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978-0-521-88257-6 - Astronomical Spectrographs and their History
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Excerpt
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1 • The historical development of astronomical spectroscopes and spectrographs

1.1 COLOUR, REFRANGIBILITY AND WAVELENGTH

The concepts of colour, refrangibility and wavelength have been crucial for the development of spectroscopes and spectroscopy. Indeed the first prism spectroscopes were built partly for measuring the refractive indices or refrangibility of different glasses, while diffraction gratings were used for early measurements of wavelength.

1.1.1 The refraction of light

The Dutch astronomer Willebrord Snell (1591–1626) is usually credited with the discovery of the law of refraction, in the early seventeenth century in Leiden. René Descartes (1596–1650) later included the law in his treatise *Dioptrics* of 1637 (without however acknowledging Snell), and he used it to account for the formation of a rainbow, but not explicitly for the colours that the rainbow produces.

Isaac Newton's (1642–1726) first paper, published by the Royal Society in 1672, but based on his optical experiments undertaken six years earlier, came to important conclusions on the relationship between refrangibility and colour [1]. Newton studied the refraction of the Sun's rays in a glass prism, and projected the resulting spectrum onto a wall of his room. He concluded: '. . . light consists of rays differently refrangible, which, without any respect to a difference in their incidence, were, according to their degrees of refrangibility, transmitted towards divers parts of the wall.' He found that the Sun's light was composed of rays of different primary colours, each with its different refrangibility, which gave rise to the dispersive power of the prism. He went on: 'As the rays of light differ in degrees of refrangibility, so they also differ in their disposition to exhibit this or that particular colour . . . To the same degree of refrangibility ever belongs the same colour, and to the same colour ever belongs the same degree of refrangibility.'

These experiments were the fundamental starting point for the science of spectroscopy. Newton himself referred to 'the celebrated Phaenomena of Colours', indicating that he was far from the first to study the solar spectrum (the word was his term for the 'colour-image'). His apparatus was a primitive spectroscope, and comprised a small hole in his window shutters, a glass prism, and a wall 22 feet distant from the prism used as a screen onto which the spectrum was projected. At first no lenses were employed, but later he inserted a lens after the prism and noted that a spectrum of greater purity could thereby be produced.

In his *Lectures opticae* of 1669 (but published posthumously in 1728) Newton used his theory of colours to account for the colours of the rainbow, which contained the primary 'Colours in order red, yellow, green, blue and purple, together with all the intermediate ones, that may be seen in the Rain-bow; whence will easily appear the Production of Colours in a Prism and the Rain-bow' [2].

It is interesting that Newton observed the same phenomenon of a continuous spectrum using the planet Venus, by allowing the planet's light to enter the eye directly from the prism. Even stars of first magnitude were observed in the same way, and he remarked that a telescope would both increase the quantity of light for stellar spectroscopy as well as reduce the undesirable effects of atmospheric scintillation.

Newton's experiments led him to believe that the dispersive power of prisms was related to the refractive index of the glass. He concluded: 'The denser the Matter of the Prism is, or the rarer the incompassing Medium is, *caeteris paribus*, the greater will be the Difference of Refraction, and hence the Appearance of the Colours will be more manifest' [2, see Proposition XXIV].

1.1.2 Wavelength, colour and spectral lines

Thomas Young (1773–1829) in 1801 was the first person to use a simple diffraction grating to demonstrate the wave nature of light and to show that the wavelength could be obtained from the groove spacing of the grating. His first gratings comprised a series of parallel grooves ruled on glass at the spacing of about 500 grooves per inch. Using sunlight incident at 45°, he found four bright orders due to the interference of the light. The sines of the angles of diffraction ($\sin\beta$) increased in accordance with the integers 1:2:3:4, and from this progression he was able to estimate the wavelength of sunlight [3]. According to Young, the visible spectrum covered a range of wavelength from 675 down to 424 nm, with yellow light corresponding to 576 nm.

Joseph Fraunhofer (1787–1826) continued experiments with diffraction gratings in the early 1820s. His first gratings were coarse transmission gratings, made by stretching fine parallel wires between the threads of two screws – typically with spacings of up to 325 wires per inch.[1] He was able to measure the angular positions and hence wavelengths of prominent absorption lines in the solar spectrum with such a grating, including a value of 5888 Å for the orange line that he labelled D [4].

In later experiments Fraunhofer produced gratings by ruling with a diamond directly onto glass. Thus in 1822 he produced one with 3340 grooves per inch and which gave a higher dispersion. He was able to confirm Young's finding that the diffraction orders had $\sin\beta \propto n$ (here n is the order number of the diffraction, an integer), instead of simply $\beta \propto n$ that he had used previously [5]. Gratings as finely ruled as 7790 grooves per inch were produced the following year [6].

One of Fraunhofer's main interests was the determination of refractive indices for the different glasses that were produced by the Benediktbeuern glass works in Bavaria. As refractive index varied with wavelength, he had the foresight to use different emission lines as wavelength standards at which refractive indices could be measured [4]. Thus the relationship between refractive index (measured by applying Snell's law of refraction to a prism spectroscope) and wavelength (from a diffraction grating of known groove spacing) could be explored. Such experiments laid the basis for the future of spectroscopy and of spectroscope design, as well as the design of telescopes employing achromatic doublets for the objective lenses.

Fraunhofer's early prism spectroscope comprised a 60° prism mounted in front of a small 25-mm aperture theodolite telescope with cross wires seen in the eyepiece. The prism in turn was 24 feet from a narrow opening in the window shutters. It was with this apparatus that he first recorded several hundred absorption lines in the solar spectrum [7, 8, 9].

In 1823, for his more extensive observations of stellar spectra, Fraunhofer used a larger telescope of aperture 10 cm, in front of which he mounted a prism of apex angle 37° 40′ to form an objective prism spectroscope [6]. With this instrument he was able to observe the absorption line spectra of six bright stars, as well as of Mars, Venus and the Moon.

None of Fraunhofer's spectroscopes employed a collimator. For his solar observations the light traversed a narrow slit of width 0.07 inches; at a distance of 24 feet from the prism, the slit subtended no more than an arc minute, giving a resolving power ($R = \lambda/\delta\lambda$) probably of about 2000, easily sufficient to observe the lines in the solar spectrum.

In England in 1802 William Wollaston (1766–1828) had earlier observed five lines (a term he introduced) in the solar spectrum, without realizing their true significance [10]. His apparatus was similar to Newton's, except that the crevice in his window shutters was just 0.05 inches wide, and his flint glass prism was placed at 10 to 12 feet. Thus the benefit of a narrow slit to improve resolving power was established by the pioneering spectroscopists in the early nineteenth century.

1.2 THE COLLIMATOR IN PRISM SPECTROSCOPES

A collimator was introduced into laboratory spectroscopes by several spectroscopists from 1839, in order to achieve a higher resolving power, and probably as the result of independent developments. The first such use was most likely in a spectroscope by Jacques Babinet (1794–1872), which was presented to the Académie des Sciences in 1839 by François Arago (1786–1853) [11],

[1] Fraunhofer quoted values in Paris inches. A Paris inch is 26.7 mm. They have been converted here to the more familiar imperial inch of 25.4 mm.

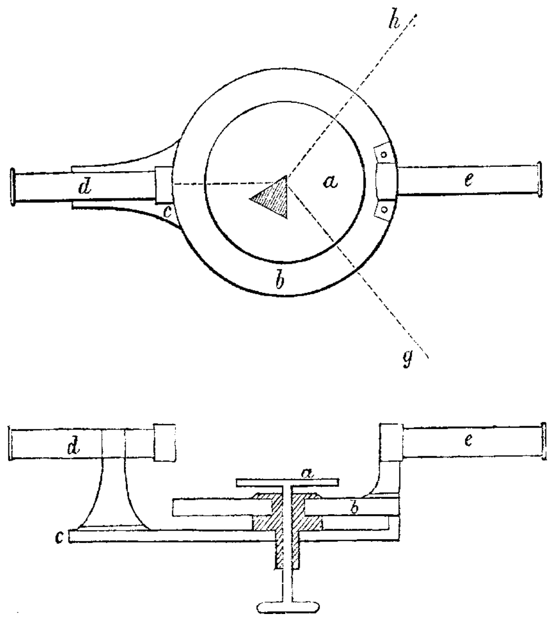

Figure 1.1. Prism spectroscope of William Simms, 1840, for solar spectroscopy. Here d is the collimator, e is the viewing telescope, a is the prism on the prism table and b is the graduated circle.

in which a lens was placed in front of the prism so as to render the rays parallel. The instrument was designed for measuring the refractive indices of glass.

A more detailed description of a slit and collimator spectroscope was presented by the famous optical instrument maker, William Simms (1793–1860) in 1840. His instrument is shown in Fig. 1.1. He introduced the word 'collimator', and wrote:

> There are two telescopes, e and d; one to be used for making the observation, and the other as a collimator. In general the former is attached to the graduated circle b, and the latter to the stage c; but their positions can be changed at pleasure. The observing telescope is fitted with eye-piece and cross wires, in the usual way; but the collimator has in the principal focus of the object-glass two metallic plates, the straight edges of which open parallel to each other, so as to form a line of any required breadth, and at the end of the tube a plane mirror reflects light from the sun or sky, through the slit of the collimator [12].

As Simms mentioned, the instrument was intended for solar spectroscopy. Yet his design also became a model for many laboratory spectroscopes of the mid nineteenth century. In particular, the use of a graduated circle for the telescope and a rotating table to carry the prism permitted great ease of use when measuring angles of refracted rays.

In the following years collimators became increasingly common. William Swan (1818–94) included one in his astronomical spectroscope of 1856 [13]. By about 1860 the collimator was essentially a universal feature of all astronomical and laboratory spectroscopes.

1.3 SOME NOTABLE ASTRONOMICAL PRISM SPECTROSCOPES OF THE MID NINETEENTH CENTURY

The basic arrangement of a prism spectroscope devised by William Simms in 1840 was widely copied. It comprised a slit, a collimator, a circular prism platform carrying one or more prisms, and a viewing telescope with cross wires and an eyepiece. Both collimator and telescope tubes could rotate about the centre of the prism table with graduated scales.

One such instrument was made by C. A. von Steinheil (1801–70) in Munich for Gustav Kirchhoff (1824–87) in Heidelberg and was used for Kirchhoff's famous study of the solar spectrum, 1861–3 [14, 15]. There were four prisms in this instrument (see Fig. 4.5), three of 45° and one of 60°, which had to be repositioned manually on the table for different telescope angles when observing different spectral regions. The adjustable slit had a small reflecting prism over part of its length, allowing spark spectra to be viewed simultaneously in one half of the slit with a solar spectrum in the other half, thereby facilitating a direct comparison of the two for line coincidences.

At about the same time as Kirchhoff's solar spectroscopy, several astronomers almost simultaneously and independently embarked on a study of stellar spectra, by attaching prism spectroscopes to refracting telescopes. Giovanni Donati's (1826–73) spectroscope was one such instrument, which was attached to a lens of 41 cm aperture that comprised his refractor objective [16, 17]. The spectroscope itself had a single prism, a collimator and a small movable viewing telescope, but in place of a slit there was a cylindrical lens, which broadened the spectrum, making it easier to view.

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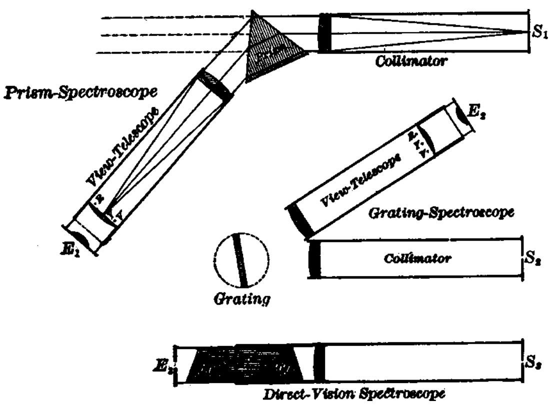

Figure 1.2. Three different types of spectroscope that were depicted by C. A. Young in his *Text Book of General Astronomy* of 1888.

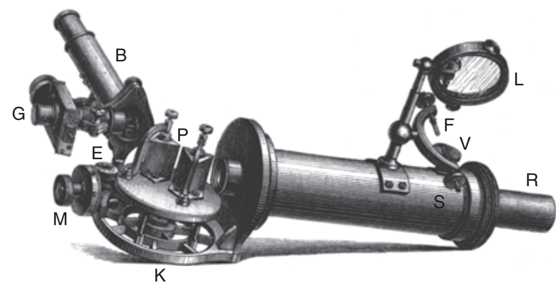

Figure 1.3. Two-prism Browning spectroscope used by Huggins and Miller on the 8-inch refractor at Tulse Hill Observatory, 1864.

Von Steinheil also built a stellar spectroscope in 1862 which, like Donati's instrument, was slitless so as to admit the maximum amount of light [18]. The collimator and viewing telescope were in fixed positions, so as approximately to achieve minimum deviation.

Of the early stellar spectroscopists, one of the most successful was William Huggins (1824–1910). His stellar spectroscope was constructed with the assistance of William Miller (1817–70) and mounted on Huggins' 8-inch Clark refractor at Tulse Hill in London. The instrument was described in detail by them in their classic paper of 1864 [19]. The spectroscope comprised two flint glass prisms to achieve a high dispersion (about 430 Å/mm in the blue). They received light from a collimator and slit and a cylindrical lens ahead of the slit with its axis orthogonal to the slit height, broadened the spectrum. The viewing telescope had an aperture of 0.8 inches and was equipped with cross wires to enable accurate setting on spectral lines. The position of the viewing telescope was adjusted with a micrometer screw.

A comparison spectrum could be viewed simultaneously with this instrument, as with Kirchhoff's solar spectroscope, by means of a small reflecting prism directly in front of the slit, and by this means Huggins and Miller were able to carry out a qualitative analysis of the principal chemical elements to be found in the brightest stars [19].

Shortly afterwards, Huggins and Miller had a similar but less dispersive two-prism instrument constructed for them by John Browning (1835–1925), and this second spectroscope was used for observations of the light of gaseous nebulae [20], though in this case the cylindrical lens, which was useful for stellar point sources, was generally dispensed with. Figure 1.3 shows the two-prism Browning spectroscope used by Huggins and Miller.

Huggins' illustrious contemporary in stellar spectroscopy research was the Jesuit priest Angelo Secchi (1818–78) in Rome. He chose a compact direct vision spectroscope for his initial investigations of stellar spectra. The instrument was made by the Parisian optician, August Hoffmann, who had made a similar spectroscope for Jules Janssen (1824–1907) [21]. The concept of the direct vision spectroscope was due to the Italian physicist Giovanni Battista Amici (1786–1863), in 1863. It comprised a flint glass prism in contact with two reversed crown glass prisms, so arranged as to give dispersion without deviation of the centre of the spectrum. In Hoffmann's arrangement, a higher dispersion was achieved with a train of two flint and three crown prisms – see Fig. 1.4.

Secchi used his instrument on the Merz 24-cm refractor at the Collegio Romano Observatory from December 1862. The instrument was described in papers in 1863 [22] and 1866 [23], though in the first of these a train of as many as nine prisms is shown. The spectroscope was donated to the Académie des Sciences in 1867 [24].

The circumstances in which Secchi first used a spectroscope for stellar spectroscopy were related in his book *The Stars* in 1879 [25]:

> This spectroscope was known in Rome almost at the same time as the paper by Donati. Immediately I had the idea of using it on the stars, by mounting

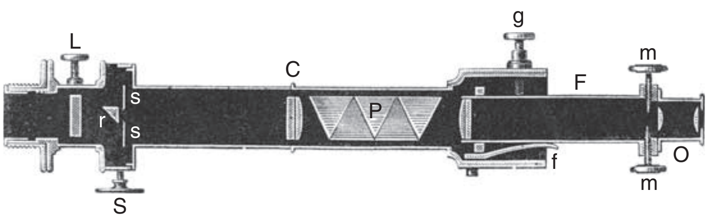

Figure 1.4. Angelo Secchi's direct vision Hoffmann spectroscope of 1862. P is the prism train comprising three crown glass and two flint glass prisms. s is the slit and C the collimator. The viewing telescope is F with eyepiece O. Light from a comparison source could be reflected off the small prism r in front of the slit.

> it to our large refractor, in the hope of obtaining better results than those of Donati, thanks to the perfection of our Merz objective lens. The instrument was ordered at once, but did not arrive until December of the same year. Meanwhile Mons. Janssen had come to Rome to study the solar spectrum, and as he had with him one of these small instruments, I begged him to mount it on our refractor, so we could use it provisionally until my own arrived. He agreed, and we undertook together these first investigations which were presented to the Academy of Sciences in Paris.

These events, in which Janssen and Secchi mounted the Hoffmann spectroscope on the Merz refractor, were also reported by Secchi elsewhere [22]. When they did so, Secchi wrote, '. . . we were astonished by the magnificent results that were obtained at the first attempt'.

A few years later Secchi introduced an objective prism spectroscope to his stellar spectroscopy programme [26]. He described the new instrument thus:

> The method that I have used is that which had been in a simple way adopted by Fraunhofer. It consists in putting a prism in front of the objective. For reasons of economy, I have had to limit the size of the prism to 6 inches (= 16 centimetres) diameter. Its refracting angle is 12 degrees and it is made from a very pure flint glass. It is supported in a suitable armature and placed in front of the objective of the large equatorial telescope and is capable of perfect adjustment in each coordinate. The aperture of the refractor remains thus reduced by more than half of its area. But, in spite of that, the light is so intense that it far exceeds that obtained with the use of direct vision prisms near the eyepiece [26].

Secchi used this objective prism instrument with two cylindrical lenses as an eyepiece, which broadened the spectra perpendicular to the dispersion. The objective prism and its mount were made by the firm of Merz in Munich, and it was the first thin prism of this type designed for a large refractor as a slitless spectroscope. It is shown in Fig. 5.1.

Lewis Rutherfurd (1816–92) was an amateur astronomer in New York state who also embarked on a programme of stellar spectroscopy in 1862, using his Fitz $11\frac{1}{4}$-inch refractor. He was a skilled instrumentalist and built his own slit spectroscope with a 60° flint glass prism and rotating viewing telescope [27]. A later paper discussed the simultaneous viewing of a comparison spectrum using a spirit lamp and he also experimented with carbon disulphide liquid prisms [28] (see also [29]). The carbon disulphide gave a high dispersion, especially useful at longer red wavelengths, and a high ultraviolet transparency, but suffered from a very high sensitivity of its refractive index to temperature (see [30] for details).

Rutherfurd criticized the spectroscopic instrumentation of his European contemporaries, finding a variety of deficiencies in the apparatus of Donati, Airy [31] and Secchi [32].

1.4 IMPROVEMENTS IN PRISM SPECTROSCOPE DESIGN IN THE LATER NINETEENTH CENTURY

In the second half of the nineteenth century numerous technical improvements in laboratory spectroscopes were devised, and some of these had a direct influence on the practice of astronomical spectroscopy. Some of these improvements resulted from the growth of firms specializing in optical and astronomical instruments.

Famous instrument makers of the later nineteenth century were mainly located in Britain and Germany, and included Troughton and Simms, Adam Hilger and John Browning (all in London), Howard Grubb (in Dublin), Schmidt and Hänsch, Hermann Wanschaff, Hans Heele, Otto Toepfer und Sohn (all in Berlin), G. Merz, C. A. von Steinheil (both in Munich) and August Hoffmann and Jules Duboscq (both in Paris). All these made prism spectroscopes for astronomy.[2]

Laboratory spectroscopy began developing strongly as a subject from about 1860, following the definitive study by Robert Bunsen (1811–99) and Gustav Kirchhoff on the flame and spark spectra of the different chemical elements [33, 34], which provided the basis for the chemical analysis of laboratory and celestial sources (see Fig. 1.5).

One of the improvements of the mid nineteenth century was the use of more than one prism to give higher dispersion and resolving power. The concept of a multiple-prism train was used by Hippolyte Fizeau (1819–96) and Léon Foucault (1819–68) in 1848, when they employed up to five prisms in their instrument, and hence obtained much superior resolving power, including for solar spectroscopy [35]. Such an arrangement was employed, for example, by William Huggins (and many others) for his laboratory study of the lines of the chemical elements, for which he used a spectroscope with six 45° prisms [36], as well as by Gustav Kirchhoff [14].

The London instrument maker John Browning, whose business flourished from about 1866 to 1905, built many multiple-prism spectroscopes and devised a mechanism for maintaining the circular arc of prisms always in the position of minimum deviation, regardless of the wavelength selected by the viewing telescope [37] – see Figs. 1.6 and 1.7.

His first instrument of this type with six prisms was built for John Peter Gassiot (1797–1877) at the Kew Observatory for solar work. It was criticized by Richard Proctor (1837–88) for having a fixed orientation of the first prism (relative to the collimator) [38], but subsequent improvements in the design overcame the problem alluded to [39, 40, 41]. A Browning spectroscope with seven flint glass prisms, though not of the automatic type, was used by Norman Lockyer for his pioneering work on the spectroscopy of the solar chromosphere [42, 43] – see Fig. 1.8. In Dublin, Howard Grubb included an automatic three-prism laboratory spectroscope in his firm's catalogue of 1885. An instrument of this type with compound prisms was supplied to the Royal Dublin Society.

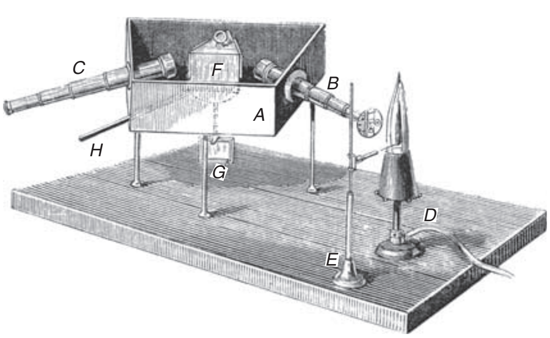

Figure 1.5. Early prism spectroscope used by Robert Bunsen for laboratory studies of flame spectra, circa 1860. A is the prism box, B the collimator, C the viewing telescope, D the burner, E a holder, F the prism.

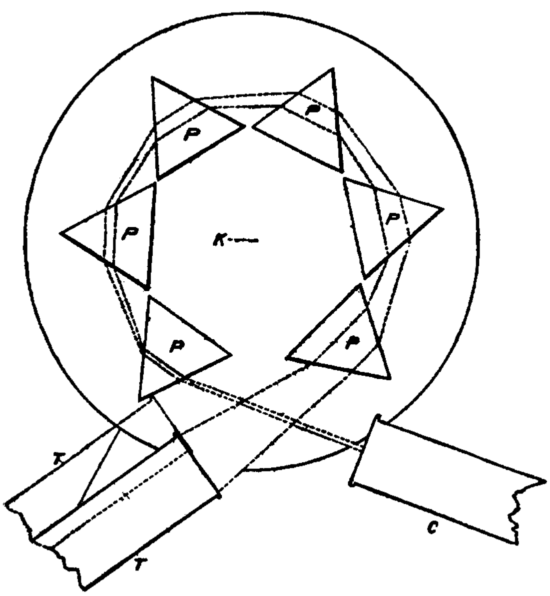

Figure 1.6. Browning automatic six-prism spectroscope, 1870. C is the collimator and T the movable viewing telescope.

[2] The Berlin instrument firm and clock-maker of Johann Bamberg acquired the Wanschaff company in 1919, Toepfer und Sohn also in 1919 and the Heele company in 1923, forming the company Carl Bamberg Friedenau. This eventually became part of Askania Werke AG in the early 1920s.

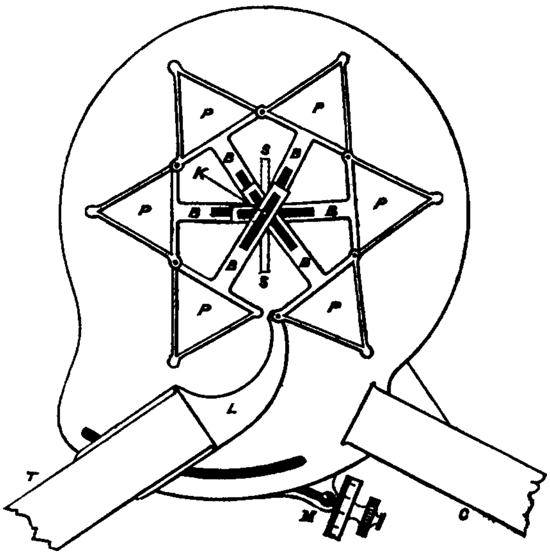

Figure 1.7. Browning automatic six-prism spectroscope, 1870, showing the mechanism for maintaining the prisms at minimum deviation when the position of the telescope T is adjusted by the micrometer M.

The idea of increasing the dispersion, not by adding more prisms, but by passing the light through one or more prisms twice after reflecting it back on itself, was another much used technique, which has been originally ascribed to the Paris optician Jules Duboscq (1817–86) in about 1860 (see [44, p. 511]). Such an arrangement was copied in various forms by many instrument makers. One of the better known was the automatic spectroscope (i.e. an instrument that always gave minimum deviation) built by Otto von Littrow (1843–64) in Vienna, which had four prisms, each used twice, thus giving the effective dispersion of eight prisms [45]. The light emerging from the collimator lens returned in the opposite direction through the same lens, which now served as the objective of the viewing telescope. This arrangement, in which the light returned back from the dispersing element along the same path, came to be known as the Littrow configuration, a term that has been widely used in spectroscope and spectrograph design, even for grating spectrographs, when the angles of incidence and refraction are arranged to be equal.

One method of achieving a double pass through the prisms was to fold the beam using a totally reflecting 90° prism at the end of the prism train. The return beam then went back through the prisms, but in a higher level (the prisms had to be twice the height), which therefore enabled the separation of collimator and viewing telescope. Such an instrument was constructed by Howard Grubb (1844–1931) in 1870 for William Huggins [46]. Separating the collimator lens from the viewing telescope objective was advantageous, as it avoided back-scattered undispersed light from the collimator lens being seen as a bright background illumination superimposed on the spectrum.

Even more complicated designs were built or proposed. Alfred Cornu (1841–1902) had a single-prism spectroscope in which the prism was traversed four times [47]. Louis Thollon's (1829–87) spectroscope of 1878 had four prisms each traversed twice in upper and lower levels, which he used for observing the solar spectrum at high dispersion [48]. Secchi also acquired a high dispersion double-pass instrument of this type, which comprised four and a half prisms for dispersion in an automatic arrangement – see Fig. 1.10.

In Cambridge, H. F. Newall (1857–1944) built a single-prism double-pass spectroscope for stellar spectroscopy, in which all three faces of the 60° prism were used as refracting surfaces [49, 50]. Here reflection of the collimated beam from the first prism face gave a white (undispersed) slit image in the field of view, which was seen superimposed on the spectrum. By rotating the prism assembly, this fiducial line could be seen at any desired wavelength, thus serving as a useful aid for line identifications or for measurements of line positions in spectra. Newall's arrangement was criticized by Frank Wadsworth[3] (1867–1936) [52], because

[3] Donald Osterbrock [51] made the following comments on Frank Wadsworth: 'Wadsworth dropped completely out of astronomy after 1904 ... He was at Clark University as an instrumental assistant to A. A. Michelson 1889–92, and then an assistant in charge of the astrophysical observatory under Langley 1892–94. Then he was assistant professor of physics (1894–96) and of astrophysics (1897–98) at Yerkes Observatory ... He was never promoted to associate professor at Chicago, but wanted to be, and left a year after it was denied to him. He was director of Allegheny Observatory 1900–04 and a consulting engineer to John Brashear 1901–04 ... Wadsworth was a very self-confident person, who believed he knew all the answers about instrumental design and construction, and that no-one else was competent to discuss such issues with him.

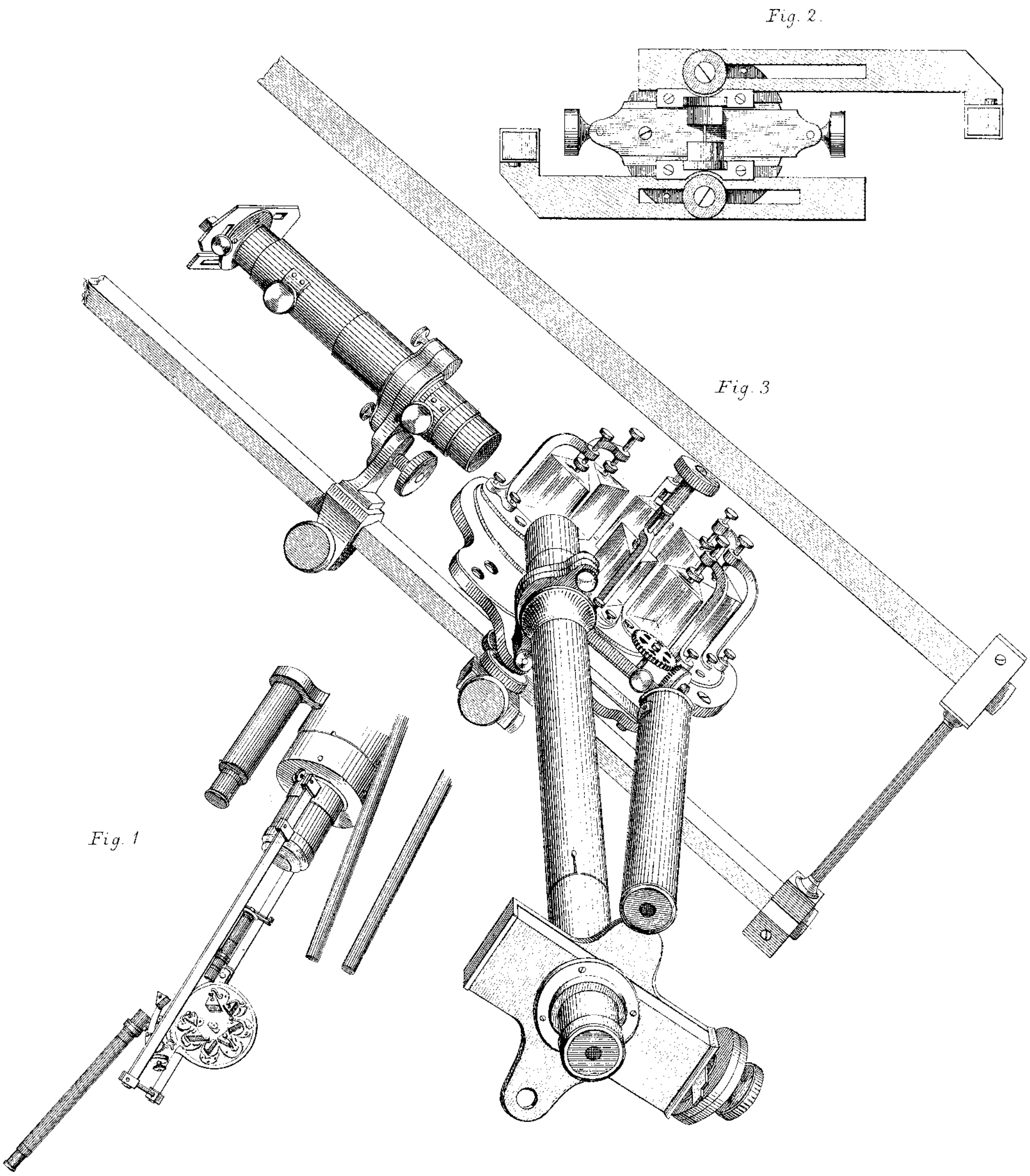

Figure 1.8. Norman Lockyer's seven-prism Browning spectroscope used for his pioneering observations of the solar chromosphere, 1869.

Michelson got tired of him and was very glad to pass him on to Hale, who was also evidently fed up with his arrogance and wrote a definitely luke-warm recommendation for a promotion, prompting Wadsworth's strong protests. There are signs that he was also 'on the outs' with Brashear very soon after getting there. Wadsworth wanted a lot of money for all kinds of new instruments; Brashear, who was chairman of the observatory committee [at Allegheny], knew there was no money and didn't want to raise any. Brashear had idolized Keeler, a very diplomatic person; Wadsworth was the opposite and there are almost no positive remarks from Brashear about him after his first year there [at Allegheny]... Wadsworth had never done any real astronomical research, and I suppose there was no place he could get a job in astronomy after Yerkes and Allegheny.' He was a consulting engineer for glass and metal companies after 1904.

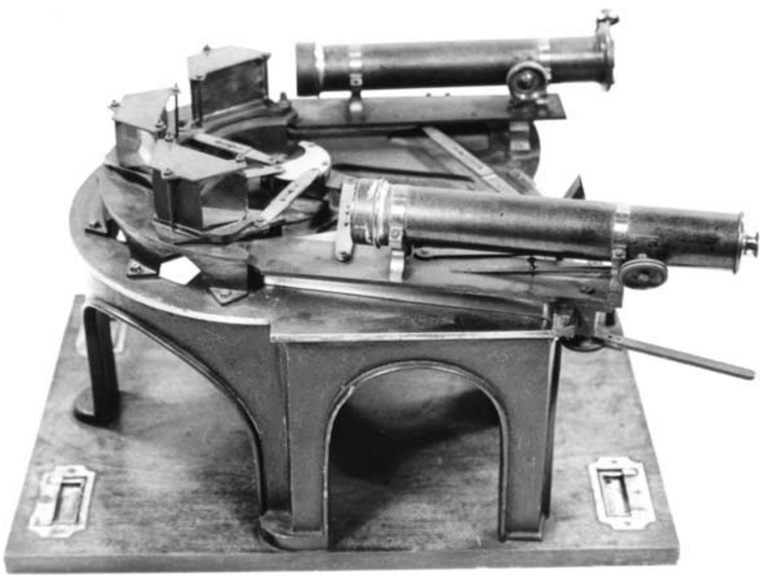

Figure 1.9. Howard Grubb's automatic compound prism laboratory spectroscope as supplied to the Royal Dublin Society. This spectroscope appeared in Grubb's 1885 catalogue of astronomical instruments; a similar instrument also appeared in Grubb's catalogue of 1877.

the light did not necessarily traverse the prism at minimum deviation, which was usually assumed to be necessary for maximum spectroscope efficiency (see Section 2.3 for a discussion of the minimum deviation condition).

Wadsworth himself devised a spectroscope comprising a single prism of equilateral cross-section, which was traversed by the light rays six times (twice through each pair of faces) using a system of plane mirrors [52]. Such an arrangement, however, was wasteful of light and could only be justified in cases where the prism material (such as fluorite for ultraviolet spectroscopy) was scarce.

Wadsworth was also the advocate of what he called a fixed-arm spectroscope, meaning an instrument where the viewing telescope was fixed in its orientation relative to the collimator [53, 54]. The direct vision instrument (180° between collimator and telescope) is one special case of this type of spectroscope, as is also the Littrow instrument (with 0° between collimator and telescope). The advantage of a fixed-arm spectroscope for astronomy was its mechanical rigidity, which was always a factor for an instrument mounted on a moving telescope. In general the fixed-arm concept is ideal when the dispersion is low, thereby

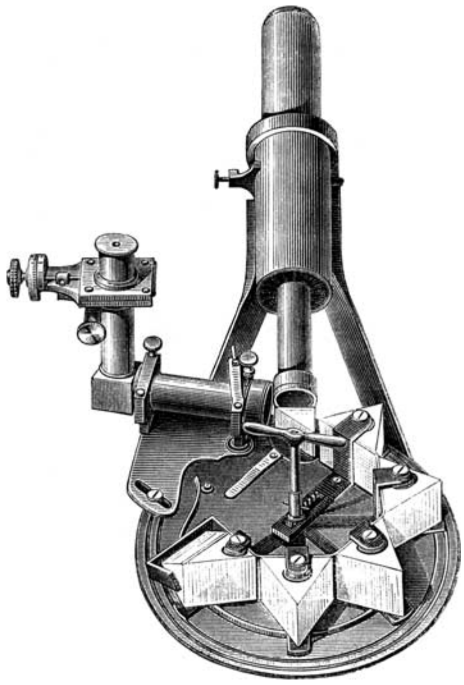

Figure 1.10. Secchi's high dispersion automatic double-pass spectroscope of about 1870. The first small prism reflects the light into the lower half of the prism train; it returns through the upper half into the viewing telescope on the left.

permitting the whole spectral region required to be seen in the eyepiece. However, Wadsworth designed fixed-arm instruments that were still able to scan in wavelength, by using a small rotatable mirror to reflect different spectral regions into the viewing telescope. He thus devised fixed-arm one-prism and two-prism instruments and also a Littrow spectroscope with two and a half prisms (the last half-prism being silvered) for astronomical use [54].

1.4.1 Spectroscope slits

A spectroscope slit is required to define the spectral resolution by admitting light from just a narrow angular range in the source. Albert Mousson (1805–90) in Zürich discussed the desirable properties of a slit mechanism, being one that prevents the delicate jaws from touching and maintains their parallelism for all jaw positions [55]. Mousson's slit mechanism, however, had one fixed jaw, the other movable, an arrangement that changed the mid-slit position for different slit widths.

More complex slits had two moving jaws, thereby maintaining the slit centre in a fixed location, which in turn left line positions unchanged for different resolutions. Such symmetrical slit mechanisms were described by Sigmund Merz [56], by H. Krüss [57], and by Frank Wadsworth [58, 59].

It is well known that the lines from a tall slit appear curved when viewed in a prism spectroscope (see for example [60, 61, 62]). The curvature is in the sense of the concave side of the lines being towards the shorter wavelength end of the spectrum. The effect arises from the light from the slit extremities not falling on the prism in the normal plane to the refracting surfaces. Such curved lines can make the measurement of line position more difficult.

In Dublin, Thomas Grubb (1800–78) devised a spectroscope in which the slit jaws were curved, so as to cancel their intrinsic curvature and hence render the lines straight [63]. Such a curved slit would be useful for high dispersion laboratory or solar telescopes where the source has large angular size (so as to illuminate a large slit height) and accurate line position measurements are required. On the other hand, Lockyer had a curved slit for solar spectroscopy for quite a different reason – in his case it was designed to match the curvature of the solar limb to enable observations of the chromosheric spectrum in the absence of a solar eclipse [64].

Deckers, which are cover plates to reveal just a selected part of the slit height, became a standard tool for spectrum photography. They were usually adjustable, and mounted just ahead of the slit. They are described by Johannes Hartmann in 1900 [65]. Frequently a small reflecting prism in front of the slit was used to send light from a comparison lamp into the spectroscope or spectrograph. Such a device was employed by Kirchhoff and Bunsen [66] and by many others since. For photographic work, the deckers then allowed comparison and celestial spectra to be recorded side by side.

Frequently stellar spectroscopes employed a cylindrical lens either with or without a slit. Thus Donati in 1860 had such a lens, but no slit [16, 17], so as to widen the spectrum. Huggins, on the other hand, placed such a lens just ahead of the slit, so as to produce a line image on the slit jaws [19] – see Section 1.5.

1.4.2 Projected scales and automatic line recorders

The measurement of the positions of spectral lines for the purposes of element identification and wavelength determination was a major activity throughout the history of laboratory and astronomical spectroscopy. The provision of projected scales or at least of fiducial reference markers, seen in juxtaposition with the spectra, became common from the 1870s. Thus Browning projected an illuminated cross onto the spectrum of a direct-vision spectroscope, by reflecting rays from the side off the last prism face [67]. Henry Procter instead had an illuminated scale similarly reflected [68], while Alexander Herschel proposed a scale produced by a row of equally spaced small holes illuminated with sodium light, each hole producing a small reference mark on the spectrum being investigated [69]. Maurice de Thierry also, like Procter, projected a scale off the last prism surface from the side, but he also had a micrometer wire that could be set on any point in the scale so as to facilitate measurements of line position [70]. An instrument of this type is shown in Fig. 1.11.

Further ingenious devices were arranged for recording line positions in spectra. One was built by Howard Grubb for William Huggins, with a view to