FAILRE AND SUCCESS: TWO EARLY EXPERIMENTS WITH CONCAVE GRATINGS IN STELLAR SPECTROSCOPY

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Henry Crew tried to use a Rowland concave grating for stellar spectroscopy with the Lick 36-inch refractor in 1892-93. He did not succeed. A few years later George Ellery Hale planned a similar instrument for Mount Wilson Observatory. His attempt was highly successful, although the spectrograph became quite different along the way. It is instructive to examine the differences between Crew's failure and Hale's success.

Crew graduated from Princeton in 1882, and afterward studied physics in Germany for one year, attending lectures by Helmholtz, Kirchoff, and Kayser. Then he returned to the U.S. and became a physics graduate student under Henry Rowland at Johns Hopkins University. Crew wrote his thesis on the spectroscopic determination of the rotation period of the Sun as a function of latitude. He used a large laboratory grating spectrograph, and a small, primitive heliometer to bring the solar image to the slit. The result he found, that the rotation period decreases from the equator to the pole, was contrary to the direct evidence from sunspots known at the time, and has been proven incorrect by better spectroscopic measurements since. After earning his PhD in 1887, Crew stayed in Baltimore for one year as an assistant to Rowland, and then got a job as instructor and head of the physics department at Haverford College, near Philadelphia.

In 1891 when James E. Keeler left Lick Observatory to become director of Allegheny Observatory, Edward S. Holden hired two men, W. W. Campbell and Crew, to carry on the spectroscopic program Keeler had initiated. Holden rightly considered the spectroscopic determination of stellar "motions in the line of sight", (or radial velocities, as we say today) then just getting underway, the most important program of the observatory. Campbell had only an undergraduate education from the University of Michigan in engineering and in the older astronomy of position, but he had good experience in astronomical spectroscopy, for he had worked as Keeler's volunteer assistant the whole summer of 1890. Crew, the first Lick faculty member with an earned PhD, was well-schooled in laboratory spectroscopy, but had practically no astronomical training or experience.

Holden wanted Campbell and Crew to work together, to complement each other's skills, but Crew refused, took his fight with the director all the way to the University of California Regents, and won. They ruled that he should be allowed to observe on his own with the 36-inch one night each week. Campbell, given two nights a week for himself, added a photographic camera to the prism spectroscope Keeler had designed as a visual instrument, and began the pioneering research that was to make him famous.

Crew started the program that he had wanted to do from the first, the application of the Rowland concave grating to astronomy. Gratings form a spectrum by diffraction, an interference effect dependent on the wave nature of
Fig. 1. Henry Crew's rough sketch of the concave-grating spectrograph he designed for the Lick Observatory 36-inch refractor (Mary Lea Shane Archives of Lick Observatory).
light, in contrast to prisms, which depend upon refraction, a process familiar in rainbows, cut glass and diamonds. In 1881 Rowland had developed a ruling machine with which thousands of equally spaced, exactly parallel lines could be cut into a flat, speculum-metal blank, converting it into a plane grating. These plane gratings, made in his laboratory at Johns Hopkins, were distributed by instrument maker John A. Brashear to physicists and astronomers throughout America. Keeler had used a Rowland plane grating for his spectroscopic research at Lick.

A few years later Rowland recognized that for some purposes concave gratings, which focus the spectrum at the same time they produce it, are superior to plane gratings. Such a concave grating, mounted in the “Rowland circle” arrangement, does away entirely with both the collimator and focusing lenses of the conventional type of spectrograph, and thus saves the light that would otherwise be lost at their surfaces in each reflection, and by absorption within them. Rowland himself was primarily interested in concave gratings for his gigantic program of precision measurement and identification of all the absorption lines in the spectrum of the Sun.\(^5\)

Crew had seen and undoubtedly used the new concave gratings in the Johns Hopkins laboratory. He wished to apply one of them to stellar spectroscopy at Lick Observatory. He did not have any funds to buy a concave grating but he persuaded Brashear to let him have one on a long-term loan. However, the grating Brashear lent Crew was ruled with only 2800 lines/inch, providing considerably lower dispersion than the more closely ruled 14,438 lines/inch gratings for which there was much more demand. Crew brought this borrowed low-dispersion grating with him when he came to Lick Observatory in late September 1891.\(^6\) He hoped to do great things with it, but he had not analysed the problem carefully enough, for he did not clearly realize (as Keeler had) how greatly the natural astigmatism of the concave grating would widen, and thus weaken, the spectrum of a star.\(^7\)

Crew did not receive much help from Holden, but got his concave grating spectroscope into operation for visual observations in January 1892. There was no machinist and no instrument shop at Lick Observatory; Crew had to get the carpenter to make the spectrograph for him out of wood.\(^8\) He soon found that it was a failure in practice. Even very bright stars like α Leonis produced spectra too faint for him to see any lines with the “largest and most powerful telescope” then in existence, the 36-inch refractor. Crew did not advertise this failure, but switched to attempts at spectroscopy of a nova, a comet and one or two stars with the regular observatory instruments. He was not conspicuously successful in any of these projects.\(^9\)

By June 1892, following Campbell's lead with the prism spectrograph, Crew had a photographic camera mounted with his concave grating on the 36-inch refractor. He experimented the rest of the summer with it, but found that even for the brightest stars like α Bootis, α Cygni, and α Lyrae, very long exposure times, one to two hours, were not enough to produce satisfactory spectrograms. Crew published a brief description of the concave-grating spectrograph,\(^10\) and a single rough sketch as well as a photograph of it have been found at Lick Observatory (see Figures 1 and 2). The grating was used in the “Abney mounting”, an arrangement in which the grating and the focal point are fixed on a diameter of the
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Fig. 2. Photograph, taken by S. W. Burnham, of Crew’s concave-grating spectrograph mounted on the 36-inch refractor (Mary Lea Shane Archives of Lick Observatory).

Rowland circle, and the slit may be swung on another radius about the centre of it.\textsuperscript{11} The distance to the entrance slit was smaller than the distance to the plate, in order to compensate for the relatively coarse ruling and increase the dispersion. This however meant that only a very narrow slit could be used. Thus most of the starlight was lost before it ever entered the spectrograph. There was no provision for seeing the star’s image on the slit, and guiding could only be done by light reflected from the grating itself, a method so crude that much of the time all the light was lost.

Thus the program was a complete failure, at least partly because of Crew’s inexperience in observational astronomy and his refusal to work with Campbell. The Rowland gratings were unblazed; that is, they spread light over several different orders (or spectra) and were not particularly efficient in any of them. Crew’s spectrograms are not in the plate vault at Lick Observatory, but George Ellery Hale, who saw them, reported that “while they were fairly sharp, the exposure required was very long”.\textsuperscript{12}

In his brief paper, written after he had left Lick Observatory, Crew gave only a
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sketchy description of the instrument, with very few specific dimensions or details. He reported no scientific results whatsoever, but stated in glowing terms the promise of concave gratings for the future. Campbell, in a personal letter, was more forthright: “As to Crew: he is a bright fellow. But he had the 36-inch about 50 nights, and what observation of the least value have we to show for it?”

Crew was rescued by a job offer from Northwestern University in Evanston, Illinois, obtained on the basis of a recommendation from Hale, among others. Crew’s last entry in his observing book, on 10 August 1892, after a one-hour exposure on α Cygni with the concave-grating spectrograph, was “Clouds stopped work.” It was symbolic of his whole year at Lick Observatory. He left Mount Hamilton with a bitter public blast against Holden, and went on to a long and highly successful career as a laboratory spectroscopist at Northwestern.

A little over a decade later, Hale approached the same problem in a very different manner—and with very different results. Scion of a wealthy Chicago family, he had been encouraged from childhood in his interest in science, especially astronomy and spectroscopy. As a boy he had his own private tutor, and was sent to special schools. His doting father bought him every instrument he needed, from his first telescope (at the age of 14) and his first spectroscope (at the age of 18), to the large, specially designed, custom-built spectroscope he used for his bachelor’s thesis at M.I.T. After graduation Hale’s father bought him a 12-inch professional-quality refracting telescope, optimized for solar research, which he had erected at his own Kenwood Observatory, in the back yard of the family mansion on Drexel Boulevard.

In 1892 Hale and President William Rainey Harper of the University of Chicago persuaded Charles T. Yerkes to put up the money to build Yerkes Observatory with its 40-inch refracting telescope, the largest in the world. Before it was completed in 1897, Hale, financed again by his father, had an optician working on a 60-inch parabolic mirror for an even larger reflecting telescope. By 1899, soon after his father’s death, he was already planning to erect this telescope in California.

Hale’s chief interest was the Sun, but he saw it as a representative star that could be observed at close range and thus studied in special detail. Part of his program was always to compare other stars with the Sun, and thus to deepen his knowledge and understanding of both. To do this in most detail, he wished to obtain high-dispersion spectra of bright stars and, with the same instrument, of the Sun.

When the 40-inch was completed, Hale tried some experimental work on high-dispersion spectroscopy of stars with it, but soon convinced himself that it was not the right instrument for this project. The problem was that the exposure times required were too long. A high-dispersion spectrograph is necessarily very large, with a long focal-length camera. The motion of the giant refractor, following the diurnal motion of the stars in the sky, subjected the spectrograph and camera to changing components of the force of gravity during the exposure, leading to “flexure” or slight bending of the instrument. This destroyed the necessarily precise focusing and alignment of the spectrograph, and ruined the image. Furthermore, as the night went on and the dome gradually cooled, uneven thermal contraction of the spectrograph further distorted the spectrum. Hale soon lost interest in the 40-inch, and essentially turned it over to E. E. Barnard and S. W. Burnham for the old visual observing that was so boring to him, and to
Edwin B. Frost and Walter S. Adams for the routine spectroscopic stellar radial-
velocity measurements that were only slightly less so.

Hale then conceived the idea of building a fixed horizontal reflecting telescope,
solidly mounted on the ground, with a large spectrograph attached to it. The light
from the Sun or a star would be directed into the telescope by a coelostat, a pair of
plane mirrors, one of which was the only moving part of the instrument. Barnard
and George W. Ritchey had had great success in photographing the solar corona
with a temporary instrument of this type at the solar eclipse of 1900; now Hale
planned to use a permanent one to obtain high-dispersion spectra not only of the
Sun, but also of a few of the brightest stars as well. Flexure would not be a
problem, and neither would thermal distortion if Hale could have a good
insulating structure built around the spectrograph.18 His undergraduate thesis at
M.I.T. had been carried out with a primitive version of just such a system, used to
form a spectrum of the Sun.

In his early solar research, Hale had designed his spectrographs and had them
built around Rowland plane gratings, combined with collimator and camera
lenses of equal, long, focal lengths, to get very high dispersion.19 In his
spectroscopic laboratories, first at Kenwood Observatory in Chicago and later at
Yerkes Observatory, he had become familiar with concave gratings.20 Now for
high-dispersion spectroscopy of the stars, he was prepared to use either a plane or
a concave grating, whichever would better serve his purposes. Hale was well aware
of the natural astigmatism of a concave grating, and therefore had no intention of
mounting one in a Rowland circle. Instead, he planned to use it in the
arrangement advocated by Frank Wadsworth, the head of his Yerkes instrument
shop, in which a lens serves as a collimator, and the concave grating focuses the
spectrum it produces.21 This Wadsworth mounting has one more reflection than
the Rowland circle, but this arrangement does away with nearly all of the
astigmatism of the grating, and thus for small light sources (like stars) more than
makes up for the additional light loss.

Hale's main difficulty was in laying his hands on a suitable grating of either
type. Rowland and his technician Charles Schneider had made only a limited
number of them, and nearly all of these were relatively small, suitable for
laboratory spectroscopy but not for work on stars which, even with large
telescopes, are much fainter than arcs, sparks and gas discharge tubes.22 After
Rowland's death in 1901, the laboratory he had created was in a state of flux.
Joseph S. Ames, his former junior colleague, succeeded him as professor of
physics and director of the laboratory, while Lewis E. Jewell, his former assistant,
took over the grating-ruling operation. Jewell considered himself a universal
scientist, an expert not only in making gratings but in using them for laboratory,
solar, and stellar spectroscopy, and in interpreting the results in terms of his own
firmly held but often quite peculiar theories. He was in a constant state of tension
with Ames, who continued to urge him to get on with the work and produce more
gratings. Hale more diplomatically kept up a steady stream of letters in which he
flattered Jewell by taking his ideas seriously, but firmly kept on the pressure for a
large concave grating. Finally, in November 1902 Hale went to Baltimore himself
and succeeded in prying a fairly large, fairly satisfactory one out of Jewell's
hands.23

With this grating installed in the Wadsworth spectrograph attached to the
fixed, horizontal 24-inch reflecting telescope on the grounds of Yerkes Observatory, Hale was soon able to obtain good laboratory spectra, and good spectra of the Sun. He did not do so well on the stars, probably because the telescope and spectrograph were not sufficiently well insulated, but he was still experimenting when on 23 December disaster struck. A fire raced through the wooden, jerry-built telescope housing. It completely destroyed the structure, melted the metal grating, and destroyed most of the other parts, twisting the frame of the spectrograph beyond repair. Hale was back at square one.

He was already deeply involved in negotiations with high officials of the Carnegie Institution of Washington, attempting to raise funds for his latest “scheme”, a new observatory on Mount Wilson, in California, to be built initially for solar research, but to include the 60-inch reflector, for stellar work, as soon as it could be financed and completed.

In 1903 Hale succeeded in securing a grant from the Rumford Fund of the American Academy of Arts and Sciences to purchase a large concave grating to replace the one lost in the fire. He persuaded Helen Snow, a wealthy Chicagoan, to finance a new, improved version of the horizontal telescope. By this time only 35 years old, he had become essentially a promotor, a fundraiser, and a conceptualizer of research, who farmed out the details of doing the actual work to a corps of dedicated, loyal assistants. By autumn a new house for the horizontal telescope had been built, raised twenty feet off the ground to get away from uneven heating and air convection near the ground. The telescope had been rebuilt, and Hale was again waiting impatiently for a concave grating from Jewell. But by now he was determined to leave Yerkes Observatory and begin anew in California. Finally the Carnegie grant came through, and Hale cut his ties with the University of Chicago and launched Mount Wilson Solar Observatory, as a department of the Carnegie Institution.

By 1905 Hale had set up on Mount Wilson the Snow telescope, the new fixed long-focus horizontal reflector, with a mirror 24 inches in diameter, designed mainly for solar research. Very soon he had his assistant Walter S. Adams (whom he brought with him from Yerkes and who later succeeded him as director of Mount Wilson Observatory) begin observing stellar spectra with it, for comparison with the Sun. The object Hale selected was α Bootis, the fourth brightest star in the sky, with apparent magnitude zero. He still had not yet received the new concave grating he had ordered after the fire, and had instead to use a plane grating with two identical long-focus lenses as collimator and camera. The resulting dispersion was 4.3 Å/mm, quite high even by today’s standards. One spectrum of α Bootis required a 14-hour exposure, spread over three successive nights, a second, “made when the mirrors were badly tarnished”, of 24 hours extending over five nights. Even though the grating was mounted on a thermostated water bath that held its temperature constant to 0.1 °C, it was impossible to keep the huge spectrograph stable for such long periods of time. The definition of the spectrograms suffered. They were not as good as the short-exposure spectrograms of the bright Sun.

Nevertheless the high-dispersion spectrograms of α Bootis had much better resolution than any that had previously been obtained. Adams measured and analysed them in detail. He compared them with spectra of sunspots, taken with the same instrument, and showed that there was “very striking” agreement
between the two sources. Many lines could be seen at the same wavelengths in α
Bootis and in the sunspots, with similar patterns of relative intensities. Adams
correctly concluded “that the physical conditions existing in sun-spots and in the
atmosphere of this star are nearly identical”. He further correctly stated that most
probably it was their temperatures that are nearly the same.30

Hale regarded these spectrograms as experiments that would help him decide
on the type of large grating spectrograph to be designed for the 60-inch reflector,
which would deliver over six times as much light as the Snow telescope when it
was completed. He and Adams obtained even higher-dispersion spectra of
sunspots with the Snow telescope, the same plane grating, and a longer focal-
length lens, serving as both the collimator and the camera in the “Littrow”
arrangement. These spectrograms had the very high dispersion of 1.5 Å/mm, but
Hale hoped to do still better in the future with a larger grating and lens.31

Part of his plans was always to carry forward research in laboratory
spectroscopy, along with the solar and stellar observations. At Kenwood and later
at Yerkes Observatory he had used laboratory concave-grating spectrographs.20
Now he had Adams work out the detailed design for a large spectrograph of this
type to be erected in the laboratory atop Mount Wilson. In making these
calculations, Adams rediscovered the fundamental problem of concave gratings,
their astigmatism. Even with a reasonably bright laboratory arc as the light source
this astigmatism would widen and significantly weaken the spectrum. Adams
checked his reasoning with Henry G. Gale, a laboratory physicist from the
University of Chicago who was a temporary member of Hale’s team in the
summer of 1906. Gale confirmed his results and they both agreed that for their
purposes a plane grating with two lenses would be far superior to a concave
grating instrument even in the laboratory. The same conclusion applied even
more forcefully for stellar spectroscopy, as they all then realized.32

To push the comparison with the Sun to α Orionis, a slightly fainter star than α
Bootis, with the Snow telescope would require even longer exposure times unless
the spectrograph could be speeded up. The plane gratings of that day were not
blazed; they spread light over several different orders and thus were relatively
wasteful of light in any single order. Hale and Adams decided to replace the
grating with a prism. To get high dispersion they had to use a large-angle (64°)
dense flint-glass prism. The largest prism they had was a little over two inches
wide, only big enough to accept half the beam of light from the collimator lens, but
even so it was more efficient than the grating. With this spectrograph they were
able to obtain a high dispersion spectrogram of α Orionis in two nights. It was not
fully exposed, and the dispersion, 10 Å/mm in the yellow regions, was not as high
as in their previous work, but it was good enough to be prime research material.
The spectrum of α Orionis proved to be similar to sunspot spectra, but to differ
even more from the spectrum of the Sun itself than do those of sunspots and α
Bootis. By now Hale, Adams and Gale, in a very thorough laboratory
investigation of the temperature dependence of the spectra of several elements,
had convincingly demonstrated that sunspots are cooler than the Sun. Thus the
conclusion was clear: α Bootis has a lower temperature than the Sun, and α
Orionis has a lower temperature still.33

The 60-inch reflector was designed to be used not only at the Newtonian and
Cassegrain foci, but also at the coudé, with a special long-focus Cassegrain
secondary mirror to direct starlight, via flat mirrors, down from the polar axis to a large fixed spectrograph. This spectrograph had been designed long before the telescope was completed. On the basis of their experiments with the Snow telescope, Hale and Adams had concluded that the most efficient system would be a large prism spectrograph, mounted in the Littrow arrangement with a single long-focus lens. A mirror was placed behind the large prism, so that the light went through it twice, doubling its dispersive effect. The spectrograph was housed with its axis vertical, in an underground pit, to keep the temperature as nearly constant as possible and to simplify making adjustments.

The resulting dispersion was 1.4 Å/mm at \( \lambda 4300 \), 2.4 Å/mm at \( \lambda 5000 \), and 6.2 Å/mm at \( \lambda 6500 \). (The dense flint glass of the prism absorbed so strongly that it was impossible to obtain spectra below \( \lambda 4200 \).) The photographic plates used were 17 inches long, and gave good resolution over their entire length. Since the prism was not large enough to accept the whole beam, half the incident light was lost, but the large aperture of the 60-inch telescope more than made up for it. It was possible to obtain well-exposed spectrograms of \( \alpha \) Canis Majoris, \( \alpha \) Canis Minoris, \( \alpha \) Bootis, \( \beta \) Orionis, and \( \beta \) Scorpii. By this time Hale had added the laboratory spectroscopist Arthur S. King and Harold D. Babcock to the Mount Wilson staff. The latter helped Adams take these long-exposure spectrograms, each of which required many hours. The plates were measured by Adams, Louise Ware and Jennie B. Lasby. The chief scientific goal was to try to detect slight wavelength differences between difficult groups of lines that might be interpreted to give the pressures in the atmospheres of these stars, basic information that was completely unknown at the time. Adams was unsuccessful in this, but did obtain a wealth of information on the absorption lines present in the atmospheres of the stars, which much later was translated into the abundances of the elements in these objects.

The spectrograph, developed on the 60-inch telescope, was the direct forerunner of the much more advanced coudé instruments that succeeded it on the 100-inch Mount Wilson and 200-inch Palomar telescopes. They were the workhorse instruments with which much of our knowledge of the physical properties of the stars and the abundances of the elements was obtained. The final version, using an off-axis paraboloidal collimating mirror, a large plane, blazed grating (or mosaic of such gratings) and a Schmidt camera, was completely different in detail, but it had evolved naturally, as technology improved, from the first vertical Littrow prism spectrograph in the pit below the 60-inch.

Hale's vision, the need for large gratings, and the unsatisfactory situation at Johns Hopkins after Rowland's death led ultimately to the creation of the Mount Wilson ruling engine. In the hands of Horace W. Babcock it produced many excellent plane gratings, used not only at Mount Wilson and Palomar Observatories, but at most other research institutions throughout the 1950s and 1960s.

Concave gratings never did catch on for stellar spectroscopy, though Adams tried one at the Cassegrain focus of the 60-inch reflector in 1913, and Paul W. Merrill tried it again in a different spectrograph on the 100-inch in 1922. In both cases the exposure times even for bright stars were prohibitively long. The basic problem is that concave gratings cannot be made with optically fast focal ratios. However, for a few applications, particularly ultraviolet spectroscopy from
rockets and space vehicles, they are unmatched.39

Thus Hale's program turned out to be a great success, though Crew's had been a
great failure. What was the difference? Crew, though an expert in laboratory
physics, had no real training or research experience in astronomy. He was
working on his own, without the support of (and often in direct opposition to) the
director of his observatory. He had no funds at his disposal, no shop, no
assistants, and had only a year to get results. How could he have been expected to
succeed?

Hale, on the other hand, had an excellent education and years of practical
experience in spectroscopy and in astronomy. He was the director of his
observatory, and had direct control over funds that he could use to buy
instruments and hire staff members. He surrounded himself with hard-working
subordinates like Adams, Gale, King, and Babcock, and a corps of skilled
instrument makers and measuring assistants. Hale had time to have a new
instrumental system tested in actual use, evaluated, and either improved or
discarded. He had the resources to rebuild after a disaster. He stuck with the
concave-grating concept as long as it appeared promising; when his experts found
it would not be effective he abandoned it, just as he later abandoned plane gratings
for the prism which, though decidedly old-fashioned, gave the best results in
practice. Eventually he was able to command the 60-inch reflector, the largest and
most efficient telescope in the world in 1910. How could he have been expected to
fail?

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