The Challenge of the RULED

Sometimes an old and tried method is so steadily fruitful and so promising in what it might reveal if improved that it has served as a continuous challenge to successive generations of physicists. This is so with the diffraction grating used for spectroscopy. But it is often easier to meet the demands of increasing accuracy by changing one's approach than it is to pursue the original method of attack. The history of ruling gratings is outlined here, as are some of the new attacks on the problem.

by ***George R. Harrison***

Few problems of experimental physics have a more colorful background than that involved in the ruling of large diffraction gratings. Nor is any problem of such great importance more widely misunderstood. After more than a hundred years of trying, by dozens of physicists and their associated instrument makers, by Nobel prizemen and amateurs alike, no one has succeeded in producing gratings having the size and power needed by modern spectroscopists. In fact, we are now in somewhat the same psychological state about the availability of large gratings as was the world about human flight at the time the Wright brothers began their experiments. Flying seemed desirable, but so many able people had tried it and failed that it appeared likely that the problem never would be solved.

One well known experimental physicist, after spending much of his life in ruling the best gratings yet available, announced that production of the still more powerful gratings needed was the most difficult problem that experimental physics afforded, and ultimately renounced the attempt, turning his attention instead to the production of a 200-inch telescope mirror. His new problem was satisfactorily solved, but the one he left still awaits successful attack.

To rule a large grating does not sound difficult, and to this fact we may ascribe much of the difficulty. One need only procure an optically perfect mirror twelve or more inches wide and engrave on its surface a large number of straight and parallel grooves, all equally spaced. These grooves may be separated by almost any small distance desired; that usually chosen is one fifteenth-thousandth or one thirty-thousandth of an inch. However, once the distance between the first and second grooves has been set, the operator of the ruling engine is committed to maintaining this spacing until the entire width of the grating has been covered. Not only must the position of the third groove relative to the second be correct to within a millionth of an inch, but the last groove (perhaps the 180,000th, ruled a week or two after the first) must also be within a millionth of an inch of its correct position relative to the first. It is this necessity of avoiding any accumulation of small errors that has defeated past experimenters long before they had ruled the desired number of grooves.

Once a grating has been ruled with grooves properly spaced, its power to separate a beam of light into its constituent wavelengths is remarkable. Most of the information we now have about the electronic structures of atoms and molecules has come to us as a result of studies made with powerful spectrographs containing diffraction gratings. The greater the width of ruled surface on a grating the greater is its power to separate close-lying wavelengths which otherwise may be indistinguishable. In fact, the re-

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George R. Harrison became interested in spectroscopy at Stanford University in 1920, and wrote his doctor's thesis on the absorption of the principle series of sodium vapor in 1922. When he went to MIT in 1930 he built up an outstanding spectroscopy laboratory there, but always used diffraction gratings ruled by others. In fact, he is said to have taken a vow never to allow himself to be beguiled into constructing a ruling engine. This was evidently due to some strong inner compulsion, for during the past three years he has spent such time as he could spare from his duties as dean of science at MIT in remodelling the Michelson ruling engine discussed in his article.

GRATING

solving power of a good grating, which is defined as the mean wavelength of any two light rays which can just be distinguished as differing in wavelength with its aid, divided by the difference in their wavelengths, is limited only by the distance between the first and last grooves of the grating.

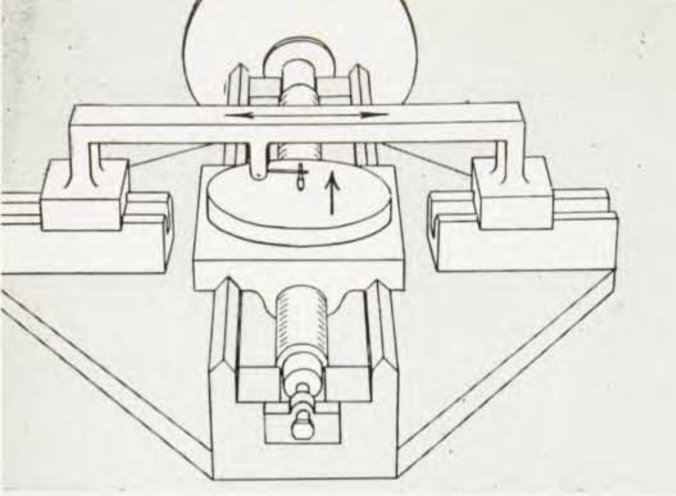
To separate properly lines in spectra as complex as those emitted by uranium or thorium atoms, we need gratings with at least twelve inches of ruled width, and fifteen inches would be better. It is easy to calculate that we should theoretically be able to control the position of the diamond tool with which the grooves of such a grating are engraved much more closely than is necessary. However, in its micro-structure metal bends, cracks, and flows; to control over-all groove position to one part in seven million has proved possible, but to control it to the one part in twelve or fifteen million that is badly needed sets an unsolved problem.

Trade Secrets

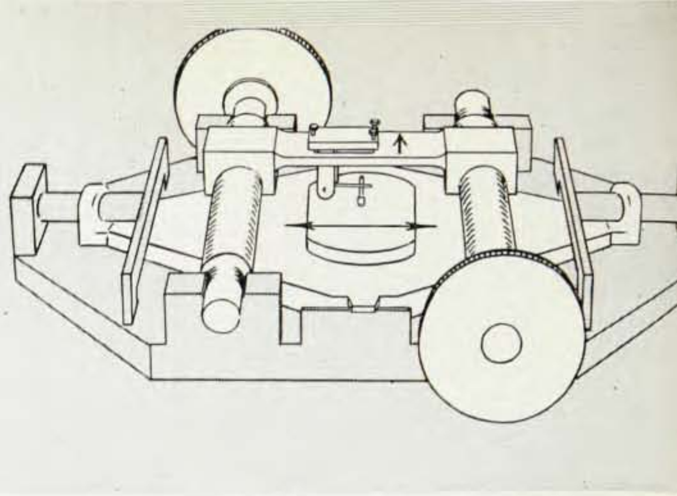
The early rulers of gratings played their cards very close to their vests. Herr Norbert, who ruled a number of tiny gratings that served for the experiments of Lord Rayleigh and others in the 1870's, never did divulge the secret of his ruling process. The papers of H. J. Grayson, an Australian nurseryman who as an amateur attempted grating ruling in the period between 1893 and 1917, and added much to the ruling art, were burned by his wife within a few hours of his death. Even the great Henry A. Rowland, inventor of the concave grating and father of the modern ruling art, restricted publication of his methods to a description of how he made a "perfect" screw, and it remained for his friends to publish the detailed description of his ruling engine after his death.

Albert A. Michelson, of Chicago, who followed Rowland, was notoriously erratic in his willingness to share secrets of his ruling technique, and Henry G. Gale, his successor, though ordinarily most cooperative, once figured in an amusing example of surliness. P. A. Ross, of Stanford University, after spending a sabbatical year at Cornell where he had opportunity to play with an old ruling engine that aroused his interest, stopped off to visit A. H. Compton on the return trip to California, and asked to see the famous University of Chicago ruling engines. Compton immediately started with him toward the ruling rooms, but suggested that on the way they stop to see Gale, who was in charge. Gale, however, brusquely stated that he would not show the engines to anyone, particularly to anyone interested in ruling gratings himself. This unexpected repulse was later found to have been induced by an earlier visit from a well known ruler of gratings who was said to have been shown a new trick by Gale for improving the ruling process, and to have issued a few months later a description of this method as his own. Such vagaries of genius are now fortunately rarer in the grating field, and instead of regarding others constructing ruling engines as competitors, devotees of the art are more likely to help each other, as befits companions in attack on a

W. H. Perry, long a technician responsible under Professor R. W. Wood and his successors for the operations of the ruling engines at Johns Hopkins University, looks over the shoulder of Professor John Strong at the new ruling engine designed by the latter. Photo courtesy J. Strong.



The principle of the Rowland Engine



The principle of the Strong Engine
Courtesy J. Strong

problem that has thus far defied human, or for that matter superhuman, solution.

Rowland

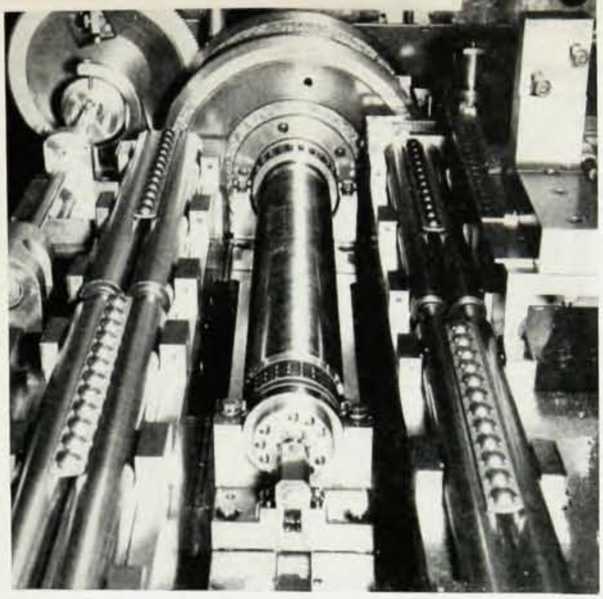
Rowland of Johns Hopkins is the greatest name in grating ruling, for it was he who learned how to produce gratings that greatly exceeded the dispersive and resolving power of the best prisms available. His first contribution was a method of correcting screws by lapping (producing an extremely accurate, highly finished surface, using abrasive) that made possible construction of an engine in which the grating blank or mirror could be advanced between grooves much more uniformly than hitherto. His second great contribution was the concave grating. With this he eliminated the need for lenses and other transparent optical parts, and thus opened up to investigators great new regions of the ultraviolet and infrared spectrum, and simplified vastly the determination of wavelengths in any region.

Rowland apparently got interested in the problem of ruling gratings as the result of a challenge which, with typical Rowland self-confidence, he could not bring himself to refuse. In the late 1870's, when Rowland, a youngster of 31, was "the" professor of physics at Hopkins, one of his colleagues reported to the weekly department discussion group on the ruling of diffraction gratings. At that time the most successful rulings had been made by L. M. Rutherfurd, a New York attorney with an amateur's interest in the problem of diffracting light into a spectrum. Fraunhofer and Norbert had ruled small gratings before him, but by 1870 Rutherfurd had succeeded in ruling a width of some two inches of mirror surface with some 35,000 grooves.

The report before the Hopkins physics group emphasized the difficulty of spacing the grooves uniformly. In the discussion that followed, Rowland characteristically expressed the opinion that this should not be a very difficult problem, and was immediately challenged by the speaker to do it himself, then, if it was so easy. Rowland thereupon of course announced that he would do so, and proceeded at once to go to the root of the problem. Two years later, with the assistance of his mechanician Schneider, he had built a small engine capable of ruling gratings up to six inches in width, which proved immediately successful.

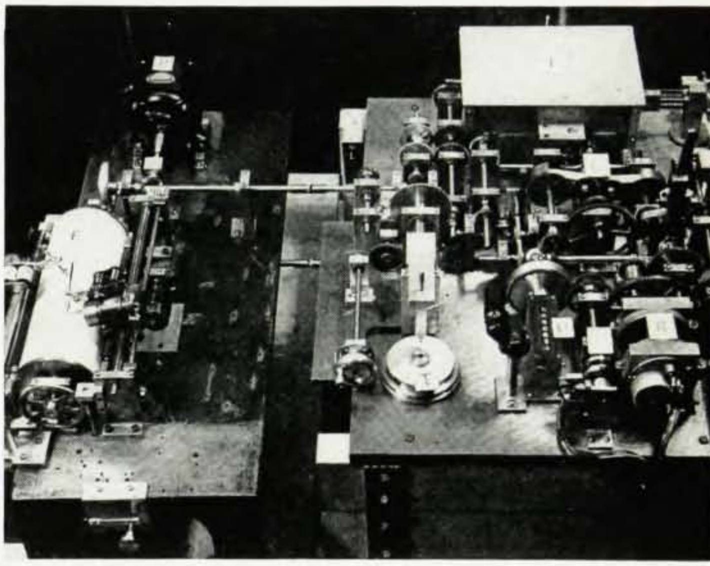
A year later, in 1883, Rowland had produced several 6-inch gratings each having more than 90,000 grooves, with resolving powers in excess of 150,000. These were not what we would call "good" gratings today, for in spite of Rowland's new lapping process the screws he made contained rather serious periodic errors, and the gratings produced spectra filled with the false lines we now know as "Rowland ghosts". However, in those days spectroscopists were so happy to have the more powerful instruments thus made available that they were not so "ghost conscious" as they became later.

Rowland worked continuously on the improvement of grating ruling, and before he died of diabetes in 1901 at the age of 52 he had completed three separate engines. These survived the Baltimore fire of 1904, during which they were damaged by water, but succumbed in part to the later ministrations of a well meaning custodian who attempted to prepare close-fitting nuts by heating the screws until he could cast babbit metal in contact with them. The screws promptly buckled, and thereby illustrated the great importance of "experimental intuition" in the makeup of anyone attempting to build or rebuild a ruling engine. The great Rowland had used wood for the threads of the precision nuts



Screw and ways of the 14-inch Michelson ruling engine at MIT. MIT photo.

The Harrison "Commensurator" for controlling grating ruling in terms of interference fringes. MIT photo.



of his engines. This sounds antiquated and ineffective yet turns out to be a most desirable way of eliminating numerous difficulties. Casting a nut against a screw sounds offhand like the best possible way of insuring a perfect fit, but is in fact horrible in its implications.

It was not until J. A. Anderson had new screws made that the Rowland engines were again put into operation in 1909. Then, and under the later supervision of R. W. Wood and his successors, they have turned out a fairly steady stream of the world's outstanding gratings, and their capacity of seven inches of ruled width has set the upper limit in resolving power of broad range spectrographs. The three engines have survived to this day, but only as a result of frequent careful overhaul, and somewhat in the form of the "genuine antique hatchet more than 100 years old", which has had three new heads and five new handles during that period. The most important thing that has survived is the impetus given the ruling art by Rowland; until very recently all ruling engines, each less successful than his, have been based on his design.

Michelson

At the University of Chicago Michelson started the construction of a large ruling engine in 1900, a project that was to last more than fifty years, for it is, in fact, still in progress elsewhere. Rowland had raised the resolving power of the grating to perhaps 200,000. Michelson wanted to raise it higher, so he designed his engine to rule 14-inch gratings. Its years of greatest success were between 1906 and 1915, when it produced two gratings of 9.3-inch width having 11,000 grooves per inch, for which resolving powers of 600,000 were claimed. In an earlier article (for a more technical history of grating ruling the reader is referred to "The Production of Diffraction Gratings: I. Development of the Ruling Art" in the June 1949 issue of the *Journal of the Optical Society of America*) I set this mark as perhaps a world record for resolution by ruled gratings. My statement was received with loud protests from the confraternity of grating rulers, however, who with some justification claimed that gratings which no longer exist for checking should be ineligible for the great resolving power sweepstakes. It is certainly true that offhand estimates of resolving power can easily be in error by a large factor.

No one now can tell whether Michelson was unduly optimistic or not, for he took his first 10-inch grating with its 100,000 grooves to a banquet held to celebrate the award to him of the Nobel prize. The grating was to be taken to Sweden so that the King might see how well justified the award had been, and at the dinner it reposed on the table in front of Michelson in a handsome wooden case. During his after dinner speech Michelson raised the box to display the grating, but the cover had come unlatched and the precious grating fell to the floor, where it broke into several dozen pieces. Through the kindness of Miss M. O'L. Crowe, one of Michelson's students who was present at the dinner, I have a piece of this ill-fated grating with its faint patina of lines. This gives impressive evidence of how much easier it is to rule a grating today than in those earlier days when chip diamonds were used to scratch hard speculum instead of carefully shaped diamonds to burnish soft aluminum. Michelson tried again, and ruled a second large grating, but this proved to be on a blank too thin to maintain optical flatness, and it has warped so much as to be useless. It now reposes in the Michelson museum at Inyokern.

In 1910 Michelson started a second engine, on which his group worked for twenty years, to continue later under the leadership of Gale. Some dozen or so 6-inch concave gratings were ruled on this engine, which had a 12-inch capacity. These reached 400,000 in resolving power, a mark also attained by Anderson at Hopkins, which is presumably the legitimate world's record. In 1947 the Gale engine was presented to the Bausch and Lomb Optical Company, while the other engine, having been rebuilt several times since Michelson's original start, was given to the Massachusetts Institute of Technology, where it is now being rebuilt for a fourth time.

Michelson's greatest contribution to the ruling art was the use of interferometry in testing his engine and its product, and the building up of a remarkable group of optical and mechanical workers, in which the names of Julius and Fred Pearson, deKhotinsky, and O'Donnell stand out. These workers accumulated a vast lore of testing and design data that was never published, much of which is now outdated in detail but is being used with profit in the Bausch and Lomb and MIT engines. The large screws of these two engines are mounted on balls, for example, and in the MIT engine even the heavy carriage rolls on balls. During the past two years I have been able to watch these engines being put back into operation, and to admire the magnificant workmanship that went into them.

Michelson was more interested in improving the grating than in producing gratings for wide distribution. A temperamental genius, he gave his grating project an impetus the full power of which will not be realized for another dozen years.

Several other large ruling engine projects have been undertaken in the years since Rowland's original success, but most have resulted in production of satisfactory small gratings only up to four or six inches in ruled width. At the Mt. Wilson Observatory two engines have been in operation for some years under J. A. Anderson and H. D. Babcock and their successors, and at the National Physical Laboratory in England and in Siegbahn's laboratory in Stockholm successful ruling has been carried out on gratings of intermediate size. Various commercial engines produce small gratings on a routine basis, and beyond these is a vast array of ineffective engines constructed by expert machinists, amateur inventors, and plain cranks.

New Attacks

Most beginners at the ruling game focus their attention on the screw, which is to advance the blank mirror under the ruling diamond from one groove to the next by a precisely controlled amount. This is probably because Rowland's great contribution was a method of making precision screws with six inches of nut motion. Actually, making a precision screw or correcting one with errors is by no means the most difficult part of constructing the engine, whose ways must be straight and parallel to a degree difficult to realize. The screw difficulty was greatly overplayed in the early days; Michelson in 1912 stated that the time required to lap a screw varies as the amount of material to be removed, and that the lapping of the 20-inch screw for his engine required fifteen years. This was by way of emphasizing the great size of his engine, for a screw for one of Rowland's engines could be lapped in a month or less. New methods of lapping were later developed at Chicago, and I have been informed by T. J. O'Donnell that two screws made for use in the (now) MIT engine required for lapping only about three months of one man's time, spread over a period of one year.

To eliminate need for a screw, inventors commonly suggest some sort of "inching" mechanism, whereby electromagnets pull the blank hand over hand along a wire or a hydraulic mechanism whereby measured drops of oil raise the carriage level each a definite distance. Thus far these methods have all been found to suffer even more than a screw from temperature changes, compression, impermanence of position, uneven friction, and other difficulties.

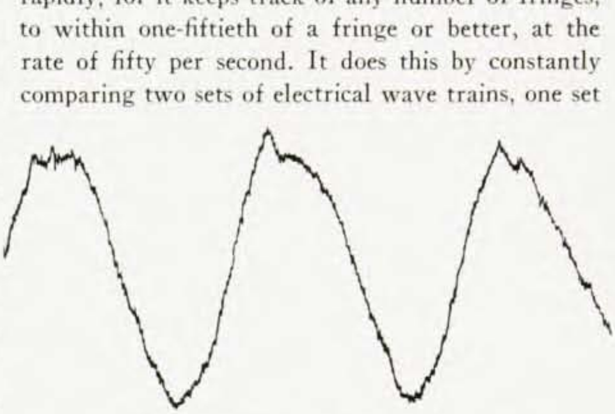
There is no question that a new style of attack on the large grating problem is needed, and this is now being carried on in at least two laboratories. At Johns Hopkins, John Strong has recently completed a small engine designed to be as impervious as possible to external influences; at MIT a group is following the opposite course of exercising continuous control of the engine during the ruling process by means of interference fringes so that effects of external variations can be compensated for.

Strong's engine rules gratings up to 6-inch width with 15,000 grooves per inch. Instead of one screw he uses two, placed oppositely so that when one screw expands the other does also, but in the opposite direction. Instead of moving the grating blank the screws advance the diamond, thus their load is reduced; the grating blank is then reciprocated under the diamond for the ruling stroke. This method has the great advantage that if the ways are not straight the diamond still rules grooves that are parallel, whereas with Rowland's system curved ways result in fanning of grooves, which will reduce resolving power.

Strong's engine marks the greatest improvement in the ruling art since the days of Rowland. He has also increased the speed of ruling to twenty strokes a minute for grooves three inches long, so that a grating of some 80,000 grooves can be completed in three days. Previously the cross stroke was produced by a revolving crank shaft, giving sinusoidal motion to the diamond. By using a cam to move the carriage Strong advances this slowly and uniformly during the ruling stroke and returns it quickly. It may well be that Strong will have solved the large grating problem when he builds a bigger engine.

In the Spectroscopy Laboratory at MIT we have adopted the policy of making the engine as impervious to external disturbances as is easily possible, then of keeping external conditions as uniform as possible, then finally of keeping a check on the engine during operation by constantly comparing the position of the carriage with its proper position, using interferometry. This has been done with a device which we call a "commensurator" because it reconciles two incommensurable quantities, one the standardizing wavelength of the green line emitted by mercury isotope 198, and the other the lead of the engine screw of two-millimeters pitch.

When Michelson measured the length of the standard meter bar in terms of the cadmium red line he counted the fringes in a small fixed interferometer or "etalon"; then he measured the number of times this etalon was needed to fill a longer etalon and the number of remaining fringes; then the number of these etalons plus fringes in the length of the meter. Thus he saved himself the eyestrain and possible error involved in counting some three million interference fringes of red light. With the commensurator this job could be done much more rapidly, for it keeps track of any number of fringes, to within one-fiftieth of a fringe or better, at the rate of fifty per second. It does this by constantly comparing two sets of electrical wave trains, one set



Portion of the error curve of a screw as recorded by the commensurator.

produced from interference fringes which tell how much the carriage of the engine moves, and one produced by a generator turned as the screw of the ruling engine is turned. If the screw advances the nut uniformly the two wave trains will stay in almost exact synchronism. If one wave train advances relative to the other by as little as one-fiftieth of a wave, a motor is made to turn slightly. It thus records the errors of the screw by moving a pen tracing a curve on a chart, and also corrects the errors by bringing the two wave trains back into phase. Thus errors in the screw as small as a fifth of a millionth of an inch can be measured and eliminated.

The commensurator is found to repeat its calibration of a screw to within the tolerances required for ruling a grating twenty inches wide. A sample curve for a screw with a periodic error sufficient to give ghosts one-hundredth as strong as their parent line is illustrated. This very beautiful screw, made at the University of Chicago with twenty inches of thread cut on a hollow tube three and a half inches in diameter, was originally correct to within seven-millionths of an inch over its entire length, an error readily correctible. During the war years the screw was stored with its ends resting on blocks but its center unsupported, and it sagged about one ten-thousandth of an inch. This was enough to introduce a periodic error some forty times as great as could be tolerated without correction.

It is planned to use the commensurator to control the great Michelson engine at MIT in several successive stages. First it is being used to calibrate the screw in terms of a new nut that is being fitted. Then it will be used to plot a helical correction cam which, when fitted to the engine, should remove ninety percent of the reproducible error found. Then it will be used with the corrected screw to determine any residual and any nonreproducible errors that may appear, and automatically feed in the correction needed to offset these as they occur. Finally, it will plot a curve showing the actual performance of the engine as it rules a grating, giving orders for changes of as little as one-thousandth of a degree in the temperature of the oil bath in which the engine is immersed when these seem needed, and otherwise monitoring the ruling of each groove.

By such means it appears possible to put jointly on a precision screw and a train of interference fringes the responsibility for accurately locating the grating grooves as they are ruled. Each alone is unsuited to handling the job, but together they appear to serve admirably. The screw is steady and entirely trustworthy over short distances of ruling and short periods of time. The fringe field may disappear on occasion, but when available it is precise and reliable. The commensurator was devised to join the best features of both.

The Echelle

An outcome of the current MIT investigation of how to rule large gratings was the development of the echelle, a device which brings to the grating field the advantages of interferometry without most of the limitations of the latter. (See "The Design of Echelle Gratings and Spectrographs" by the author in the July 1949 issue of the *Journal of the Optical Society of America.*) The echelle is a ruled plane grating having only from one hundred to two thousand flat-sided grooves to the inch. The narrow edges of the step-shaped grooves are to be illuminated normally with parallel light at a fairly high angle of incidence. Orders of interference from the one-hundredth to the one-thousandth are used, and an ordinary stigmatic spectrograph provides crossed dispersion for the separation of overlapping orders. By this means broad range spectrographs superior in dispersive and resolving power to the largest concave grating installations should become available, and they should have much higher speeds than the latter, and require less than a tenth as much space. Owing to the peculiar cyclic nature of the echelle spectrogram it is possible with an echelle to record a given spectrum on fewer than one-tenth as many plates as would be required with an equivalent orthodox grating spectrograph.

The accompanying echelle spectrogram, taken by David Richardson with a Bausch and Lomb echelle having a resolving power of about 300,000, shows the increases in dispersion and resolution that result when an echelle is used with an ordinary spectrograph. The upper spectrum is that of iron taken with an ordinary quartz prism Littrow spectrograph; the lower shows the same spectrum when an echelle is used with the same instrument. Resolution has been increased more than tenfold, while the time of exposure needed was only slightly more than trebled.

A great advantage of the echelle is that since it has only from one-tenth to one-fiftieth as many grooves as an orthodox grating, it can be ruled much more rapidly than the latter. The ruling period for a 20-inch grating may thus be reduced from days to to hours, without loss of resolving power.

Whether the problem of ruling large diffraction gratings having high resolving power will be solved in the near future remains to be seen. Many hitherto unsolved problems of science awaits its solution.

Above, a portion of the iron spectrum taken with a Littrow quartz spectrograph. Below, the same when crossed with an echelle. Photo courtesy *Bausch & Lomb Optical Co.*