The Cover Design

LEWIS M. RUTHERFURD: PIONEER ASTRONOMICAL PHOTOGRAPHER AND SPECTROSCOPIST

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Although much of the history of science has proceeded in the absence of notable technological changes, during some periods the development of new techniques has made possible new types of observations for the theoreticians to ponder. For astronomy, the mid-19th century was a time when technological influence was important. The scientists who used the new tools and who described their work in the published literature are well known to historians; but the men who designed and made the tools are often overlooked. The significance of these technological innovators, producers of works rather than words, needs increased historical recognition.

Many of the techniques of astronomical photography and spectroscopy, used with great success during the second half of the 19th century, were first developed by Lewis Morris Rutherfurd, an amateur scientist. When Rutherfurd turned his attention to astronomy around midcentury, photography was still in its infancy, and the ground rules of spectrum analysis had not yet been clearly enunciated. The apparatus needed for experiments in these sciences was as undeveloped as the sciences themselves. Rutherfurd's talents equipped him well for this situation. He understood which observations could be, but had not yet been, made. He designed the instruments necessary for his researches; and when he did not actually construct them, he personally supervised their construction. His use of the instruments often went no further than showing what observations they made possible. Then, turning to new problems, he made his apparatus available to other scientists who would profit from his innovations.

Rutherfurd (1816–92) was a member of a prominent New York family, with enough money to free him, for most of his life, from the

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necessity of earning his livelihood.[1] His interest in scientific pursuits developed early and lasted throughout his life. As a student at Williams College, he worked closely with the professor of mathematics and natural philosophy. For about ten years after graduation he practiced law, without, however, neglecting his scientific labors. Then followed a lengthy trip to Europe, during which Rutherfurd gained familiarity with the languages and the current scientific work of France, Germany, and Italy. Upon his return to the United States, Rutherfurd was ready to devote himself to a scientific career.

To understand Rutherfurd's role in the history of scientific technology, it is necessary to look beyond his bibliography to the many pieces of apparatus made by him or made according to his designs, and to the experiments and observations they made possible. It is also necessary to uncover as much as possible of Rutherfurd's spoken but unpublished remarks and to take note of his working friendships.

Although Rutherfurd did publish some formal papers, his primary channel of communication with other scientists was through professional societies. He was an original member of the National Academy of Sciences, an officer and active member of the American Photographical Society,[2] an associate of the American Academy of Arts and Sciences, and a foreign associate of the Royal Astronomical Society.[3] At meetings of these groups, Rutherfurd often spoke about and showed his recent work. Publication of his remarks depended on the whim of a reporter or recording secretary. Once published, however, Rutherfurd's comments received wide circulation in America and Western Europe, since numerous journals, starved for original articles, filled their pages by quoting each other.

Among Rutherfurd's many friends, five in particular significantly influenced his scientific work. Three of them were professional scientists: the chemist Wolcott Gibbs, the physicist Ogden Nicholas Rood, and the astronomer Benjamin Apthorp Gould. The extant correspondence of Gibbs[4] and Rood[5] indicates a warm friendship as well as a close working relationship among these four men. Indeed, for many

[1] Most of the available biographical information is included in Benjamin A. Gould, "Memoir of Lewis Morris Rutherfurd, 1816–1892," *National Academy of Sciences, Biographical Memoirs* (Washington, D.C., 1895), 3:417–41.

[2] Deborah J. Warner, "The American Photographical Society and the Early History of Astronomical Photography in America," *Photographic Science and Engineering* 11, no. 5 (1967): 342–47.

[3] *Monthly Notices, Royal Astronomical Society* 33 (1872): 65.

[4] In the Franklin Institute, Philadelphia.

[5] At Columbia University, New York.

summers the Rutherfurds and the Gibbses had neighboring houses in Newport, R. I., while the Roods stayed across the bay and Gould, in Argentina, wished he could join them. Rutherfurd probably met Gibbs during the late 1850s, when the latter was teaching at the Free Academy in New York City. For a few years, Gibbs wrote to Rood, then in Troy, N.Y., describing Rutherfurd's work. Later, after Gibbs became Rumford Professor at Harvard and Rood became professor of physics at Columbia, news went the other direction. Rood apparently spent many hours with Rutherfurd, and his letters to Gibbs were often reports of what he had seen or what he and Rutherfurd had done the evening before. In 1874 Rutherfurd received the Rumford Medal of the American Academy of Arts and Sciences for his "improvements in the processes and methods of Astronomical Photography."[6] That he was so honored was due largely to the efforts of Gibbs who had been arguing his case for several years.[7] Gould, who so often clashed violently with others, was humble before Rutherfurd and often praised his stellar photogrammetry.

The two other friends—Henry Fitz and Daniel C. Chapman—were artisans rather than scholars. Fitz was a competent photographer and one of the first commercial telescope makers in the United States. He opened a workshop close to the Rutherfurd residence in 1845, and Rutherfurd immediately ordered a 4-inch aperture objective lens. According to Fitz, Rutherfurd was so anxious about this lens that he went to the shop almost every day to see how it was progressing.[8] More than anxiety seems to have been involved, since Rutherfurd learned from Fitz his techniques for figuring lenses.[9] During the succeeding years, Rutherfurd bought several telescopes from Fitz, some complete and some which he finished himself. In return, Rutherfurd gave wide favorable publicity to Fitz's work.[10] After Fitz's accidental death in 1863, Rutherfurd took his seventeen-year-old son Harry under his wing, and helped him become a scientific instrument maker. Chapman was Rutherfurd's

[6] *Proceedings, American Academy of Arts and Sciences* 9 (1873–74): 304–8.

[7] Gibbs to Rood, March 1, 1870, Wolcott Gibbs Correspondence, Franklin Institute, Philadelphia.

[8] Henry Fitz to his sister Susan, December 9, 1845, Fitz correspondence owned by a descendent, Mrs. James Rich of Peconic, N.Y.

[9] Lewis M. Rutherfurd, "Astronomical Photography," *American Journal of Science* 39 (1865): 304–9.

[10] Lewis M. Rutherfurd, "Observations during the Lunar Eclipse, September 12, 1848," *American Journal of Science* 6 (1848): 437.

assistant for some ten years, beginning around 1870.[11] Like Rutherfurd and the Fitzes, Chapman was an active member of the American Photographical Society. He worked with spectroscopy as well, and many if not all of the Rutherfurd diffraction gratings were actually made by Chapman.

Early Astronomical Photography

In 1856 Rutherfurd built an astronomical observatory in the garden of his house at Eleventh Street and Second Avenue. The main instrument, an equatorial refracting telescope, was made by Fitz, while its $11\frac{1}{4}$-inch objective, achromatized for visual observations, was figured by Rutherfurd himself. The following year, encouraged by the recent successful experiments made by Whipple and the Bonds at the Harvard College Observatory, Rutherfurd decided to try his hand at celestial photography.[12] The 1857 attempts to photograph the stars at Harvard succeeded because of two recent innovations, whereas the attempts in 1850 had failed. The relatively slow daguerreotype plates were replaced by the more sensitive, wet collodion plates; and the drive mechanism of the large telescope had just been equipped with a Bond spring-governor, thus ensuring an equable equatorial motion. Following their example, Rutherfurd used wet collodion emulsion and had Alvan Clark & Sons install a similar driving clock on his telescope. To counteract the chromatic properties of his objective lens, Rutherfurd located the photographic plate at the actinic focus of the telescope, $\frac{7}{10}$ inches outside the visual focus. With this apparatus, he recorded images of the moon, Jupiter, Saturn, stars as faint as fifth magnitude, and the sun showing spots and faculae. Although his results were equal to any yet made, Rutherfurd was dissatisfied.

A visual achromatic refractor was obviously not a good instrument for photography. To improve his pictures, Rutherfurd tried at least three expedients before finding a satisfactory solution. In 1859, he inserted various combinations of lenses between the object glass and the photographic plate, but to no avail. In 1860, he purchased a visual achromat from the Clarks and then placed between the crown and flint lenses a ring "of such a width that the best visual and photographic foci were united." This instrument was taken to Labrador by a U.S. Coast Survey expedition to observe the total solar eclipse of that year. The results were good—they surpassed those achieved with an uncorrected objective—but not good enough. In 1861, Rutherfurd and Fitz made a re-

[11] Visitors to Rutherfurd's observatory often mentioned meeting Chapman. See, e.g., Hermann Vogel, "Astronomical Photography in America," *Photographic News* 15 (1871): 31.

[12] Rutherfurd, "Astronomical Photography" (see n. 9 above), pp. 304–9.

flecting telescope with a silvered glass mirror; but the tremors of the city so shook the instrument, and pollutants in the city so corroded the silver film, that they were forced to abandon that device.

Early Spectroscopy

Rutherfurd's successful photographic telescopes resulted directly from his spectroscopic investigations, a subject then much in vogue. The study of spectral lines, published by Fraunhofer in 1814 and not entirely neglected during the succeeding years, received a healthy boost from the 1859 announcement of Bunsen and Kirchhoff that the positions of the emission and absorption lines were uniquely defined by the constituent elements. Rutherfurd was but one of many scientists who turned his attention to spectroscopy at that time. Communication was fast, and there were several channels through which Rutherfurd could have learned about the new science. In the fall of 1861 the American Photographical Society devoted several meetings to the analysis of light, and its monthly publication, the *American Journal of Photography*, reprinted numerous European articles on the subject. According to Rutherfurd's own testimony, however, it was Wolcott Gibbs who, in December 1861, suggested to him "the continuation of Fraunhofer's observations upon the spectra of the heavenly bodies."[13] Gibbs's role in encouraging spectrum analysis in America is further substantiated by noting the coverage he gave this subject in his "Scientific Intelligence—Chemistry" column in the *American Journal of Science*.

Since spectroscopy was such a new subject, spectroscopes were not readily commercially available, and so Rutherfurd's first task was to devise a suitable instrument.[14] Following Bunsen and Kirchhoff, he adopted a simple chemical spectroscope with a 60-degree flint-glass prism and three telescopes: a collimator with adjustable slit, a viewing telescope, and a telescope showing a scale of equal parts for measuring the positions of spectral lines. When attached to his 11¼-inch telescope, the spectroscope worked well for observations of sun, moon, and planets. For stars, Rutherfurd found it necessary, as had Fraunhofer, to insert a cylindrical lens to elongate the images.

With this instrument, Rutherfurd made two important observations. The first, which he apparently did not pursue further, was that stellar spectra can be classified and correlated with other stellar characteristics. Of the twenty-four stars he observed, eight were similar to the sun in color as well as in the number and position of absorption lines; ten

[13] Lewis M. Rutherfurd, "Astronomical Observations with the Spectroscope," *American Journal of Science* 35 (1863): 71–77.

[14] Ibid.

white stars, like Sirius, had absorption lines notably darker and differently positioned than the first group; and six white stars showed no absorption lines whatsoever. These conclusions were similar to those reached, independently and simultaneously, by Angelo Secchi in Rome.[15]

Rutherfurd's second observation was that the spectroscope could be used to test the color correction of a lens. Since starlight not in focus would not pass through the slit, the spectroscope had to be moved relative to the objective lens in order to admit the entire spectrum, and thus the focus for light of various wavelengths could be found. Alternately, the image formed by an achromatic objective would be dispersed by a spectroscope into an even line, while that formed by a poorly corrected objective would be dispersed into an irregular line, narrow for colors in focus and wider for colors out of focus. Rutherfurd actually used spectroscopes to test photographic lenses, and in this he was followed by professional telescope makers, such as Alvan Clark & Sons.

Lunar and Stellar Photography

Rutherfurd's first photographic telescope was ready for use in December 1864. In ordinary cameras and in the Kew photoheliograph used by the British astronomical photographer, Warren De La Rue, the visual and photographic rays were brought, as far as possible, to one focus. Rutherfurd rejected this compromise, even though it permitted an instrument to be visually focused, as being detrimental to the photographic image. His new objective lens was achromatized for the actinic rays and so quite worthless for visual observations. Since the photographic lens had an aperture of 11¼ inches, the same as the old visual lens, the two could be used interchangeably in the same tube and mount.

As soon as the lens was finished and sufficiently clear nights occurred, Rutherfurd succeeded in taking pictures of the moon and stars that far surpassed all previous efforts. The stellar photographs did not, at the time, receive due recognition; but the lunar photographs were widely circulated and praised. The best moon picture was taken on March 6, 1865, three days after first quarter (see fig. 1). The original negative, 1.7 inches in diameter, was clear enough to withstand enlargement to 21 inches. Rutherfurd immediately publicized his apparatus and achievements in talks and articles.[16] He sent some copies of the picture to

[15] Angelo Secchi, "Note sur les spectres prismatiques du corps célestes," Académie des sciences, *Comptes rendus* 57 (1863): 71–75.

[16] Rutherfurd's talk to the American Photographical Society, quoted in the *American Journal of Photography* 7 (1864–65): 540–41; and Rutherfurd, "Astronomical Photography" (see n. 9 above), pp. 304–9. Both accounts were extensively quoted.

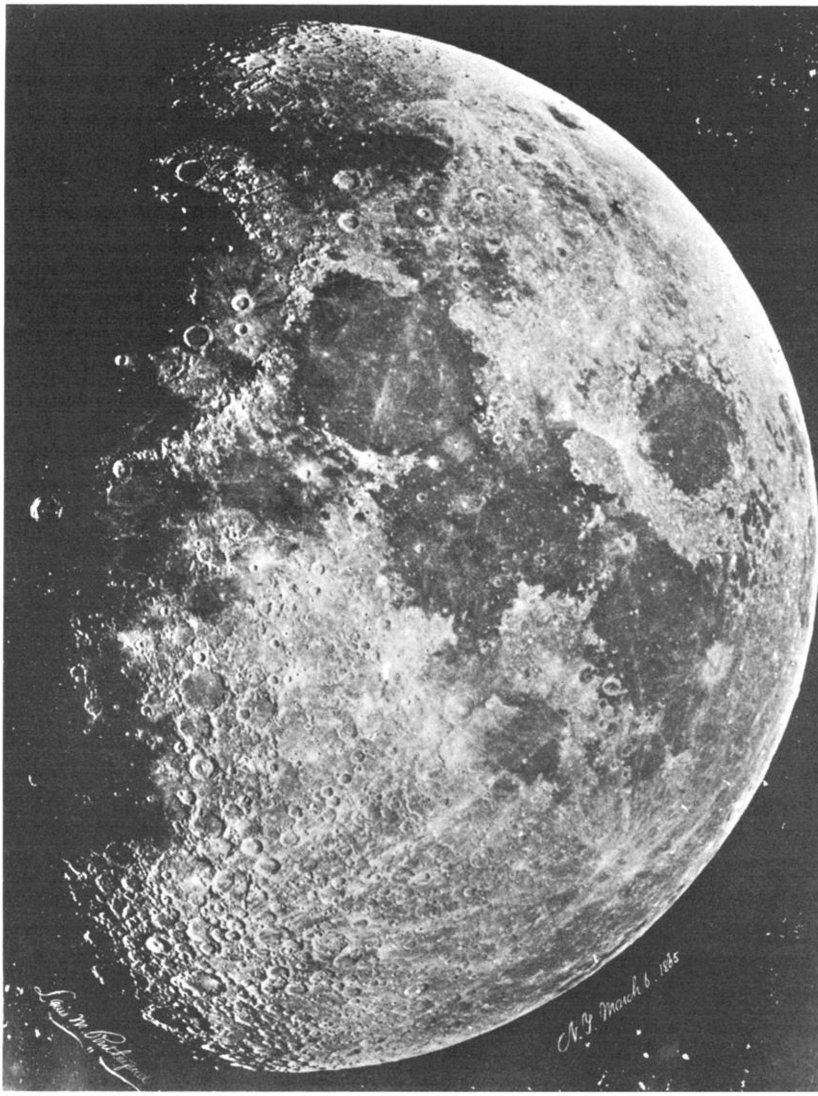


FIG. 1.—Photograph of the moon, taken by Lewis M. Rutherfurd on March 6, 1865 (print in National Museum of History and Technology, Smithsonian Institution); photo courtesy Smithsonian Institution.

friends; commercial distribution of the rest was put in the hands of Oscar G. Mason, a professional photographer who had helped manipulate the plates.[17] Mason did his job so well that the lunar photograph was soon admired at several meetings of scientific and photographic societies.[18] Numerous prints from this negative can still be seen in observatories and museums. Several years later, equipped with his 13-inch visual/photographic refractor, Rutherfurd took another series of pictures of the moon which were as greatly appreciated as the first.[19] These too were widely distributed. In Manchester, England, Alfred Brothers published some of these pictures together with Beer and Mädler's map of the moon and sold the portfolio for twenty-one shillings.[20]

Rutherfurd often combined two photos, of the sun or of the moon, for viewing through a stereoscope. When combined in this way, the pictures gave an impression of the sphericity of the celestial body. They could also be used to illustrate lunar libration—to show that areas near the edge of the moon, as seen from the earth, are alternately in sight and hidden from view.[21] Although celestial stereoscopes had been made previously and used for these purposes by De La Rue, Rutherfurd was apparently unaware of them when he began.

Stellar photography presented many more problems, yet had greater scientific importance, than lunar photography. In 1865–67, using his 11¼-inch photographic objective, Rutherfurd took about forty-five pictures of the Pleiades and Praesepe. The best of these, with exposures of about three minutes, showed images of stars as faint as ninth magnitude—at least two magnitudes fainter than anyone previously had been able to reach. The use of wet collodion prevented exposures long enough to record fainter stars. Rutherfurd immediately recognized that "the pow-

17 "Rutherfurd's Photograph of the Moon," *Philadelphia Photographer* 3 (1866): 36–39.

18 The Englishman De La Rue admitted that "to an American we are indebted for the best pictures of our satellite yet produced" (quoted in George F. Chambers, *Descriptive Astronomy* [Oxford, 1867], p. 691). Hermann Vogel, in Berlin, thought the lunar pictures "the most exquisite specimens of photography" he had ever beheld. His remarks were quoted in the *American Journal of Photography* 8 (1865–66): 135–36. Leon Foucault, when presenting a print to the Académie des sciences in Paris, remarked on the clearness and richness of image details; see *Comptes rendus* 61 (1865): 516.

19 Faye, "Sur les photographies de la lune de M. Lewis Rutherfurd," *Comptes rendus* 75 (1872): 1071–74.

20 "Astronomical Photographs," *English Mechanic* 13 (1871): 636; see also, advertisement in *Observatory*, vol. 1 (1877–88).

21 Lewis M. Rutherfurd to Alexander Wilcocks, December 11, 1865, in the *Philadelphia Photographer* 3 (1866): 58–59.

er to obtain images of the 9th magnitude stars with so moderate an aperture promises to develop and increase the applications of photography to the mapping of the sidereal heavens."[22] With stars this faint it was difficult to distinguish real images from spots in the collodion. De La Rue had circumvented this problem by putting the plate slightly outside the photographic focus, thus getting slightly blurred stellar images rather than point images that could be confused with the spots. Rutherfurd's solution was to take one good impression, stop the clock drive for a few seconds, then restart the clock and take a second impression on the same plate. Thus, the star images were double, and the spots were not. Furthermore, connecting the images of a bright star was a star trail, an image of an arc of constant declination, which was useful for measuring position angles.

The primary purpose of photographing star clusters was to measure the relative positions of the stars in order to determine proper motions and parallax. As soon as the first pictures were dry, Rutherfurd, with various female assistants, measured the photographic plates, and then Gould, acting on Gibbs's suggestion, reduced the figures. From Rutherfurd's linear measures of the distances between the stars in the Pleiades, Gould derived the angular distances and compared them with the results of visual measurements. In August 1866, at the Northampton meeting of the National Academy of Sciences, Rutherfurd described his techniques and showed pictures of his apparatus for photographing and measuring star clusters. Rutherfurd's talk was never published. The one reporter who covered the talk omitted mention of all details of Rutherfurd's apparatus, but he wrote, "The extraordinary accuracy of the work done by it we can only measure by the amazement of the authorities present, who pressed eagerly about him."[23] At the same meeting, Gould discussed his reductions of the Pleiades plates and made a strong argument for the use of photography in "practical astronomical research."

The following year Gould presented his reductions of the Praesepe pictures. The impact of this work was less than it might have been, because Gould refrained from publishing his papers until Rutherfurd published his. Indeed, the only contemporary published account of Rutherfurd's star photographs was an all-too-brief note from Gould to the editors of the *Astronomische Nachrichten*.[24] Even briefer notices

[22] Rutherfurd, "Astronomical Photography" (see n. 9 above), pp. 308–9.

[23] "Improved Apparatus for Astronomical Observation," *Annual of Scientific Discovery for 1866 & 1867* (Boston, 1867), pp. 349–50.

[24] "Schreiben des Herrn Dr. Gould an den Herausgeber," *Astronomische Nachrichten* 68 (1866–67): 183–86.

of this same work appeared in various photographic journals in 1870.[25] Not until 1888 did Gould realize the futility of his polite wait, and see his own papers published.[26]

Although Rutherfurd intended to measure all his plates, and reduce the measurements to celestial positions, poor health and other projects prevented him from actually doing so. In 1890 he gave all his negatives of the sun, moon, solar spectrum, and star groups, twenty folio volumes containing measures of many of the plates, and a sum of money, to Columbia University. Seven years earlier he had given most of his astronomical apparatus to this school, of which he had been a trustee since 1858. The work of measuring and reducing the photographs was then undertaken by faculty and doctoral candidates, and the results were issued in volumes 1–4 of the *Contributions from the [Rutherfurd] Observatory of Columbia University.*

Micrometers

For measuring the stellar photographs, a micrometer, or reading microscope, was needed. As very few of these instruments had yet been made or used, Rutherfurd was forced to devise his own. The fate of his first two micrometers is still unknown, and no pictures or descriptions of them have yet come to light. There is evidence, however, that they were essentially similar to an instrument marked "L. M. R. No. 3 1870" which is now in the collections of the National Museum of History and Technology. In this micrometer (fig. 2), the photographic plate was held on a horizontal bed, illuminated from below, and read from above through a microscope. For obtaining measures in rectangular coordinates, the microscope was moved over the plate by two mutually perpendicular micrometer screws. For determining position angles, the plate and its bed were rotated, and the angular distance read on a graduated circle.

Despite his most painstaking efforts, Rutherfurd was never satisfied with this first form of micrometer. At the 1870 meeting of the National Academy of Sciences, he explained that he "had been obliged to give up the idea of using screws on account of the rapid changes in their errors caused by friction and consequent wear," and he described his plans for an improved instrument. This new micrometer, in use by

25 "Photography among the Pleiades," *Anthony's Photographic Bulletin* 1 (1870): 90. See also, *Photographische Mittheilungen* 6 (1870): 270.

26 Benjamin A. Gould, "On the Reduction of Photographic Observations, with a Determination of the Position of the Pleiades, from Photographs by Mr. Rutherfurd"; and idem, "Reduction of Photographic Observations of the Praesepe," *Memoirs, National Academy of Sciences* 4, pt. 1 (1888): 173–90, 193–99.

March 1871, proved notably more reliable than the earlier versions.[27] The base and graduated circle for position angles of the improved micrometer were similar to those used in "L. M. R. No. 3 1870." The micrometer screws, however, were replaced by two mutually perpendicular divided glass scales. As the viewing microscope moved over

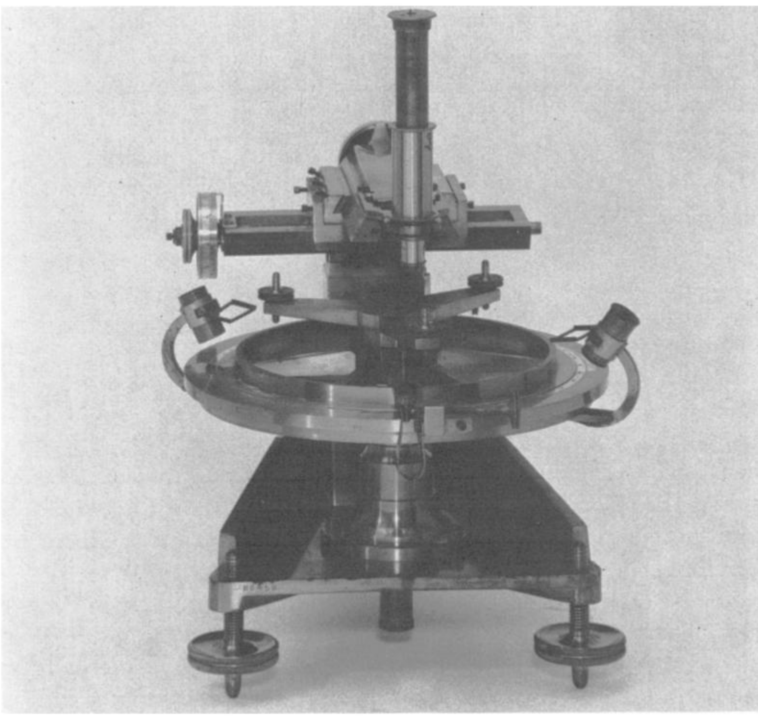


Fig. 2.—Micrometer for celestial photographs, marked "L. M. R. No 3 1870" (in National Museum of History and Technology, Smithsonian Institution); photo courtesy Smithsonian Institution.

the photographic plate, it carried two reading microscopes past the scales (see the cover design and fig. 3).

Besides making photographic micrometers for his own use, Rutherfurd was largely responsible for their diffusion throughout the astronomical community. The "L. M. R. No. 3 1870" was made from Rutherfurd's own designs, and under his immediate supervision, for the U.S. Coast Survey. In preparation for the 1874 transit of Venus, the micrometer was intended to illustrate the reliability of photography

[27] Lewis M. Rutherfurd, "A Glass Circle for the Measurement of Angles," *American Journal of Science* 12 (1876): 112.

for solar observations. Accordingly, its first assignment was measuring photographs taken during the total solar eclipse of August 7, 1869. In the opinion of Benjamin Peirce, then superintendent of the Coast Survey, the results indicated the "exceeding value" of this method, and its "decided superiority . . . to the observations of contact with eye and ear, as hitherto practiced."[28]

This micrometer was later used by Charles S. Peirce, also of the Coast Survey, to compare the lengths of various centimeter scales for his study of the acceleration of gravity.[29] Rutherfurd's improved, glass-

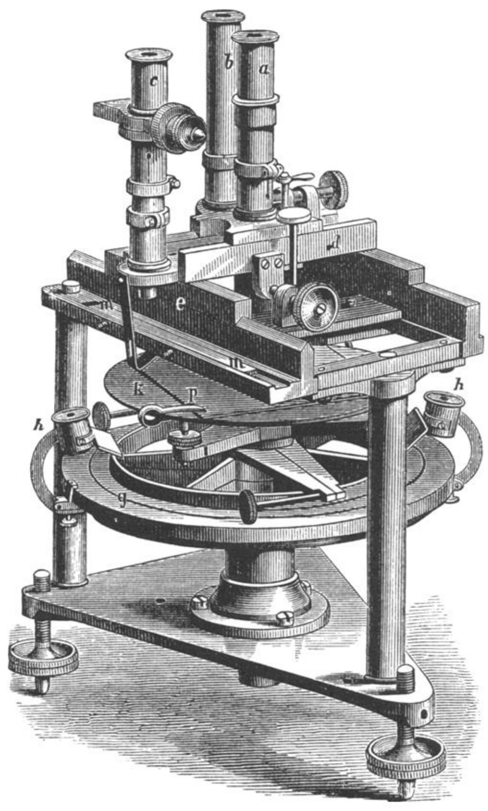


FIG. 3.—Rutherfurd's improved micrometer for celestial photographs, employing graduated glass scales rather than micrometer screws (from *The American Cyclopaedia* [New York, 1875], 11:512); photo courtesy Smithsonian Institution.

[28] Charles A. Schott, "Report on the Results of the Micrometric Measures of Photographic Pictures of the Solar Eclipse, of August 7, 1869, taken at Springfield, Illinois," *U.S. Coast Survey Report for 1869*, p. 186.

[29] C. S. Peirce, "Measurements of Gravity at Initial Stations in America and Europe," *U.S. Coast Survey Report for 1876* (Appendix 15), pp. 282–89.

scale micrometer was illustrated and extensively described in the *American Cyclopaedia*, published in 1875.[30] Photographs taken by the American expeditions to observe the transit of Venus of 1874, and probably that of 1882 as well, were measured by micrometers built according to Rutherfurd's pattern.[31] Gould's stellar photographs taken at Cordoba were measured with a micrometer supplied by Rutherfurd.[32]

The reliability of the linear glass scales of his improved micrometer led Rutherfurd to suggest that glass circles might replace the metal ones commonly used in scientific instruments. In 1867 he had Stackpole, a well-known New York instrument maker, graduate a glass circle of about 10 inches diameter. Using a diamond stylus, Stackpole could scratch very fine lines 10 minutes of arc apart. Because the glass permitted good illumination, with micrometer microscopes the graduated circle could be read to single seconds. Rutherfurd substituted this glass circle for the metal one in a small spectrometer and was pleased with the results.[33]

Although few doubted that celestial photographs could be accurately measured, there was a healthy skepticism about the permanence of photographic plates. By how much and how evenly did a photograph expand or contract after exposure? The Bonds made a point of showing how closely their measures of Mizar and Alcor agreed with the visual measures made by Struve;[34] and Gould compared Rutherfurd's results with those Bessel had obtained with a heliometer. The question of the stability of the photographs became especially crucial in the early 1870s, when plans were being made to observe the transit of Venus. These transits occur so seldom, and the 1874 one would only be visible so far from centers of Western civilization, that it would have been foolhardy to have risked all on an as-yet-unproven technique. Rutherfurd's confidence in collodion plates and his work with micrometers were strong factors in the decisions to rely on photographic observations of this event. In 1873 Rutherfurd presented his results of tests of wet collodion film on glass plates properly albumenized.[35] His micrometric measures

[30] "Micrometer," *The American Cyclopaedia* (New York, 1875), 11:512.

[31] Charles André and A. Angot, *L'astronomie pratique et les observatoires en Europe et en Amérique* (Paris, 1877), 3:152–53.

[32] Benjamin A. Gould, *Cordoba Photographs* (Lynn, Mass., 1897), p. 5.

[33] Rutherfurd, "A Glass Circle for the Measurement of Angles" (see n. 27 above), pp. 112–13.

[34] "Letter from Mr. Bond, Director of the Observatory, Cambridge, U.S., to the Secretary," *Monthly Notices* 17 (1856–57): 230–32.

[35] Lewis M. Rutherfurd, "On the Stability of the Collodion Film," *American Journal of Science* 4 (1873): 430–33.

of numerous photographs of star clusters, taken over many years, were "so concordant as to forbid the idea of the existence of any great change in the collodion film." Perhaps, however, the plates change size between exposure and later measures. To test this possibility, he had Chapman measure plates just removed from the camera and still quite wet and then remeasure them when dry: the greatest disparity, attributable to contraction of the glass plate while drying, was no larger than the usual errors of visual observations. Stellar photography required film that was fast as well as stable, and so Chapman performed a series of experiments comparing the sensitivity and stability of various wet collodion films.[36]

The 13-Inch Refractor and Solar Photography

In 1868 Rutherfurd replaced his visual/photographic telescope with one of an entirely new and original design. The new telescope had an aperture of 13 inches, 1¾ inches larger than the earlier instrument. More than size, however, was involved. With the smaller instrument it was necessary to change the whole objective lens combination when changing from visual to photographic observations. The new telescope was easier to manipulate. The basic lens was a common visual achromat, with crown-glass and flint-glass components. The photographic correction was concentrated in a third meniscus lens of flint glass. For photographic work, the "corrector" was added to the outside of the objective lens, and the counterpoises of the telescope suitably altered.[37] These lenses were figured by the younger Fitz in Rutherfurd's house and under Rutherfurd's direct supervision. Rutherfurd gave Fitz the 11¼-inch photographic lens in partial payment for his work, and Fitz in turn sold it to Gould at Cordoba. When the 11¼-inch objective broke, Rutherfurd calculated the curves and supervised Fitz's construction of another similar one for Gould. The actual work of photographing the southern skies with these instruments was done by photographers trained by Rutherfurd in his own observatory.[38] After using the 13-inch with great success for many years, Rutherfurd gave it to Columbia University. It is now on loan to the National Museum of History and Technology.

The 13-inch served as a model for at least two other telescopes. Rutherfurd, assembling the photographic apparatus for the American expedition to Sicily to observe the total solar eclipse of December 1870, selected a 6¼-inch visual achromat and had Fitz figure a photographic

36 D. C. Chapman, "Astronomical Photography," *British Journal of Photography* 22 (1875): 630–31.

37 Robert J. Mann, "Mr. Lewis Rutherfurd's Photographs of the Sun and Fixed Stars," *Photographic News* 15 (1871): 294–95.

38 Benjamin A. Gould, "Celestial Photography," *Observatory* 2 (1878–79): 16.

corrector.[39] Unable to join the eclipse expedition, Rutherfurd entrusted the photographic observations to Chapman and Fitz.[40] More important was the great 36-inch triple-objective lens figured by Alvan Clark & Sons for the Lick Observatory.

With his 13-inch telescope Rutherfurd took some exceptionally fine daily photographs of the sun.[41] Ten years earlier, using his $11\frac{1}{4}$-inch visual achromat, he had taken solar pictures which showed "the spots with reasonable sharpness, the manifest difference in light between the center and the edge, and under favorable circumstances the faculae."[42] Pictures taken with the larger photographic telescope not only brought out the detailed structure of sunspots but also showed clearly, for the first time, the granulation of the solar surface.[43] Rutherfurd's pictures, equal to if not better than all previous ones, were often reproduced. Figure 1 of Angelo Secchi's *Le soleil* shows the sun taken by Rutherfurd.[44] A series of photographs showing the daily development of sunspots appeared in the Franklin Institute's *Journal.*[45]

During this experimental period, there was a lengthy debate over the best time to enlarge a photograph. Rutherfurd's standard procedure was to enlarge the solar image to about 3 inches diameter before it reached the photographic plate. When the commission authorized by Congress to prepare for the 1874 transit of Venus asked Rutherfurd's advice, he recommended a 5-inch-aperture visual achromat with photographic corrector and an enlarging lens.[46] The commission chose instead to follow Joseph Winlock, director of the Harvard College Observatory, who had been photographing the sun with a heliostat and fixed horizontal refracting telescope; Winlock's objective lens had such a long focal length that there was no need to employ either a photographic corrector or a separate enlarging lens.

[39] Daniel C. Chapman, "Photographing the Solar Eclipse of 1870," *Transactions, American Institute* (1870–71), p. 1124.

[40] Hermann Vogel, "The Solar Eclipse in Sicily," *Photographic News* 15 (1871): 66–67.

[41] Hermann Vogel, "Astronomical Photography in America" (n. 11 above), p. 39.

[42] Rutherfurd, "Astronomical Photography" (n. 9 above), p. 305.

[43] Lewis M. Rutherfurd's comments at May 10, 1878 meeting of Royal Astronomical Society, quoted in *Observatory* 2 (1878–79): 42.

[44] Angelo Secchi, *Le soleil* (Paris, 1875), 1:4.

[45] See *Journal, Franklin Institute,* vol. 60 (1870), plate 1; and idem, vol. 61 (1871), plate 2.

[46] Lewis M. Rutherfurd to B. F. Sands, February 11, 1872, in *Papers Relating to the Transit of Venus in 1874, Prepared under the Direction of the Commission Authorized by Congress, and Published by Authority of the Hon. Secretary of the Navy,* pt. 1 (Washington, D.C., 1872), p. 13.

Solar Spectrography

Combining his interests in photography and spectroscopy, Rutherfurd tackled the problem of photographing the solar spectrum. Although the reasons are obscure, Rutherfurd's results are not. Both his prismatic and diffraction spectrographs were excellent and, in many cases, notably better than those that had gone before.

Rutherfurd worked first with prismatic spectra, his first efforts coming early in 1863, soon after he had assembled his multiprism spectroscope. Within a year, he had taken spectrographs good enough to be shown to the National Academy of Sciences and then to European audiences and to evoke expressions of respectful admiration. After seeing a copy of the spectrograph and comparing it with his hand-drawn picture of the solar spectrum, Kirchhoff is reputed to have said that Rutherfurd's work, had it come sooner, would have saved him a year's labor.[47] Lockyer considered Rutherfurd's spectrograph the "most magnificent photograph" it was possible to obtain.[48]

Rutherfurd himself never published his spectrograph nor any account of the methods he used to achieve it. Not until 1869 was a portion of it finally published together with the corresponding portion of Kirchhoff's drawing. It was then republished several times during the succeeding decades.[49]

Details about this solar spectrum were given by Roscoe in 1865, when he showed a copy of it to the Manchester Literary and Philosophical Society:[50]

> These photographs exhibit groups of thousands of lines, extending from near the line b in the green, to beyond H in the violet, and serve as a most valuable confirmation of the accuracy of Kirchhoff's maps. Each line in these maps can be easily and distinctly traced in the photograph, whilst many bands drawn as single ones by Kirchhoff are seen in the magnified photograph to consist of bundles of fine lines. These photographs were prepared with three 60° bisulphide of carbon prisms.

Further details were related by J. Müller,[51] who had also tried, but with less success, to photograph the solar spectrum, and by Hermann

[47] Quoted in *American Journal of Photography* 8 (1865–66): 135–36.

[48] J. Norman Lockyer, "On Spectrum Photography," *Nature* 10 (1874): 254.

[49] See Henry Roscoe, *Spectrum Analysis* (London, 1869), p. 186; C. Piazzi Smyth, *Madeira Spectroscopic* (Edinburgh, 1882), p. 2; and H. Schellen, *Die Spectralanalyse* (Braunschweig, 1883), p. 206.

[50] Quoted in *Quarterly Journal of Science* 2 (1865): 319.

[51] J. Müller, "Rutherfurd's Photographie des Spectrums," *Annalen der Physik und Chemie* 126 (1865): 435–40.

Vogel.[52] Owing to the limited field of Rutherfurd's apparatus and the change in sensitivity of his collodion with wavelength of light, the spectrum had been photographed in fifteen overlapping sections. When assembled, the complete prismatic spectrograph measured 2.1 meters in length.

During the 1870s, equipped with his diffraction gratings, Rutherfurd photographed the normal solar spectrum. This work was as noteworthy as his prismatic spectrographs, but again he neglected to publish either a picture or description of it. Rutherfurd did, however, exhibit a diffraction spectrograph to various professional groups—in London, in May 1878, he showed it to the Royal Astronomical Society[53] and to the Physical Society[54]—and his comments were recorded in the published accounts of their meetings. In order to admit as much light as possible, especially light of the longer wavelengths to which his emulsion was less sensitive, Rutherfurd had widened the slit and greatly increased the focal length of his collimator. The sunlight was then dispersed by a speculum metal grating with 17,296 lines per inch. The complete spectrograph, which covered the second-order spectrum from below E (λ 5270 Å) in the green to the ultraviolet, was a composite of twenty-eight separate pictures taken with different exposures. From the original negatives, Rutherfurd had made enlarged positives, and from these he made further enlarged negatives, so that the resultant picture was about 10-feet long.

Multiprism Spectroscopes

Rutherfurd's first spectroscopic observations, like those of most investigators prior to and including 1859, were made with a simple chemical spectroscope with one 60-degree flint-glass prism. During the 1860s, when, for the first time, it was found desirable to procure a spectrum as widely dispersed as possible, several scientists and instrument makers developed multiprism spectroscopes. Rutherfurd approached the problem in the winter of 1862–63, and produced a 6-prism instrument.[55] An essential problem was adjusting batteries of prisms for angle of minimum deviation. Rutherfurd's solution, like that of John Browning in London, was to attach to the back of each prism a slotted brass bar which fit over a pin in the center of the platform. These brass bars ensured that the backs of the prisms were always perpendicular to the

[52] Vogel, "Astronomical Photography in America" (n. 11), p. 31.

[53] Rutherfurd, comments at May 10, 1878 meeting of Royal Astronomical Society (n. 43 above), pp. 42–43.

[54] Report of May 25, 1878 meeting of Physical Society, in *Nature* 18 (1878): 271.

[55] Lewis M. Rutherfurd, "On the Construction of the Spectroscope," *American Journal of Science* 39 (1865): 129–32.

radius of the platform. The six prisms were linked together by means of hinges at their back corners, so a motion imparted to one prism was communicated to all the others. The bar of the third prism was provided with teeth so that, by turning the geared central pin, this prism, and thus all the prisms, were moved radially across the platform.

The prisms presented as many problems as the mechanical adjustments. Solid flint glass was rejected because of its usual unevenness, small dispersion, and great expense. The common substitute, which Rutherfurd adopted, was a hollow glass prism filled with liquid carbon bisulphide. The frames of the prisms were of brass cast in one piece: the faces that would receive the glass plates were then filed flat, and the bases were filed so the refracting surfaces were perpendicular to the platform of the instrument. Pieces of plane glass with sufficiently parallel faces, for two of the sides of the prisms, were almost impossible to obtain. Rutherfurd finally settled on plates that had been made originally for shades for artificial horizons.[56] These he attached to the frames by a mixture of hot molasses and glue. Finally the prisms were filled with carbon bisulphide and covered with a ground glass stopper. Since commercially available carbon bisulphide was far from homogeneous, Rutherfurd kept a large quantity in a tall jar until it stratified according to density. Having solved these problems, Rutherfurd not only prepared prisms for his own use, but he made at least one set for his friend Gibbs as well.[57]

Another approach to the problem of increasing dispersion was to increase the refracting angle of the prism without increasing the loss of light by reflection at the front and back surfaces. This meant making compound prisms—prisms composed of more than one piece of glass. Rutherfurd was but one of the many scientists who worked in this area, and his designs seem to have been particularly effective. As early as 1871 he had Browning make a compound prism of two dense flint-glass prisms of 90-degree refracting angle and three crown-glass prisms; Browning thought this plan possessed some advantages over others hitherto tried.[58] Another Rutherfurd pattern, well adapted for star spectroscopes, consisted of one flint-glass prism of up to 90-degree refracting angle surrounded by two crown-glass prisms of small dispersion.[59]

[56] Lewis M. Rutherfurd, "Letter on Companion to Sirius, Stellar Spectra, and the Spectroscope," *American Journal of Science* 35 (1863): 407–9.

[57] Rutherfurd to Gibbs, February 19, 1865 and March 6, 1865, Wolcott Gibbs Correspondence, Franklin Institute, Philadelphia.

[58] John Browning, "Note of the Use of Compound Prisms," *Monthly Notices, Royal Astronomical Society* 31 (1870–71): 205.

[59] Julius Scheiner, *Astronomical Spectroscopy,* trans. E. B. Frost (Boston, 1894), pp. 8–9.

Diffraction Gratings

Almost all of the studies of spectrum analysis during the decade of the 1860s were done with prismatic spectra. The only available diffraction gratings were those ruled by Friedrich A. Nobert, of Griefswald, Pomerania; and, for many spectroscopists, these gratings were both expensive and difficult to obtain. During the following decade, thanks to the efforts of Rutherfurd, diffraction spectroscopy was widely pursued. With the help of Chapman, Rutherfurd devised engines for ruling gratings with lines more evenly spaced than those ruled by Nobert. Then, with his customary generosity, he freely made these gratings available to all who could profit from their use. Although Rutherfurd's gratings continued to be used throughout the century, they were surpassed in the 1880s by the still larger and more regular gratings ruled on Henry A. Rowland's engines.

Rutherfurd began experimenting with ruling engines as early as 1863. Gibbs[60] and Rood[61] were both interested in studying diffraction spectra and were preparing suitable instruments at that time. Considering their reliance on Rutherfurd for help in obtaining prismatic spectroscopes, it is more than likely that their enthusiasm encouraged him to attempt to improve on the available gratings. In Rutherfurd's first engine, after each line was ruled by a diamond stylus, the glass plate was pushed sideways by means of a system of levers. Motive power was provided by a turbine run by water from the city pipes. According to Gould, this machine ruled "admirable" gratings except that at times, after scratching several hundred regularly spaced lines, it would scratch a group of lines with a slightly different frequency. With Rood's help, the trouble was found in the varying friction in the machine and deemed impossible to correct.[62] There is no evidence that gratings ruled on this first machine were ever actually used.

In 1867 Rutherfurd began construction of a ruling engine in which the plate was moved to the next position by means of a screw rather than a system of levers. This design proved much more successful than the original one. The screw, the most critical part of the machine, was very carefully made, and errors caused by its eccentricity could be counteracted by means of an opposite eccentricity given to the feed

[60] Gibbs to Rood, April 15, 1863, Wolcott Gibbs Correspondence, Franklin Institute, Philadelphia.

[61] Gibbs to Rood, October 20, 1862, Rood Papers, Columbia University, New York.

[62] Benjamin A. Gould, "Memoir of Lewis Morris Rutherfurd" (n. 1 above), pp. 428–29.

wheel of the engine[63] (see fig. 4). In March 1870, while still perfecting this engine, Rutherfurd finally received three gratings ruled by Nobert. Nobert had closely guarded his techniques so that others could not copy his work.[64] After examining Nobert's gratings, Rutherfurd and Rood concluded that they resembled those produced by Rutherfurd's first engine: since the spacing errors were irregular rather than periodic, Nobert had doubtlessly not used a screw. Rutherfurd wrote immediately to Gibbs, "I am overhauling and amending my scratching ma-

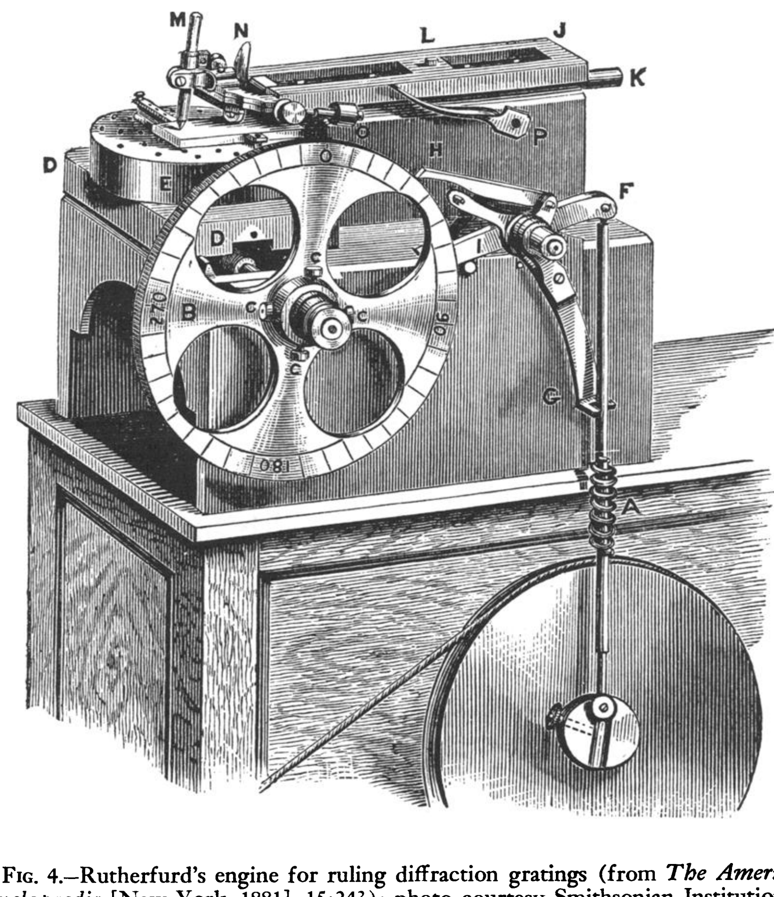


FIG. 4.—Rutherfurd's engine for ruling diffraction gratings (from *The American Cyclopaedia* [New York, 1881], 15:243); photo courtesy Smithsonian Institution.

[63] Rutherfurd's improved engine is described and illustrated in the article on "Spectrum" in *The American Cyclopaedia* (New York, 1881), 15:242–44.

[64] William A. Rogers, "On Nobert's Machine," *Proceedings, American Academy of Arts and Sciences* 11 (1875): 237–55.

chine, encouraged by finding that even Nobert can turn out mediocre work."[65]

In fact, Rutherfurd's ruling engine was modified several times to produce gratings with longer lines, covering wider areas. The early gratings were 0.64 inches (1.63 cm.) wide, with lines 1.08 inches (2.74 cm.) long. By 1877 the engine was enlarged to rule gratings about 1.7 inches (4.3 cm.) square, with spacings up to 17,296 lines per inch.

The first public announcement of Rutherfurd's diffraction gratings was made at a soiree of the Royal Society in April 1871. John Browning, the British scientific instrument maker, exhibited "a diffraction spectrum produced by means of fine lines cut about 1/1500 of an inch apart from each other on the surface of a small piece of glass," and explained that the plate had been prepared by Rutherfurd, who was then visiting London.[66] Rutherfurd attended a meeting of the Royal Astronomical Society that same month; but, curiously enough, although he spoke at length at the meeting and although many active astronomical spectroscopists were present, Rutherfurd appears to have said nothing about his gratings.[67]

Not until the end of 1872 was Rutherfurd sufficiently satisfied with his *gitter platter*, as the gratings were frequently called, to begin distributing them. At that time, Rood wrote to Gibbs, "Mr. Rutherfurd will only be too glad to present you with all the plates you want: he told me they were to be for his friends."[68] As is to be expected, Rutherfurd had numerous friends. He freely distributed at least fifty gratings to scientists around the world and in so doing made diffraction spectroscopy both possible and popular. Table 1, "Rutherfurd's Diffraction Gratings," gleaned from the general literature and far from exhaustive, indicates the impact of these gratings on the practical spectroscopic studies done during the 1870s. The table is ordered according to grating spacing in lines per inch, the most important and most frequently known dimension.

Most of the men who used Rutherfurd gratings were trying to decipher the chemical messages in the spectra. Charles S. Peirce, on the other hand, aware that standard meter bars were not invariable, was search-

[65] Rutherfurd to Gibbs, March 4, 1870, Wolcott Gibbs Correspondence, Franklin Institute, Philadelphia.

[66] "The Soiree at the Royal Society," *Engineer* 31 (1871): 289.

[67] Report of meeting of Royal Astronomical Society, April 14, 1871, in *English Mechanic* 13 (1871): 129.

[68] Rood to Gibbs, November 3, 1872, Wolcott Gibbs Correspondence, Franklin Institute, Philadelphia.

TABLE 1

RUTHERFURD'S DIFFRACTION GRATINGS

Spacing (Lines per Inch)	User	Date	Material	Size	Signature
1,500	Lewis M. Rutherfurd[1]	1871	Glass	...	...
	Henry Morton[2]	1873	...	...	...
	Etienne L. Trouvelot[3]	1882	...	...	...
	Henri Becquerel (grating owned by Mascart)[4]	1883	Glass	...	...
	Henri Becquerel (grating owned by Mascart)[4]	1883	Metal	...	...
	Charles H. Rockwell[5]	1883	...	...	...
Less than 17,200	William de Wivesley Abney[6]	1886	Glass (plate prepared by Adam Hilger)	...	Chapman
About 4,000	Angelo Secchi[7]	1874	Glass	...	...
About 4,000	Angelo Secchi[7]	1874	Metal	...	...
4,320	Ogden N. Rood[8]	1873	Glass	...	...
4,320	Thomas C. Mendenhall[9]	1877	Glass	...	...
5,760	Charles A. Young[10]	1877	Metal	10 cm. wide; lines 4.3 cm. long	"Aug. 24, 1877, 5760 per inch, 11,280 spaces, D. C. Chapman, 175 2 Ave. N.Y."
6,480	Ogden N. Rood[8]	1873	Glass	...	...
6,480	Charles A. Young[11]	1873	Metal	...	Chapman
6,480	John M. Blake[12]	1874	Glass	...	...
6,480	Wolcott Gibbs[13]	1874	...	...	...
6,480	Edward C. Pickering[14]	1874	...	...	...
6,481	Henry Draper[15]	1873	Glass	1.6 cm. wide; lines 2.7 cm. long	...

[1] "The Soiree at the Royal Society," *Engineer* 31 (1871): 289.

[2] *Scientific American* 28 (1873): 384–85.

[3] E. L. Trouvelot, *The Trouvelot Astronomical Drawing Manual* (New York, 1882), p. vi.

[4] H. Becquerel, "Phosphorographie de la région infra-rouge du spectre solaire," *Comptes rendus* 96 (1883): 121–24.

[5] E. S. Holden, "The Total Solar Eclipse of May 6, 1883," *Proceedings, American Association for the Advancement of Science* 32 (1883): 72–76.

[6] W. de W. Abney, "The Solar Spectrum from λ7,150 to λ10,000," *Philosophical Transactions* 177 (1886): 457–69.

[7] A. Secchi, *Le soleil* (Paris, 1875), p. 238.

[8] O. N. Rood, "On a Secondary-Spectrum of Very Large Size," *American Journal of Science* 6 (1873): 174.

[9] T. C. Mendenhall, "On the Wave Length of the Blue Line of the Spectrum of Indium," *Proceedings, American Association for the Advancement of Science* 26 (1877): 125–26.

[10] Now in National Museum of History and Technology, donated by Princeton University Observatory.

[11] C. A. Young, "Note on the Use of a Diffraction 'Grating' as a Substitute for the Train of Prisms in a Solar Spectroscope," *American Journal of Science* 5 (1873): 472–73.

[12] J. M. Blake, "Notes on Diffraction Gratings," *American Journal of Science* 8 (1874): 33–39.

[13] Rood to Gibbs, January 26, 1874, Wolcott Gibbs Correspondence, Franklin Institute, Philadelphia.

[14] E. C. Pickering, "Comparison of Prismatic and Diffraction Spectra," *Proceedings, American Academy of Arts and Sciences* 11 (1874): 274.

[15] H. Draper, "On Diffraction-Spectrum Photography," *Philosophical Magazine* 46 (1873): 419. Draper used other Rutherfurd gratings as well, but details are unknown; see Draper, "On Photographing the Spectra of the Stars and Planets," *American Journal of Science* 18 (1879): 423.

TABLE 1—*Continued*

Spacing (Lines per Inch)	User	Date	Material	Size	Signature
6,481	John C. Draper[16]	1875	Metal	...	...
6,481	Emil Rosenberg[17]	1878	Glass	...	...
7,021	William C. Winlock[18]	1879	Metal	...	...
About 8,000	Joseph Lovering[19]	1877	Glass	...	...
8,640	Edward C. Pickering[14]	1875	...	...	...
8,640	Charles A. Young[20]	1876	Glass	...	...
8,640	Samuel Pierpont Langley[21]	1877	Metal	...	...
8,640	William C. Winlock[18]	1877	Metal	5.2 cm. wide; lines 4.3 cm. long	"Aug. 2, 1877, 8640 per in., 17,640 spaces., Man'f by D. C. Chapman with Mr. Rutherfurd's engine. 175 2 Ave., N.Y."
8,640	William de Wivesley Abney[22]	1878	Metal	...	...
8,648	Charles S. Hastings[23]	1880	Metal	...	...
8,648	Thomas C. Mendenhall[24]	1881	Metal (alloy of tin and copper)	...	...
12,080	Robert Amory[25]	1875	Metal	...	...
12,960	Edward C. Pickering[14]	1875	...	...	...
13,321	William C. Winlock[18]	1879	Glass	...	...
About 17,000	Cyrus Fogg Brackett[26]	1882	...	...	...
17,270	Charles Fievez[27]	1883	...	5 cm. wide; lines 4 cm. long	Chapman
17,280	Edward C. Pickering[14]	1875	...	...	...
17,280	Charles A. Young[20]	1876	...	...	...
17,280	J. Norman Lockyer[28]	1877	Glass (the ruled silvered surface was covered with another plate of glass for protection)	1.96 cm. wide; lines 2.5 cm. long	...

[16] J. C. Draper, "The Fraunhofer Lines of Diffraction and Prismatic Spectra," *Scientific American* 33 (1875): 265.

[17] E. Rosenberg, "A New Method of Reduction for Diffraction Spectra Observations," *Journal, Franklin Institute* 106 (1878): 95–100.

[18] W. C. Winlock, "On the Group 'b' in the Solar Spectrum," *Proceedings, American Academy of Arts and Sciences* 16 (1880): 400.

[19] Lovering to Rood, November 5, 1877, Rood Papers, Columbia University, New York.

[20] C. A. Young, "Note on the Duplicity of the '1474' Line in the Solar Spectrum," *American Journal of Science* 11 (1876): 429–31; see also idem "Observations on the Displacement of Lines in the Solar Spectrum Caused by the Sun's Rotation," ibid. 12 (1876): 321–28.

[21] S. P. Langley, "A Proposed New Method of Solar Spectrum Analysis," *American Journal of Science* 14 (1877): 140–46.

[22] W. de W. Abney, "Photography at the Least Refrangible End of the Spectrum and on Some Photographic Phenomena," *Photographic Journal* 2 (1877–78): 80–85.

[23] C. S. Hastings, "A Theory of the Constitution of the Sun, Founded upon Spectroscopic Observations, Original and Other," *Proceedings, American Academy of Arts and Sciences* 16 (1880–81): 140–52.

[24] T. C. Mendenhall, "On the Determination of the Coefficient of Expansion of a Diffraction Grating by Means of the Spectrum," *American Journal of Science* 21 (1881): 230–32.

[25] R. Amory, "On Photographs of the Solar Spectrum," *Proceedings, American Academy of Arts and Sciences* 11 (1875): 70.

[26] C. F. Brackett, "Note on the Littrow Form of Spectroscope," *American Journal of Science* 24 (1882): 60–61.

[27] C. Fievez, "Etude du spectre solaire," *Annales de l'Observatoire royal de Bruxelles* 4 (1883): C.

[28] J. N. Lockyer, "On the Use of the Reflection Grating in Eclipse Photography," *Proceedings, Royal Society* 27 (1878): 107–8; see also idem, "Researches in Spectrum-Analysis in Connection with the Spectrum of the Sun," no. 5, *Philosophical Transactions* 172 (1881): 561–76.

TABLE 1—*Continued*

Spacing (Lines per Inch)	User	Date	Material	Size	Signature
17,280	W. de W. Abney (grating owned by Lockyer)[29]	1877	Glass	4.3 cm. wide; lines 4.3 cm. long	Ruled by Mr. Chapman of New York with Mr. Rutherfurd's ruling machine.
17,280	John C. Draper[30]	1878	Glass	...	...
17,280	John K. Rees[31]	1878	...	...	...
17,290	Henry E. Roscoe and A. Schuster[32]	1882	...	...	...
17,296	Samuel Pierpont Langley[33]	1877	Metal	4.3 cm. wide; lines 4.3 cm. long	...
17,296	Lewis M. Rutherfurd[34]	1878	Metal	...	...
17,296	William C. Winlock[18]	1879	Metal	4.8 cm. wide; lines 4.3 cm. long	...
17,296	C. Piazzi Smyth[35]	1880	Metal	1.6 inches sq.	...
17,296	Charles A. Young[36]	1880	Metal	4.3 cm. wide; lines 4.3 cm. long	"Feb. 1880, 29,880 spaces, 17,296 per inch, Manuf. by D. C. Chapman with L. M. Rutherfurd's machine."
17,296	Charles S. Hastings[37]	1880	Metal	...	...
17,296	George D. Liveing and James Dewar[38]	1881	Metal	4.3 cm. wide; lines 4.3 cm. long	Chapman
17,296	Ernst Pringsheim[39]	1882	Metal	4.3 cm. wide; lines 4.3 cm. long	Chapman
17,460	Walter N. Hartley[40]	1882	...	...	...
Nearly 19,000	Ogden N. Rood[41]	1879	Glass	...	...
Over 30,000	Charles S. Hastings[42]	1882	...	...	...

[29] W. de W. Abney, "Photographic Spectra Showing the Sun's Rotation,'' *Observatory* 1 (1877): 134–35; see also idem, "On the Photographic Method of Mapping the Least Refrangible End of the Solar Spectrum," *Philosophical Transactions* 171 (1880): 659.

[30] J. C. Draper, "On the Presence of Dark Lines in the Solar Spectrum, Which Correspond Closely to the Lines of the Spectrum of Oxygen," *American Journal of Science* 16 (1878): 257.

[31] *Annual Record of Science and Industry* (1878), p. 74.

[32] H. E. Roscoe and A. Schuster, "The Spectrum of Terbium," *Journal, Chemical Society* 41 (1882): 283.

[33] S. P. Langley, "A Proposed New Method of Solar Spectrum Analysis" (n. 21 above); see also idem, "On Certain Remarkable Groups in the Lower Spectrum," *Proceedings, American Academy of Arts and Sciences* 14 (1878–79): 92–105.

[34] L. M. Rutherfurd's comments at May 10, 1878 meeting of Royal Astronomical Society, quoted in *Observatory* 2 (1878–79): 42; and report of May 25, 1878 meeting of Physical Society in *Nature* 18 (1878): 271.

[35] C. P. Smyth, *Madeira Spectroscopic* (Edinburgh, 1882), p. 1. Smyth had two identical gratings.

[36] Now in National Museum of History and Technology, donated by Princeton University Observatory. See C. A. Young, "Spectroscopic Notes, 1879–80," *American Journal of Science* 20 (1880): 354.

[37] Hastings (n. 23 above); Hastings was at Princeton when he did this work.

[38] G. D. Liveing and J. Dewar, "On the Identity of Spectral Lines of Different Elements," *Proceedings, Royal Society* 32 (1881): 225; see also idem, "On the Ultra-Violet Spectra of the Elements," *Philosophical Transactions* 174 (1883): 187–88.

[39] E. Pringsheim, "On a Measurement of Wave-Lengths in the Ultra-Red Region of the Spectrum of the Sun," *Philosophical Magazine* 15 (1883): 235–45.

[40] W. N. Hartley, "The Analysis of Rhabdophane," *Journal, Chemical Society* 41 (1882): 215.

[41] O. N. Rood, *Modern Chromatics* (New York, 1879), pp. 25–26.

[42] C. S. Hastings, "On Modifications of the Spectrum of Sodium Vapor in a Bunsen Flame," *Proceedings, American Association for the Advancement of Science* 31 (1882): 218–20.

ing for a means to define and measure a standard length.[69] Assuming the constancy of wavelengths of light, Peirce measured several rays with Rutherfurd gratings. The use of wavelengths of light for linear measures had been suggested before, but, in Peirce's words, "It was not until our ingenious countryman Lewis M. Rutherfurd, by various mechanical achievements, and especially by his manufacture of diffraction plates of extreme accuracy, had made the attempt practicable, that any one could seriously propose to measure a wave length to one-millionth part of its own length." To determine the distance between ruled lines, Peirce compared a centimeter-wide grating with a standard decimeter scale of centimeters; the comparator used was built by Peirce in Rutherfurd's laboratory and with the assistance of Chapman. To determine the angles of deviation of the diffracted rays, Peirce used a spectrometer provided with a graduated glass circle, after Rutherfurd's design.

As perfect as he tried to make them, Rutherfurd's gratings had a few notable imperfections. Owing to an irregularity in the screw of the ruling machine, there was a periodic inequality in the spacing of the lines. Consequently, each bright emission line was accompanied by a series of "ghosts." Although much fainter than their principal lines, these "ghost" images could be, and often were, mistaken for true lines.[70] In order to identify and thus disregard these "ghosts," Peirce developed a theory defining their positions and confirmed it with measurements of "ghosts" produced by various Rutherfurd gratings. His paper on the subject was read to the National Academy of Sciences in 1879.[71]

Many of the early gratings were ruled on glass which was then silvered. Often the ruled silvered surface was protected by a plane-glass plate. Although this method gave a very brilliant spectrum, Rutherfurd found its advantages overbalanced by the impossibility of keeping both surfaces of the glass plate accurate. The later gratings were usually ruled on speculum metal.[72] Peirce called attention to the fact that spectra produced by Rutherfurd's glass gratings were of unequal brightness:

[69] Peirce's work was first presented in a paper on "Comparison of Wave-Lengths with the Metre," read at the April 1879 meeting of the National Academy of Sciences. Although the paper was never published, it was described in the *Report of the Superintendent of the U.S. Coast and Geodetic Survey* (1879), p. 28, and in *Nature* 20 (1879): 99. See also, Charles S. Peirce, "Width of Mr. Rutherfurd's Rulings," *Nature* 24 (1881): 262.

[70] G. D. Liveing and J. Dewar, "Investigations on the Spectrum of Magnesium," *Proceedings of the Royal Society* 32 (1881): 194–95.

[71] Charles S. Peirce, "On the Ghosts in Rutherfurd's Diffraction Spectra," *American Journal of Mathematics* 2 (1879): 330–47.

[72] Lewis M. Rutherfurd's comments at May 10, 1878 meeting of Royal Astronomical Society (n. 43 above), p. 43.

the spectrum on the left, for instance, was notably brighter than that on the right. The culprit was found to be a slight burr on one side of each incised line. Therefore, Peirce temporarily filled the grooves with black lead, and polished off the burr. The resulting spectra, to the left and right, were equal and of the "utmost brilliancy."[73]

Despite these imperfections, the gratings were quite good. For evidence of their quality, is is necessary to look no further than to the men who tried to better them. According to Rowland, "many mechanics in [America] and in France and Germany have sought to equal Mr. Rutherfurd's gratings but without success."[74] William A. Rogers, who around 1880 devised a ruling engine, unequivocally claimed that Rutherfurd's gratings "easily surpass all others [except perhaps my own] in their resolution of the lines of the solar spectrum."[75] Before attempting his own ruling engine, Rogers analyzed the possible sources of error. In Rutherfurd's gratings, he found "the accidental errors of single subdivisions, which are, for the most part, due to the irregular motion of the ruling diamond upon a non-homogeneous metal," are "so far wanting that it is safe to say of a given space, that it is so nearly equal to its neighbor that the most rigid investigation with the microscope will fail to reveal any difference." On the other hand, by giving an eccentricity to the index of the screw, Rutherfurd could nearly, but not entirely, eliminate the periodic errors caused by irregularities of the screw. Rogers, therefore, concentrated on obtaining as precise a screw as possible.

One of Rowland's stated objectives for his ruling engine was to produce larger gratings than had Rutherfurd—and by 1882 he could rule lines 4¼ inches long over a surface of 6¼ inches wide. Furthermore, Rowland's engine ruled consistently fine gratings, whereas "Rutherfurd's machine only made one in every four good, and only one in a long time which might be called first-class."[76]

The actual work of producing the diffraction gratings was done by Chapman, and so they are signed. By the mid 1870s, Rutherfurd's health, never very strong, so far deteriorated that he was forced to relinquish

[73] Charles S. Peirce's remarks at April 1879 meeting of National Academy of Sciences, reported in *Nature* 20 (1879): 99.

[74] Henry A. Rowland, "Preliminary Notice of the Results Accomplished in the Manufacture and Theory of Gratings for Optical Purposes," *Philosophical Magazine* 13 (1882): 469–74.

[75] William A. Rogers, "On the First Results from a New Diffraction Ruling Engine," *American Journal of Science* 19 (1880): 54–59.

[76] "Mr. Rutherfurd's Photography and Diffraction Gratings," *Sidereal Messenger* 1 (1883): 68–69.

his scientific pursuits altogether. At this time, Chapman moved to Washington, D.C., to work for the U.S. Coast and Geodetic Survey. He apparently took the ruling engine with him, since he continued to rule gratings until around 1883.

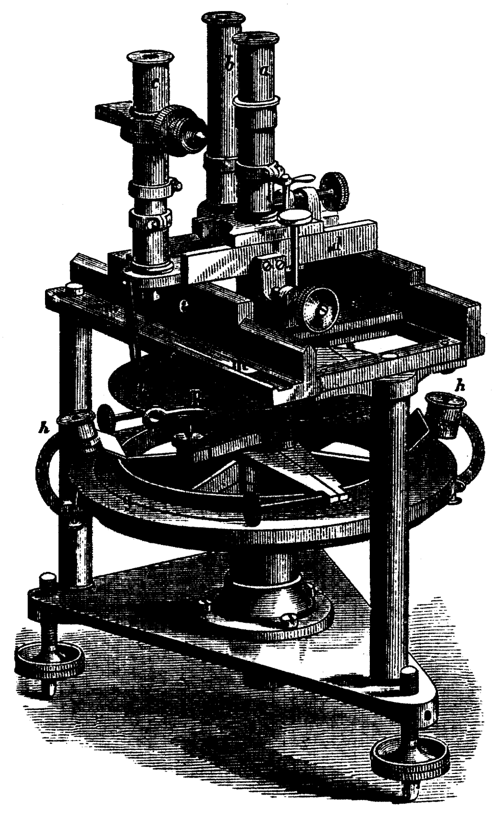
Summary

During the quarter century of his scientific activity, Rutherfurd produced several instruments needed for the two new sciences, astronomical photography and astronomical spectroscopy. His telescopes, both reflecting and refracting, designed specifically for photographic work, yielded beautifully detailed pictures. His micrometers for measuring celestial photographs showed photographic astrometry to be as reliable as visual astrometry, and much more convenient. His spectroscopic apparatus, both the multiprism spectroscopes and the diffraction gratings, produced the dispersion needed to begin to identify the celestial absorption lines. Although each of these instruments had been made before, in each case Rutherfurd's examples incorporated notable improvements. Indeed, Rutherfurd's instruments were so good that scientists around the world were encouraged to use them, to adopt them as standard tools of their trade, and consequently to improve them.

The story of Rutherfurd's work, interesting in and of itself, is also worth telling as one more example of a fruitful interaction of mind and machine—a clear case of scientific discoveries inspiring technical improvements which, in turn, made other discoveries possible. It also illustrates the importance of preserving and studying our material as well as our verbal heritage in order better to understand the products of the technicians, the tools of the scientists.

Technology and Culture

The International Quarterly of the Society for the History of Technology



APRIL 1971, VOLUME 12, NUMBER 2

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