1 • Introduction to spectroscopy, spectroscopes and spectrographs

1.1 INTRODUCTION

A favourite quotation by astronomers is a passage by the French philosopher, Auguste Comte (1798–1857). The nineteenth lesson of his *Cours de Philosophie Positive* appeared in 1835 and was one of several lessons dealing with the theory of knowledge in astronomy. With reference to the stars, he wrote:

> We understand the possibility of determining their shapes, their distances, their sizes and their movements; whereas we would never know how to study by any means their chemical composition, or their mineralogical structure, and, even more so, the nature of any organized beings that might live on their surface. In a word, our positive knowledge with respect to the stars is necessarily limited solely to geometric and mechanical phenomena, without being able to encompass at all those other lines of physical, chemical, physiological and even sociological research which comprise the study of the accessible [i.e. terrestrial] beings by all our diverse methods of observation. [1]

A little later he continued: 'I persist in the opinion that every notion of the true mean temperatures of the stars will necessarily always be concealed from us' [1].

These passages may be amusing in the light of present knowledge, and it seems probable that Comte was ignorant of Fraunhofer's investigations from about 1814 to 1823 in which he described the absorption lines in solar and stellar spectra (see Sections 2.4 and 2.5). In any case, the implications of Fraunhofer's spectroscopic work were far from apparent at that time, even in scientific circles. However, Comte has been much maligned, mainly by astronomers ignorant of his overall positivist philosophy. Immediately preceding the much quoted passage on chemical composition of the stars is the statement: 'Every research that is not finally reducible to simple visual observations is therefore necessarily disallowed in our study of the stars' [1]. Comte therefore preached that true science was impossible if not based on direct observation or experiment (in the case of astronomy, on observation), a philosophy that scientists today should be happy to espouse.

In spite of my defence of Comte's views on the composition of the stars, which were admittedly erroneous yet pardonable, this book is largely a study of the subsequent investigations by many astronomers who reached the opposing view to Comte's by the analysis of starlight using the spectroscope or spectrograph. This is the story of how first the different chemical elements were identified in stars from their spectra, of how the temperatures and other physical properties of the outer layers of stars were measured, and finally of how the chemical composition of the stars themselves has been quantitatively determined.

The story described here spans more than three centuries if the prismatic dispersion and analysis of sunlight by Isaac Newton in 1666 is taken as the starting point. Alternatively, it encompasses nearly two centuries from the early investigations of Joseph Fraunhofer mentioned earlier, or nearly one and a half centuries from the rebirth of stellar spectroscopy with work by Huggins, Secchi and others in 1863. The studies of Newton and Fraunhofer were relatively isolated events in the history of astronomical spectroscopy, and the continuous development of the subject took place from about 1860 onwards. The scope of this book covers the main events in this development until about the end of the twentieth century, though the last decade or so of the century is not covered in the same detail as the earlier epochs.

The remainder of this introductory chapter concerns some of the basic concepts in spectroscopy, which may be skipped by those already familiar with them. In addition, some historical comments on the development of astronomical spectroscopes and spectrographs are included.

1.2 BASIC CONCEPTS IN SPECTROSCOPY

1.2.1 Terminology

The word 'spectrum' is defined in the *Oxford English Dictionary* as: 'the coloured band into which a beam of light is decomposed by means of a prism or diffraction

grating' [2].[1] It was first used in the English language with this meaning by Isaac Newton in 1671, in the first paper he sent to the Royal Society concerning the composition of white sunlight (see Section 2.1). On the other hand, the introduction of words such as spectroscopy, spectroscope and spectrograph was much more recent – all three date from the 1860s or 1870s. William Huggins in London, the pioneer of stellar spectroscopy, first used the term 'spectroscopy' in 1870; Henry Draper, the first person successfully to photograph a stellar spectrum in 1872, described his apparatus as a 'spectrograph' a few years later. On the other hand, a 'spectroscope' is for the visual instead of photographic observation of spectra. It is thus seen that stellar spectroscopists devised two of these three basic scientific terms at a time that the analysis of starlight was still in its infancy.

1.2.2 Wavelength and colour

All spectroscopes or spectrographs employ a dispersing element consisting of one or more prisms or of a diffraction grating. Its function is to produce a spectrum by spreading the light into a one-dimensional strip according to a photon's colour or wavelength.

The link between the colour of light (a physiological concept) and its wavelength was demonstrated by Thomas Young in England. He demonstrated the wave nature of light from interference in 1801, and then used a simple diffraction grating consisting of a series of parallel grooves in a glass plate for measuring the wavelengths of sunlight of different colours [3]. Spectra in four different orders were obtained from this apparatus and he showed how wavelengths could be obtained from the spacing of the grooves and the angle at which light of different colours was diffracted.

After Fraunhofer had rediscovered the absorption lines in the solar spectrum (see Section 2.4) he introduced the idea of using spectral lines as wavelength standards. He used the orange line he named D in the solar spectrum and in 1821 measured a wavelength of 588.8 nm[2], using a simple grating consisting of parallel fine wires stretched in front of his telescope objective [4].

In the 1860s gratings of much improved quality became available and several attempts were made to establish an accurate wavelength scale for the solar spectrum. In this period Eleuthère Mascart (1837–1908) [5], F. Bernard [6], Leander Ditscheiner (1839–1905) [7] and V.S.M. van der Willigen (1822–78) [8] all made wavelength measurements of absorption lines in the solar spectrum, generally to an accuracy of a few tenths of a nanometre. However, all these contributions were eclipsed by the work of Anders Ångström (1814–74) in Uppsala in 1868. He used a transmission grating to produce a drawing of the solar spectrum of unsurpassed quality showing about 1000 lines [9]. Nine strong lines were used for an absolute wavelength calibration; Ångström obtained 588.912 and 589.513 nm for the close D-line doublet. In spite of the care of his measurements, this scale still contained a substantial systematic error of about a tenth of a nanometre. Ångström probably suspected this himself, but the scale was not corrected until ten years after his death by Tobias Robert Thalén, his collaborator [10]. Meanwhile the visual atlas of Ångström was extended to the ultraviolet by Alfred Cornu, and this work included a new ultraviolet wavelength scale with a comparable accuracy to Ångström's [11].

The uncertainty in the wavelength scale was essentially cleared up by Henry Rowland in Baltimore in the last two decades of the century. He photographed the solar spectrum with a concave grating [12] and determined wavelengths to about 0.001 nm precision [13].

1.2.3 Continuous, emission and absorption spectra

A spectrum can be regarded as a one-dimensional image in which the intensity of light can be analysed as a function of wavelength. The wavelength varies with position along the spectrum's length. The dispersion is a key parameter. High dispersion refers to the greatest degree of spreading of different wavelengths.[3]

Newton observed a continuous spectrum of sunlight in 1666. This is also the spectrum seen in a rainbow and from incandescent solids in the laboratory. The intensity

[1] It had been used earlier to signify a 'phantom' or 'apparition'. But the similar word 'spectre' is more normal in this context. Both date from the early seventeenth century, and both are derived from the Latin word 'spectrum,' meaning either (a) an appearance or image or (b) an apparition or spectre.

[2] In this book the nanometre (nm) is normally used for wavelength, as it is the SI unit. However, the ångström unit (1 Å $= 10^{-10}$ m $=$ 0.1 nm) is also used, especially for citing the dispersion of spectra (in Å/mm), for citing the strengths or equivalent widths of lines (given in mÅ) and in cases where quotations are cited that use ångström units.

[3] Dispersion is conveniently given in units of Å/mm. Strictly speaking this is the reciprocal dispersion, but here the notation is abbreviated and the 'dispersion' is referred to in Å/mm. Thus 'high dispersion' implies a small numerical value in Å/mm. For those forewarned of this common terminology, no confusion should arise.

of light in a continuous spectrum appears to change only slowly with wavelength. On the other hand, the spectrum of a candle flame was the best known example in the early nineteenth century of an emission spectrum. Here light occurs in bands at only certain discrete wavelengths, with at most a weak continuum or no light elsewhere in the spectrum. An emission spectrum of this sort was observed by Thomas Melvill in Scotland as early as 1752, when he observed the spectra of flames containing mineral salts [14]. William Wollaston was one of the first to study such flame spectra in more detail [15]. The light from an electric spark also produces an emission spectrum with narrow lines. This was observed by Fraunhofer in 1824 [16], and detailed observations were made later by Charles Wheatstone [17] and others.

Absorption-line spectra occur when light at discrete wavelengths is absent from a continuous spectrum. The spectra of this type were observed in sunlight by Wollaston in 1802 and by Fraunhofer in 1814 (see Section 2.4) and were the first absorption spectra to be described. Subsequently, absorption spectra were produced in the laboratory, especially by Sir David Brewster, in the 1820s and 1830s, by the passage of light from a continuous-spectrum source through a cooler gaseous absorbing medium [18].

1.2.4 Resolution and resolving power of spectroscopes

The concepts of wavelength resolution and resolving power are crucial in determining whether absorption lines are visible in the spectrum of sunlight or of a continuous source that has passed through an absorbing gas. The wavelength resolution $\Delta\lambda$ is the smallest resolvable spectral detail that can be discerned in a spectrum. It is a measure of the 'purity' of a spectrum, or the range in wavelengths present in any one spectral position. Low resolution will lead to the disappearance of narrow absorption lines. Resolving power is defined as a dimensionless ratio, $R = \lambda/\Delta\lambda$. For grating spectrographs it can be shown that this parameter is independent of the order of the diffraction and is often a more useful quantity to quote than the resolution. High resolving power in stellar spectroscopy signifies values of around several times 10^4; values as high as 10^5 are rarely achieved for other than solar spectra, nor are they required for most stellar investigations. On the other hand, low resolving powers of a few thousand are common for stellar spectral classification work, and would be typical for slitless spectra with an objective prism.

High resolving power can be achieved by employing dispersing elements of large physical size or by passing light through a narrow slit placed at the telescope's focal plane.[4] In this latter case, a collimator should be used after the slit to render the diverging rays parallel. William Swan in Edinburgh had employed a collimator in his spectroscope in 1856 [19]. However, in this respect he may not have been the first. According to Heinrich Schellen (1818–84), in his well-known treatise on *Spectrum Analysis* [20], William Simms (1793–1860) in London had constructed a spectroscope with a collimator as early as 1848.

Both a slit and a collimator were employed by Robert Bunsen and Gustav Kirchhoff in Heidelberg for their pioneering studies of laboratory and solar spectra, and also by Giovan Donati in Rome in 1860 [21]. From about 1863, at the time that several pioneers began observing stellar spectra, the slit and collimator had become standard. Rutherfurd, Secchi and Huggins all used this arrangement in their first spectroscopic observations. In particular, Lewis Rutherfurd in New York was a skilled instrumentalist, who criticized Donati's spectroscope for not having the slit at the focus of the telescope, and Secchi's for using multiple prisms of flint and crown glass that would have resulted in considerable light loss [22].

1.3 THE DEVELOPMENT OF THE SPECTROGRAPH AND SPECTROSCOPE DESIGN

Readers of this section are referred to my book *Astronomical Spectrographs and Their History* [23], which gives much further information on the history of spectrograph development.

1.3.1 Prism instruments in the nineteenth and early twentieth centuries

The development of efficient slit and collimator spectroscopes in the mid-nineteenth century was indispensable to the rapid progress of stellar spectroscopy in the 1860s. This is the view of Henry C. King in his text on *The History of the Telescope*:

> It is no exaggeration to say that the rapid rise of astrophysics was made possible by craftsmen like Carl August Steinheil and the Merz organization at Munich, John Browning, William Simms and, later, the Hilger

[4] The illumination of a grating at a large angle of incidence can also achieve high resolving power; modern échelle gratings make use of this property.

brothers of London, and Howard Grubb of Dublin. These workers soon became acknowledged experts in the design and manufacture of high-grade prisms, spectroscopes, and auxiliary spectroscopic apparatus. [24][5]

Several other instrument-makers built stellar spectroscopes privately for their own use or for others at this time, notably Hoffmann in Paris, who constructed direct-vision instruments for Jules Janssen [30], one of which was acquired by Secchi and used for his early stellar spectroscopy; and also Rutherfurd and Huggins constructed their own instruments for stellar spectroscopy. For stellar work it was necessary to broaden the stellar image on the slit using a cylindrical lens, and this was used in nearly all stellar slit spectroscopes from 1860 onwards. However, such a lens was also used much earlier by Fraunhofer with his slitless objective prism spectroscope. Only when spectrography became established did Huggins dispense with this means of widening the spectrum, and instead he trailed the star image up and down the slit during the exposure [31]. For this purpose he devised the technique of reflecting part of the stellar image obliquely into a small guiding telescope. This was later modified from using a small silvered mirror with an aperture immediately in front of the slit, to the use in 1893 of polished slit jaws made from speculum metal [32].

Henry Draper in New York State and William Huggins were the earliest pioneers of spectrum photography. Initially Draper in 1872 had used a slitless spectrograph equipped with an ultraviolet transmitting quartz prism for his 28-inch reflector. By 1876 he had developed a slit instrument which also employed a portrait lens as a camera to focus the spectrum onto the plate [33]. Huggins' experiments with spectrum photography also date from this time; his spectrograph was made by Adam Hilger in London and employed quartz lenses and an Iceland spar prism [34]. It was mounted at the prime focus of his 18-inch reflector. A new instrument by Browning for the Cassegrain focus in 1880 had two prisms and was easier to use [31] (see Chapter 4 for further details). An instrument of this type was obtained by Henry Draper on a visit to Europe in 1879, and used briefly when he resumed his stellar spectroscopy in the last few years of his life [35].

In the last two decades of the nineteenth century and the first of the twentieth, prismatic slit spectrographs became relatively commonplace at several major observatories. Apart from Huggins in London, they were developed most notably by Hermann Carl Vogel at Potsdam [36], William Campbell at Lick [37], Edwin Frost at Yerkes [38] (Fig. 1.1), Aristarkh Belopolsky at Pulkova, Friedrich Küstner in Bonn, Hugh Frank Newall at Cambridge [39] and John Plaskett in Ottawa [40]. Collimators and cameras were lenses; typically there were two or three flint glass prisms (useful in the range 380–500 nm) and the collimator-to-camera focal length ratio was generally two or three to one. This era in spectrograph design coincided with the period when new giant achromatic refractors were coming into service (such as those at Lick, Yerkes and elsewhere). However, prism spectrographs remained in widespread use at least until the end of the 1930s. An example of an advanced three-prism spectrograph is the Cassegrain instrument designed by Walter Adams for the Mt Wilson 60-inch telescope in 1912. It could produce spectra at 5.2 Å/mm at Hγ in its highest dispersion mode [41].

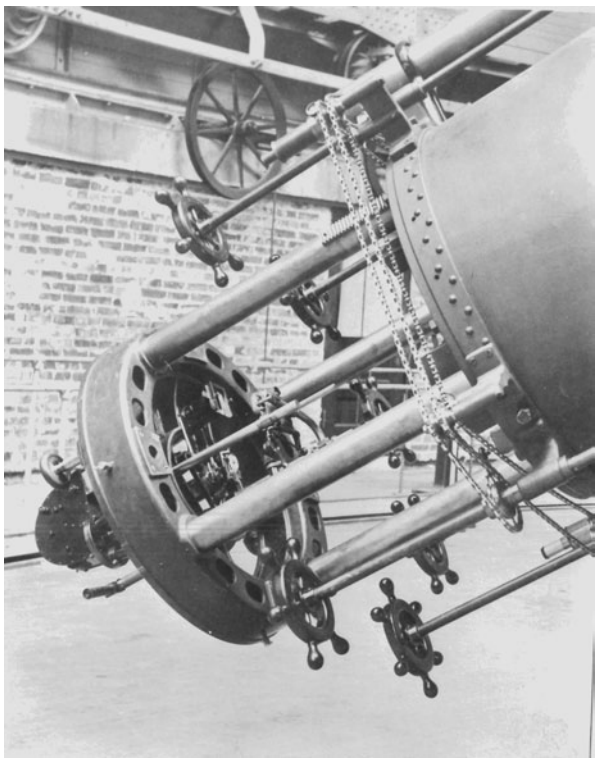

Figure 1.1. The three-prism spectrograph on the Yerkes refractor, 1903.

The problems that arose in stellar spectrograph design at this time were the need to reduce flexure of the instrument attached to the moving telescope, the need to avoid temperature changes in the spectrograph, the problem of how to pass the ultraviolet starlight efficiently through a slit

[5] Descriptions of early spectroscopes can be found in the following references: C.A. Steinheil [25]; J. Browning [26]; H. Grubb [27]; L.M. Rutherfurd [22, 28]; W. Huggins and W.A. Miller [29].

under visual guiding and the question of chromatic effects in the spectrograph lenses. Because the early photographic emulsions were sensitive in the ultraviolet and blue spectral regions, the fact that prisms gave very poor dispersion in the red and that most stars anyway seemed to have fewer interesting lines at longer wavelengths meant that most observers were happy to record their spectra in the short wavelength photographic region of the spectrum. Flexure and temperature effects both prevented longer exposures unless they were carefully allowed for. At Potsdam, Vogel rarely exposed for longer than one hour for these reasons. Campbell and Wright at Lick paid careful attention to these problems, employing counterbalancing devices and a very stiff construction to reduce the flexure effects, and insulation of the whole spectrograph in a blanket and internal heaters to offset increased heat loss as the night got colder [42, 43]. Henri Deslandres in Paris also had used a thermostat in the interior of his spectrograph in 1898 [44]. He circulated water in the hollow walls of his spectrographs as thermal insulation and proposed constructing spectrographs from 'invar', a nickel steel with a low thermal expansion.

Chromatic aberration in refractors proved a major drawback for photography and spectrography. Both Draper and Huggins had avoided these problems using reflecting telescopes, and this also allowed them to reach the ultraviolet region of the spectrum with quartz optics spectrographs. Deslandres in Paris was using the 1.2-m reflector for stellar spectrum photography from 1890 [45], and the Lick telescope installed in Chile in 1903 is another example of a reflector prominent in the early days of spectrography. However, such instruments were the exception rather than the rule, and those refractors whose objectives were corrected for visual work were generally unsuited for spectrographic use unless further modified. Newall in Cambridge inserted an extra lens in his telescope 1.5 m in front of the focus to convert it to slit spectrography.

Johannes Hartmann at Potsdam was able to overcome the problem of chromatic aberration in spectrograph camera lenses by simply tilting the plate along the length of the spectrum, thus compensating for the change in the focal length with wavelength [46]. This technique was widely copied elsewhere.

1.3.2 Early objective prism instruments

The objective prism instrument, which had been used visually by Fraunhofer and by Angelo Secchi, came into its own from the 1880s when astronomical photography became an established technique. Here neither collimator nor slit is employed and one or more prisms of small apex angle are placed in front of the object glass of an astrographic telescope. The pioneering work of Edward Pickering at Harvard using objective prism spectrographs is the subject of Chapter 5. He began this work in 1882 with a 13° prism of 20 cm aperture. Objective prism spectrography was commenced at the Paris Observatory soon afterwards [47]; here a 5° crown glass prism of aperture 21 cm was initially employed and the spectra of stars to ninth magnitude were recorded. Also in the nineteenth century, Norman Lockyer and Frank McClean in England and Eugen von Gothard in Hungary undertook objective prism spectrography. Lockyer used objective prisms mounted on his 6- and 10-inch refractors [48] from about 1890, while McClean used a 12-inch Grubb astrograph with a 20° prism from 1895. More details are discussed in Chapter 4.

Objective prism spectrographs were fast and efficient but being slitless they usually gave low resolving power of several thousand or less. However, if three prisms were mounted, which would be justified only in excellent seeing, then quite high dispersion could be achieved. On the 13-inch Boyden telescope at Harvard's Arequipa station in Peru, three prisms gave spectra 7.43 cm in length from Hβ to Hϵ, an interval of nearly 90 nm [49]. At times up to four 15° prisms were used on the 11-inch Draper telescope at Harvard [50], but the long exposures limited such work to the brightest stars.

1.3.3 Early grating spectroscopes and spectrographs

Although diffraction gratings were used regularly for solar spectroscopy in the nineteenth century (see Section 1.2.2), their use for stellar work at this time was very limited, owing to their inefficiency which resulted from the available light being divided between several diffraction orders. Thus, even though gratings could give a nearly linear dispersion and were able to disperse light in the red part of the spectrum and did not suffer from the absorption of a long train of prisms, they were still little used. In 1875 Angelo Secchi received a grating spectroscope made by Lewis Rutherfurd in New York. Rutherfurd was producing reflection gratings diamond-ruled on speculum metal by about 1850, and his reputation for high-quality gratings was considerable for the next three decades. Secchi commented: 'The spectra formed thus by interference possess a clarity and certainty which by far surpass those from prisms' [51]. However, it is probable that he was referring to a laboratory or solar source; it is not certain if either Rutherfurd or Secchi attempted stellar observations with grating spectroscopes. If they did, it seems that they were unsuccessful.

Vogel at Potsdam is known to have attempted to use a grating (ruled by Hermann Wanschaff in Berlin) for stellar spectroscopy at Potsdam in 1881 [52]. This is probably the first venture into stellar grating spectroscopy. However, the experiment was not successful, owing to insufficient light in the spectrum.

The next experiments with gratings in astronomical spectroscopy were undertaken by James Keeler at Lick from 1890 to 1891 [53]. His visual spectroscope on the giant refractor had either three prisms or a Rowland grating ruled to 14 438 lines per inch (570/mm; see Fig. 6.7). He used this instrument in the grating mode to obtain a very accurate wavelength for the green emission line of the Orion nebula and of several planetary nebulae (see Section 6.6). He also observed a number of stellar spectra with this instrument. He used the grating in the third or fourth order of diffraction, which results in a high linear dispersion and is an advantage for accurate wavelength determinations in an emission-line spectrum (where the lines are not dimmed by increased dispersion). Keeler's work was the first successful observation of grating spectra from a celestial source other than the Sun. His success can be attributed to his use of a high quality Rowland grating, to his use of a large telescope, and to his restricting his observation either to emission-line nebulae or to very bright stars.

Several further tests with gratings for stellar work followed in the first decade of the nineteenth century. For example, Walter Adams at Mt Wilson reported obtaining a blue spectrum of Arcturus with the assistance of Hale on the Snow solar telescope in 1905. As at Lick, a Rowland plane grating was employed. The exposure time was 23 hours over 5 nights [54]. William Campbell and Sebastian Albrecht used a grating spectrograph at Lick in 1910; they observed the spectrum of Mars but the instrument appears not to have been used to any great extent thereafter [55].

John S. Plaskett at the Dominion Observatory, Ottawa, can be regarded as the pioneer of successful stellar grating spectrography. In 1912 he obtained a grating from John Anderson (1876–1959), Rowland's successor at Johns Hopkins University, and the pioneer of the 'blazed' grating which was claimed to concentrate half the diffracted light into the first-order spectrum.[6] Plaskett compared prismatic and grating spectrograms of bright stars [56]. The uniformity of dispersion and lack of ultraviolet absorption from the grating led to spectra uniformly exposed from the Hβ line to 385 nm. He wrote:

> . . . although the spectra obtained from the grating are disappointingly weak. . . , yet even under this handicap it can be used to advantage when the K line is required and if spectra of uniform intensity or of uniform dispersion are needed. It would be useful in the red end where prismatic spectra are so unduly compressed. If a grating giving twice the intensity could be obtained it would be superior even to single-prism dispersion for most work [56].

It was the potential for gratings in the red and infrared parts of the spectrum, as noted by Plaskett, that motivated Paul Merrill to begin experiments at Mt Wilson in 1922 [57]. He cited the advantages that were anticipated: a longer length of spectrum of the correct exposure, a normal (i.e., uniform) dispersion, the ease of changing the spectral region under study (by tilting the grating), the small size of the spectrograph and (for the first time) shorter exposures than with a prism. By 1924 he was employing a blazed 600 line/mm plane grating ruled at Mt Wilson by Clement Jacomini who, with John Anderson, had established the ruled grating section at that observatory in 1912 (see [58]). Together with Roscoe Sanford, Merrill used this spectrograph to expose about 120 test spectrograms over the next two years. Flexure was a problem, but the instrument was found to be useful and efficient. The 1924 spectrograph was the prototype for Merrill's Mt Wilson Cassegrain grating spectrograph of 1929 (Fig. 1.2) [57]. This was the first modern and successful grating spectrograph in regular use in stellar astronomy. The elimination of flexure was a special feature of the design so as to allow for long exposures of up to six hours. The interchangeable cameras could provide three dispersions, of 111, 66 or 34 Å/mm. Some spectra were obtained on infrared sensitized plates to as far as 870 nm and these included the first stellar observations of the three strong ionized calcium lines in the spectra of cooler stars.[7]

1.3.4 The development of coudé spectrographs

The coudé configuration for a telescope is an optical arrangement devised by Maurice Loewy (1833–1907) at the Paris Observatory in the 1880s [59]. Light reaches the coudé focus after two successive reflections from plane mirrors, which direct it to a fixed point. Here it can be recorded photographically or passed into a large spectrograph, which might be too massive for mounting on the moving telescope

[6] The blazed grating is able to concentrate much of the light into one diffraction order by ruling with a specially shaped diamond which determines the groove profile.

[7] The Ca II infrared triplet lines are at 849.8, 854.2 and 866.2 nm.

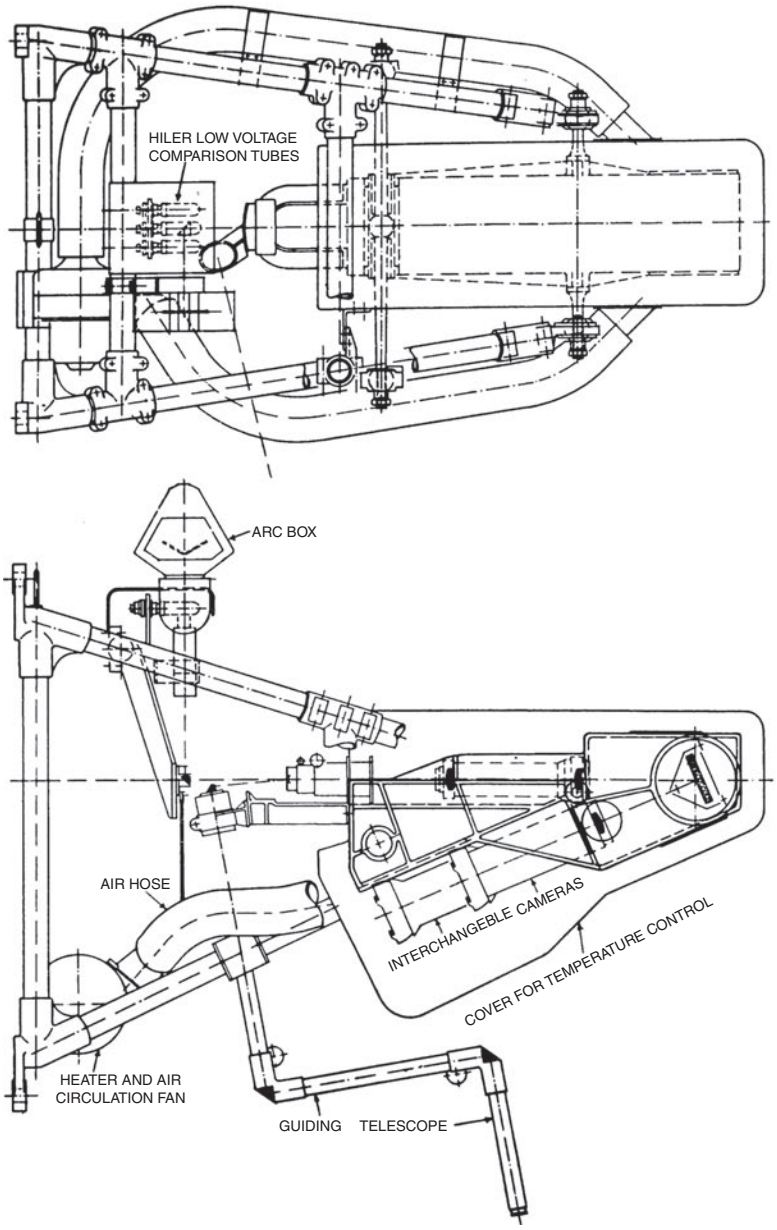

Figure 1.2. Merrill's grating spectrograph at Mt Wilson, 1929.

itself. This arrangement was used at Paris for a 27-cm coudé refractor, and then later on for a 60-cm instrument in which the converging coudé beam was directed up the polar axle to the northern pier of a two-pier equatorial mounting.

Loewy became director of the Paris Observatory in 1896 and he initiated the construction of the first coudé spectrograph on the 60-cm refractor in 1903. The construction was undertaken by the firm of Paul Gautier (1842–1909) and completed in 1907. This was a Littrow spectrograph, in which the light traversed the prism train twice after reflection. Three dispersions were available – at 4, 8 or 20 Å/mm. Forty spectra of bright stars were photographed by Maurice Hamy with this instrument in 1907 for the purpose of obtaining radial velocities of the stars by the Doppler effect [60]. Although the exposures were long, stellar spectra continued to be obtained with this instrument mainly

by Hamy and Pierre Salet for several decades, except for a six-year wartime break from 1914. The number of spectra obtained each year was, however, never very high.

The advantages of a stationary and thermally controlled environment for a large spectrograph of high resolving power, that could produce for stars what Rowland had already achieved for the Sun, were recognized by George Ellery Hale, when he designed the 60-inch reflector at Mt Wilson with a coudé focus as one of several optical arrangements that could be chosen. This telescope made its first observations in December 1908 and the coudé spectrograph was completed by 1911. The coudé beam in this case was passed vertically down into an underground pit where the spectrograph was constructed.

The first spectra obtained with this coudé instrument were described by Walter Adams [61]. The dispersion was very high, giving 1.4 Å/mm at 430 nm and the plates were 43 cm in length. Good definition spectra of bright stars were obtained over all this length by Adams and Harold Babcock (1882–1968). A single large, dense, flint-glass prism was used in a Littrow mounting as dispersing element; in this arrangement a 15.2-cm lens served as both collimator and camera. Undoubtedly the 60-inch coudé spectrograph served as the prototype for that of the 100-inch. This telescope was being planned even before the 60-inch had been completed. It was commissioned in 1918 but the coudé spectrograph was not installed by Adams until some years later, in 1925. Like the earlier coudé spectrograph on the 60-inch telescope on Mt Wilson, that on the 100-inch was a single-prism Littrow instrument; it could produce 2.9 Å/mm spectra at 430 nm with a high resolving power of 70 000. A four-element Ross lens of 4.5 m focal length served as collimator and camera. Later a system with an aluminized parabolic mirror and a quartz prism was also installed to allow wavelengths between 305 nm (short wavelength limit due to atmospheric ozone absorption) and 390 nm (the short wavelength limit for the Ross lens and dense flint prism system). Walter Adams and Theodore Dunham used this spectrograph in 1938 to study the ultraviolet spectra of bright early-type stars [62].

Although undoubtedly successful for very high dispersion work on the brightest stars, the Mt Wilson coudé spectrographs were limited by the light absorption in the necessarily large prisms, and by the inability of large-aperture fast camera lens systems to achieve good image definition over a long spectrum. These limitations were dramatically overcome in the mid-1930s by Adams and Dunham. In the words of Ira Bowen: 'Suddenly, however, the picture was completely changed by the advent of the Schmidt camera and its various modifications and by the development of the blazed grating, which permits the concentration of 60–70 per cent of the light in one order' [63]. In 1934 Dunham carried out the first test of a Schmidt camera to replace the Ross lens as a coudé camera [64]. In Dunham's words:

> It was of course W. Baade, coming from Hamburg, who brought news of the. . . invention of the Schmidt plate, by Schmidt, in about 1933, or perhaps 1932,[8] when Baade came over. . . he told us about this extraordinary development of the Schmidt plate and the Schmidt camera for photographing stars. . . to anyone in my position, this struck instantly as a possibility for revolutionizing spectroscopy. You didn't have to use lenses now. The ordinary lenses of those days, for short focus cameras were perfectly horrible compromises. So we rubbed up this aspherical plate. . . and put it up there in a wooden mounting. . . And we got some gorgeous spectra out of it instantly. [66]

The Schmidt camera was based on the work of the Estonian-born German astronomer Bernhard Schmidt (1879–1935) at the Hamburg Observatory, who in 1931 devised a wide field catadioptric camera with a spherical mirror and corrector plate to largely overcome the spherical aberration [67]. The first Schmidt camera in the coudé spectrograph in 1934 was of 76 cm focal length and gave excellent definition spectra from the ultraviolet to the red [68]. Soon afterwards it was replaced with 81- and 185-cm focal length Schmidts which were mounted on a completely redesigned steel girder framework in the coudé chamber in 1935, together with an off-axis parabolic mirror for collimation. In 1939 a third 2.85-m focal length Schmidt camera was added for spectra of the highest dispersion (Fig. 1.3).

In 1931 Adams and Dunham (Fig. 1.4) began their experiments with an Anderson plane grating to replace the prism in the coudé spectrograph. However, it was not until 1936 that Dunham acquired a grating from Robert Wood at Johns Hopkins University. This 590 line/mm grating had a high blaze efficiency, peaking at 350 nm for the second order of diffraction. The rulings were in aluminium that had been vacuum-deposited onto a pyrex base. The Wood grating gave high dispersion spectra at 10.5, 4.5 or 2.9 Å/mm, depending on the choice of camera. A resolving power of over 80 000 could be achieved with the largest camera at the highest dispersion. A sixth magnitude star, the variable Mira, was recorded in about six hours with this camera by Adams [69].

[8] See Schmidt's 1932 paper [65]. The Schmidt camera employs a spherical mirror and an aspherical corrector plate to eliminate aberrations for wide-angle photography.

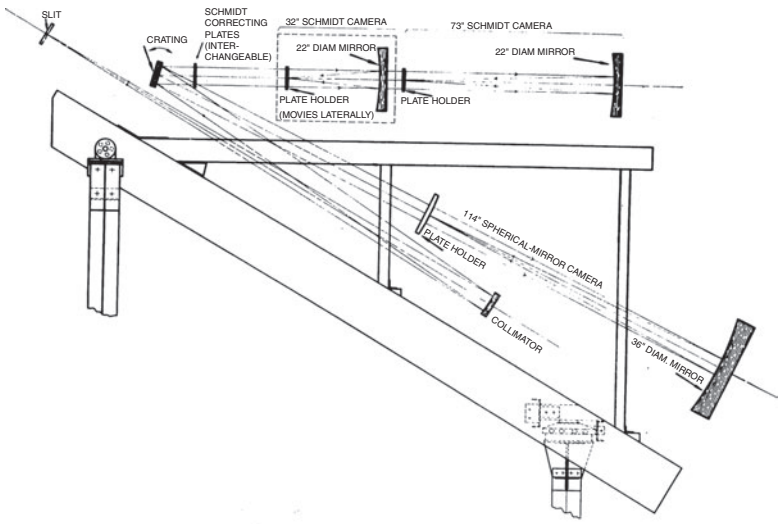

Figure 1.3. The coudé spectrograph on the Mt Wilson 100-inch telescope showing the optical configuration from 1939.

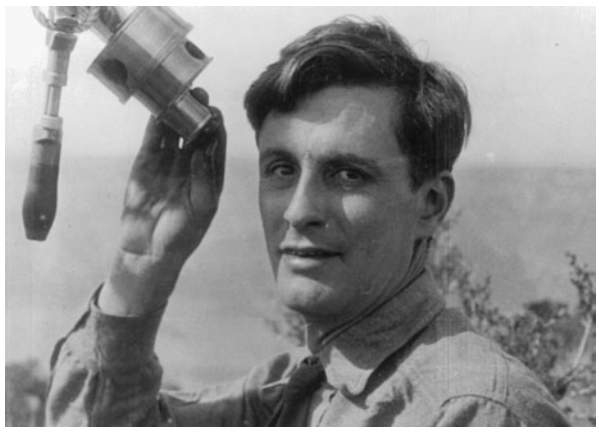

Figure 1.4. Theodore Dunham, Jr, about 1930.

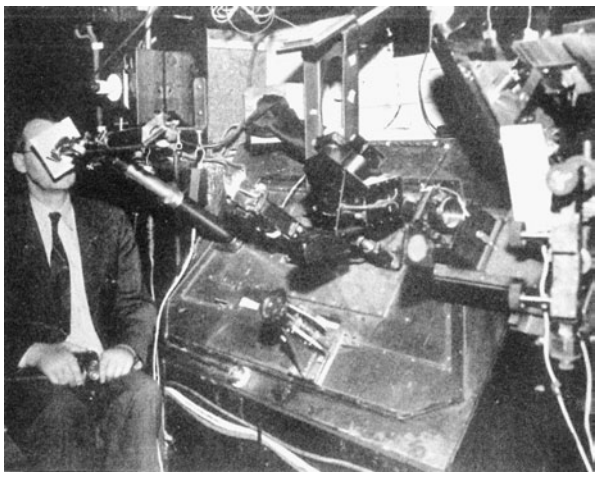

Figure 1.5. Auxiliary equipment at the coudé focus of the Mt Wilson 100-inch telescope. Ira Bowen is guiding a star on the slit, while shielding his eyes with the mask from the glare of the iron comparison arc.

The use of the Wood grating and Schmidt cameras on the 100-inch telescope coudé spectrograph (Fig. 1.5) revolutionized high-dispersion stellar spectroscopy from 1936. Several other coudé spectrographs copied the basic design features used at Mt Wilson. These were the coudé instruments built by Albert Hiltner for the 82-inch McDonald telescope in 1949 (see [63] for details), by Bowen for the 200-inch telescope at Mt Palomar in 1952 [70], and then at Haute Provence, Radcliffe, Lick and Mt Stromlo observatories over the next decade. From the late 1930s onwards blazed grating instruments increased in popularity while prism spectrographs went into decline. The clear advantages of linear dispersion, nearly uniform intensity (allowing the recording of long lengths of spectrum in one exposure), and the ease of changing the spectral region by tilting the grating, made the new coudé spectrographs the clear first choice for high-dispersion work. On the other hand, the efficiency was not always very high compared with Cassegrain instruments, because of losses at five of six mirrors and the grating before the light reached the photographic plate.

1.3.5 The development of the échelle spectrograph

The échelle grating was devised by George Harrison (1898–1979) in 1949 at the Massachusetts Institute of Technology,

where he had developed interferometrically controlled ruling engines able to produce diffraction gratings with a carefully controlled groove profile [71]. The échelle is a coarsely ruled grating with a large blaze angle allowing the incident light beam to arrive at a large angle of incidence to the normal. Such gratings with oblique incidence were shown to give a high spectral dispersion and resolving power. Echelles use multiple high orders and these have to be separated by a cross-dispersing element, which is often a prism or conventional low dispersion grating.

The use of échelle gratings in astronomy was at first fairly slow. Keith Pierce (1918–2005) and his colleagues at the University of Michigan were using an échelle grating for solar spectroscopy as early as 1951 [72], and Richard Tousey (1908–97) at the US Naval Research Laboratory had an échelle for ultraviolet solar spectroscopy fly on an Aerobee rocket in the late 1950s [73, 74]. These first instruments generally had 79 gr/mm and a blaze angle of 73°.

The échelle was only occasionally used for stellar spectroscopy in the 1960s (see [75, 76, 77]). Most observers preferred traditional coudé spectrographs for high-dispersion work. However, sometimes an échelle grating was mounted in an existing coudé instrument, as the aforementioned papers show. Another early example of a coudé mounted échelle was at Mt Stromlo on the 74-inch telescope [78]. By the early 1970s the feasibility of constructing a very compact high resolving power spectrograph for the Cassegrain focus of even telescopes of quite moderate size led to a series of Cassegrain échelle instruments at several observatories, including Pine Bluff Observatory, Wisconsin [79, 80], Mt Hopkins Observatory, Arizona [81], Harvard's Oak Ridge Observatory [82] and at Mt John Observatory in New Zealand (Fig. 1.6) [83, 84]. At first the benefit was the ability to obtain high resolving power with a compact Cassegrain instrument.

By the 1980s, échelle spectrographs were being used with electronic detectors, most notably the charge-coupled device (CCD). This immediately exploited one of the main advantages of the échelle grating over traditional coudé spectrographs with conventional low blaze angle gratings – namely the compact format of orders on the detector. In effect the spectrum was no longer a long thin strip on a photographic plate, but it was sliced up into many (possibly as many as a hundred) such strips, each covering a few tens of nanometres of wavelength, and stacked into a convenient format of parallel orders on a small detector chip.

More recently some major custom-designed échelle spectrographs have been built at the coudé focus of large telescopes, where the large beam size and large angle of incidence on the grating are both exploited to give a high resolving power. Well-known examples are the Hamilton échelle at the Lick 3-m telescope in 1986 [85, 86], the HIRES instrument at the 10-m Keck telescope on Mauna Kea, Hawaii in 1988 [87], the University College London échelle spectrograph on the Anglo-Australian Telescope also in 1988 [88, 89], the 2dcoudé instrument at McDonald Observatory in 1992 and the coudé échelle spectrograph at the Canada-France-Hawaii 3.6-m telescope in 1988 [90].

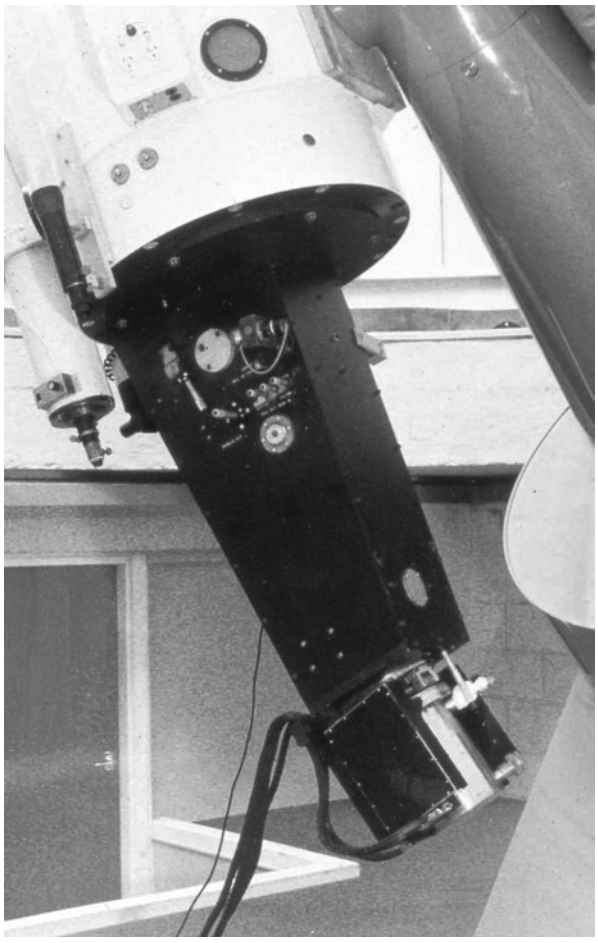

Figure 1.6. The Cassegrain échelle spectrograph on the 61-cm telescope at Mt John, New Zealand. This instrument came into operation in 1977, the first Cassegrain échelle in the southern hemisphere. It is seen here in 1986 with a Reticon diode array detector.

A further development of the échelle spectrograph is the use of optical fibres to link the telescope focal plane to a static spectrograph which can be housed in a temperature-controlled enclosure. Fibre-fed échelle spectrographs date from the mid-1980s and were pioneered by Laurence Ramsey (b. 1945) and his colleagues at Pennsylvania State