- and third-order spectra, for the coude spectrograph of the Mount Wilson 100-inch telescope. The delivery of the first of these large gratings allowed the diameter of the collimated beam to be doubled, along with the speed and resolving power of the spectrograph. Within a few years, four gratings with groove spacings from 400/mm to 900/mm were in use and could be employed in any combination with four Schmidt cameras. These cameras had focal lengths ranging from 40 to 285 cm. Cameras of long focal length give higher dispersion, permitting one to take advantage of the high resolving power of large gratings, for sufficiently bright stars.

The improved gratings, which were very nearly free of ghosts and scattered light, rendered accurate profiles of absorption lines in stellar spectra, thereby promoting the analysis of stellar atmospheres.

Up to the decommissioning of the 100-inch telescope in 1984, its coude spectrograph produced some 24 150 glass-plate spectrograms in a large number of research programs by staff astronomers and guest investigators.

Interferometric control system for a diffraction-grating ruling engine. The moving mirror of the Michelson interferometer is on the grating carriage. The circular fringe system, which is imaged at A, is modulated by oscillation of a tilted compensating plate. Any displacement of the chosen fringe is measured by the phototube-amplifier-demodulator system; the motor then applies the appropriate correction during the next spacing operation. This control system can respond to errors as small as a few millifringes, and allows one to make the spacing between grooves correspond to a chosen integral number of fringes.

Figure 5



Roger F. Griffin conducted an appraisal of one of the gratings and used the spectrograph to produce¹⁰ *A Photometric Atlas of the Spectrum of Arcturus* $\lambda\lambda 3600-8825 \text{ \AA}$, and with Rita Griffin used¹¹ the instrument for *A Photometric Atlas of the Spectrum of Procyon* $\lambda\lambda 3140-7470 \text{ \AA}$. Observers also made numerous photoelectric observations of line profiles.

Two types of research depended critically on the resolving power offered by the new gratings. One of these was the observation of the sharp interstellar spectral lines seen in absorption against the continuous spectrum of a bright star. Such lines are sometimes split into closely spaced components because of the differential motion of the clouds in which the atoms of the absorbing elements are situated.¹² The second type of research was the study of stellar magnetic fields through the analysis of broadening and polarization in line profiles due to the Zeeman effect. Such a magnetic field was first measured in 1946 in the Ap star 78 Virginis; this was the first detection of polarization in starlight. We used the coude spectrographs of the 100-inch and 200-inch telescopes to detect and measure¹³ the variable field strength and polarity of more than 100 such stars. The strongest field measured was 34 000 gauss, in the star HD 215441.

Composite gratings

In 1949 the 200-inch Hale Telescope at Palomar Mountain was in operation but its coude spectrograph, designed by Bowen and Bruce H. Rule, was not yet functional as it lacked the essential gratings. Modeled on its predecessor at the Mount Wilson 100-inch telescope, but much larger, this spectrograph had a collimated beam 30 cm in diameter, requiring a $30 \times 40\text{-cm}^2$ grating. Its Schmidt cameras had focal lengths in the range 20–366 cm, giving spectrograms with corresponding dispersions of roughly $40 \text{ \AA/mm}$ to $2 \text{ \AA/mm}$. Because it was impossible to obtain or to rule such a large grating anywhere, Bowen proposed¹⁴ using a composite of four matched, rectangular gratings, each $15 \times 19 \text{ cm}^2$. The gratings would be mounted in a special holder fitted with micrometric adjustments for obtaining exact superposition of their spectra. The elements of the composite would not require optical phasing as the resolving power of a single element would be adequate. There would be 400 grooves/mm and the blaze would be in the third-order violet at $4100 \text{ \AA}$.

The cover of this issue shows the four nearly identical gratings that were ruled on the B machine and mounted in the spectrograph of the 200-inch Palomar telescope in 1950. Each of the four gratings has a measured resolving power

of $\lambda/\Delta\lambda$ close to 500 000 and a luminous efficiency close to 65%. The large composite grating showed satisfactory stability, requiring only semiannual inspection and an occasional minor adjustment to maintain the coincidence of the images. It must be conceded, however, that critical tests of the definition of the spectrum lines with the longest camera at the 200-inch spectrograph showed the definition to be slightly inferior to that obtained with the longest camera at the 100-inch spectrograph and its single grating.

Between 1950 and 1983 the coude spectrograph on the Palomar 200-inch telescope recorded more than 15 300 stellar spectra. The original composite grating served for 33 years before being replaced by other composites because of a need for blazing better suited to the ultraviolet. Even in 1983, however, no one could make a single grating that would accept a 30-cm beam.

The measurement and analysis of the nearly 40 000 spectrographic plates that staff astronomers and visiting investigators made with the coude instruments of the 100-inch and 200-inch telescopes are for the most part complete, so these plates have served their initial purpose. However, as a record of innumerable details of a large number of stars, these plates, many of them 20 cm or more long, have an archival value that is increasing with time. The total amount of information stored is large, and the nature of the record—spectra as recorded by photography—is such that one can quickly identify and easily compare them. Science will benefit from the preservation of the plate collections in the vaults of the observatories.

Solar spectroscopy

Until around 1950 solar spectroscopy was limited by inadequate diffraction gratings. Investigators needed accurate line profiles at satisfactory intensities and could realize this goal if they could obtain large, modern, blazed gratings free from ghosts and scattered light and having resolving powers of 600 000 or more. Spectrograph design in other respects was in many cases quite satisfactory, as witnessed by the 23-m vertical-pit spectrograph on Mount Wilson, whose thermal and mechanical stability and stagnant air path assured excellent internal seeing.

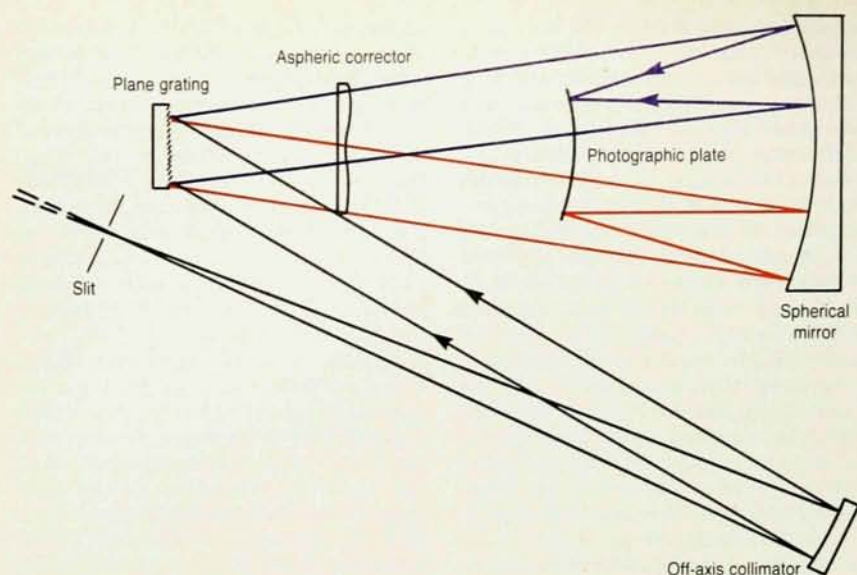
Several of the gratings that we produced on the B machine between 1950 and 1962 were designed for solar spectroscopy. We ruled them mostly at 600 grooves/mm with a blaze in the fifth-order green; some gratings were 25 cm wide with grooves 15 cm long. One of these gratings, supplied to the University of Michigan, quickly resulted in Robert R. McMath's discovery¹⁵ of "wiggly lines"—the term refers to the

differential Doppler effect of adjacent solar granules—in the spectrum of the solar photosphere. An earlier and larger project with one of our gratings at the University of Michigan produced¹⁶ the *Photometric Atlas of the Near Infrared Solar Spectrum* $\lambda\lambda 8465$ to $\lambda 25242$. At the Jungfrauoch in the Swiss Alps, a project originated by M. V. Migeotte used one of our gratings to produce¹⁷ the *Photometric Atlas of the Solar Spectrum* $\lambda\lambda 7498$ to $\lambda 12016 \text{ \AA}$ in 1963 and its sequel in 1973.

Another of our solar gratings, 20 cm wide, underwent comprehensive tests at the University of Michigan in 1956. A. Keith Pierce conducted the tests and reported¹⁸ that a visual examination of the green mercury line in the fifth order showed the grating to have measured and theoretical resolving powers of 676 000 and 679 000, respectively. A photographic measurement of two hyperfine-structure components of the mercury line at $5769 \text{ \AA}$ indicated a resolving power of 630 000. Pierce published a photograph showing "the first resolution of the central components of Hg $\lambda 5461$ by other than interferometric means." This represents a resolving power in the sixth order of 660 000. Pierce made several measurements of the line at $2536 \text{ \AA}$ in the 11th-order spectrum of mercury-198, and using the Rayleigh criterion found an observed resolving power of 1 200 000, compared with a theoretical value of 1 340 000.

The availability of large gratings offering resolving powers of 600 000 or better permitted a new approach to the longstanding problem of the "general magnetic field" of the Sun, which had absorbed so much of Hale's attention. In 1952, at the Hale Solar Laboratory in Pasadena, we demonstrated¹⁹ an instrumental system that used a powerful spectrograph with an electro-optic modulator to measure the Zeeman effect with the help of a synchronous detector. The new system, called the solar magnetograph, proved capable of measuring photospheric magnetic fields down to a fraction of a gauss and of mapping the field intensity and polarity over the visible surface of the Sun in about one hour. Within a few months of this instrument's introduction, Harold Babcock and I found²⁰ the first convincing evidence that the Sun has a poloidal magnetic field. This 1–2-gauss field, antiparallel to that of the Earth in 1953, appeared in the high heliographic latitudes beyond $\pm 65^\circ$. By 1959 the Sun's poloidal field had reversed, becoming parallel to that of the Earth.²¹

The magnetograph provided much new information that has advanced knowledge of magnetohydrodynamic activity not only in the Sun's photosphere but, by inference, below and



Coudé spectrograph designed by Theodore Dunham Jr and Donald O. Hendrix for the Mount Wilson 100-inch telescope. The Schmidt camera is simply a thin aspheric corrector and a spherical mirror. The long, narrow photographic plate is bent so that its center of curvature is at the aspheric corrector, as is the center of curvature of the spherical mirror. Figure 6

above that level as well. In 1961 I proposed²² a semi-empirical model to account for the 22-year solar magnetic cycle, including the reversal of the poloidal magnetic field and the severing and reconnection of the emergent flux loops that break away with their associated plasma to form the large interplanetary magnetic field patterns and the associated solar wind. The model embodied many of the new findings and synthesized them with related solar phenomena.

In 1959 the 150-foot tower on Mount Wilson received a second, more highly developed solar magnetograph, again using one of the better large gratings from the B ruling engine. Various observatories have constructed and operated other magnetographs. A partial listing would include the Crimean Astrophysical Observatory; Izmiran, near Moscow; Sibizmiran, in the city of Irkutsk, Siberia; Sacramento Peak Observatory in New Mexico; Kitt Peak Observatory in Arizona; the Tokyo Astronomical Observatory; Ondrejov Observatory in Czechoslovakia; and the Kiepenheuer Institute in Germany.

Fate of the technology

One of the pleasant aspects of operating the diffraction-grating laboratory was the opportunity to welcome a considerable number of visiting astronomers and physicists who were interested in the ruling engines and in discussing the uses and specifications of gratings. Also, in keeping with our policy of promoting the transfer of grating technology to industry, we received more extended visits from several instrument engineers engaged in the development of ruling machines at the Bausch & Lomb Optical Company, the Fisher Scientific Company and Diffraction Products Inc.

Through its operation of the Mount Wilson Observatory, the Carnegie Institution of Washington was able not only to provide research-quality diffraction gratings for spectrographs at the Mount Wilson and Palomar Observatories, but also to fill many requests from other observatories and laboratories around the world. The table on page 36 gives a fairly complete listing of the distribution of gratings from the B machine.

The decision to terminate our laboratory in 1963 was forced by the inability of privately funded science to maintain support for an activity that may be regarded, rightly or wrongly, as peripheral to basic research in astronomy. While it may seem ironic that our ruling engine had to be consigned to oblivion (or perhaps to a museum) just as it was reaching a long-sought level of precision and productivity, one can take satisfaction in the fact that it assisted in the advance of science.

* * *

This article is based on a talk I gave on 14 June 1984 at The Johns Hopkins University at a celebration marking the 100th anniversary of Rowland's concave grating. The proceedings of this meeting, including a more detailed version of my talk, will appear later this year in Vistas in Astronomy (Pergamon, Oxford).

References

1. H. A. Rowland, *Astrophys. J.* **1**, 29, 131, 222, 295, 377; **2**, 45, 109, 188, 306, 360; **3**, 141, 201, 356; **4**, 106, 278; **5**, 11, 109, 181 (1895-97).
2. D. M. Livingston, *Michelson, Master of Light*, Scribner's, New York (1973).
3. *Revision of Rowland's Preliminary Table of Solar Spectrum Wave-Lengths*, Carnegie Institution of Washington, Washington, DC (1928).
4. H. D. Babcock, *Proc. Natl. Acad. Sci. USA* **15**, 471 (1929).
5. H. D. Babcock, *J. Opt. Soc. Am.* **34**, 1 (1944).
6. J. Strong, *Astrophys. J.* **83**, 401 (1936).
7. H. D. Babcock, H. W. Babcock, *J. Opt. Soc. Am.* **41**, 776 (1951).
8. G. R. Harrison, G. W. Stroke, *J. Opt. Soc. Am.* **45**, 112 (1955). G. R. Harrison, *J. Opt. Soc. Am.* **39**, 413 (1949).
9. H. W. Babcock, *Appl. Opt.* **1**, 415 (1962).
10. R. F. Griffin, *A Photometric Atlas of the Spectrum of Arcturus $\lambda\lambda 3600-8825$ Å*, Cambridge Philos. Soc., Cambridge, England (1968).
11. R. Griffin, R. Griffin, *A Photometric Atlas of the Spectrum of Procyon $\lambda\lambda 3140-7470$ Å*, Cambridge Philos. Soc., Cambridge, England (1979).
12. G. Münch, *Astrophys. J.* **125**, 42 (1957).
13. H. W. Babcock, *Astrophys. J. Suppl.* **3**, no. 30 (1958). H. W. Babcock, *Stars and Stellar Systems*, vol. 6, Univ. Chicago P., Chicago (1960), p. 282.
14. I. S. Bowen, *Astrophys. J.* **116**, 1 (1952).
15. R. R. McMath, *Astrophys. J.* **122**, 565 (1955); *Astrophys. J.* **123**, 1 (1956).
16. O. Mohler, A. K. Pierce, R. R. McMath, L. Goldberg, *Photometric Atlas of the Near Infrared Solar Spectrum $\lambda\lambda 8465$ to $\lambda 25242$* , McMath-Hulbert Observatory, Univ. Michigan, Ann Arbor (1950).
17. L. Delbouille, G. Roland, *Photometric Atlas of the Solar Spectrum $\lambda\lambda 7498$ to $\lambda 12 016$ Å*, Univ. Liège, Liège, Belgium (1963).
18. A. K. Pierce, *J. Opt. Soc. Am.* **47**, 6 (1957).
19. H. W. Babcock, H. D. Babcock, *Astrophys. J.* **118**, 387 (1953).
20. H. W. Babcock, H. D. Babcock, *Publ. Astron. Soc. Pac.* **64**, 282 (1952).
21. H. D. Babcock, *Astrophys. J.* **130**, 364 (1959).
22. H. W. Babcock, *Astrophys. J.* **133**, 572 (1961). H. W. Babcock, in *Proc. Plasma Space Science Symposium*, C. C. Chang, S. S. Huang, eds., Reidel, Dordrecht, The Netherlands (1965), p. 7. □