

# 1

## Historical Remarks

The purpose of this book is to provide an introduction to present-day astronomical spectroscopy. Thus, this chapter on the historical development will be restricted to a brief outline of selected milestones that provided the basis for the contemporary techniques and that are helpful for an understanding of the present terminologies and conventions. The reader interested in more details of the historic evolution of astronomical spectroscopy may find an extensive treatment of this topic in two excellent books by John Hearnshaw (1986, 2009). Additional information can be found in older standard works on astronomical spectroscopy, which were published by Hiltner (1964), Carleton (1976), and Meeks (1976). Apart from (still up-to-date) historical sections, these books provide extensive descriptions of methods that have been used in the past, before they were replaced by the more efficient contemporary techniques.

### 1.1 Early Pioneers

Astronomy is known for its long history. Accurate quantitative measurements of stellar positions and motions were already carried out millennia ago. On the other hand, spectroscopy is a relatively new scientific tool. It became important for astronomical research only during the past 200 years. The late discovery of spectroscopy may have been due to the scarcity of natural phenomena in which light is decomposed into its different colors. Moreover, for a long time the known natural spectral effects were not (or not correctly) understood. A prominent example is the rainbow. Reports of rainbows and thoughts about their origin are found in the oldest known written texts, and in most parts of the world almost everybody alive has seen this phenomenon. That rainbows are somehow caused by the reflection of sunlight in raindrops was suggested already by the ancient Greek and Arabian astronomers, and the basic geometry of the rainbow

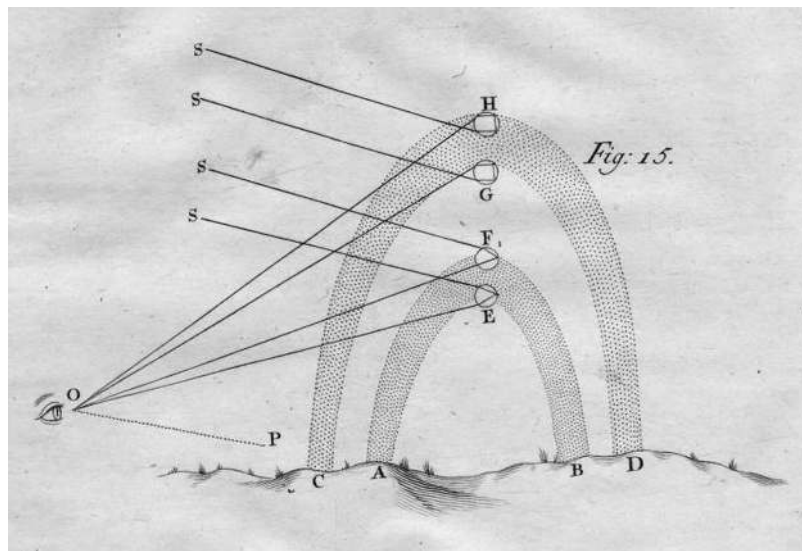


Figure 1.1. Newton's explanation of the colors of the primary and secondary rainbow as spectra of the sunlight produced by refraction and internal reflection in spherical raindrops. From Newton (1740).

(shown in Figure 1.1, taken from Newton's work) was described correctly already at the beginning of the fourteenth century by the Dominican friar Theodoric of Freiberg (about 1250–1310; see, e.g., Grant, 1974), who concluded that rainbows result from a combination of reflection and refraction of sunlight in small spheres of water. The correct explanation of the observed colors as a solar spectrum, however, was given only about three centuries ago by Isaac Newton (1642–1722).

Newton based his conclusions on extensive studies of the refraction of light in lenses and prisms. For most of his experiments, Newton used the light of the Sun. Hence, Newton not only started spectroscopy, but he also was the first one to study the spectrum of a celestial object.

Newton described his optical experiments and their results in the large three-volume work *Opticks*, which first appeared in 1704, followed by several improved and corrected editions. Later, *Opticks* was translated into Latin, which in Newton's time still was the *lingua franca* of science. The Latin version, titled *Optice*, became widely known outside England. Figures 1.1 and 1.2 have been taken from this Latin edition.

Figure 1.2 shows some of the early optical arrangements that Newton used to obtain solar spectra. In his first experiments, Newton produced a circular

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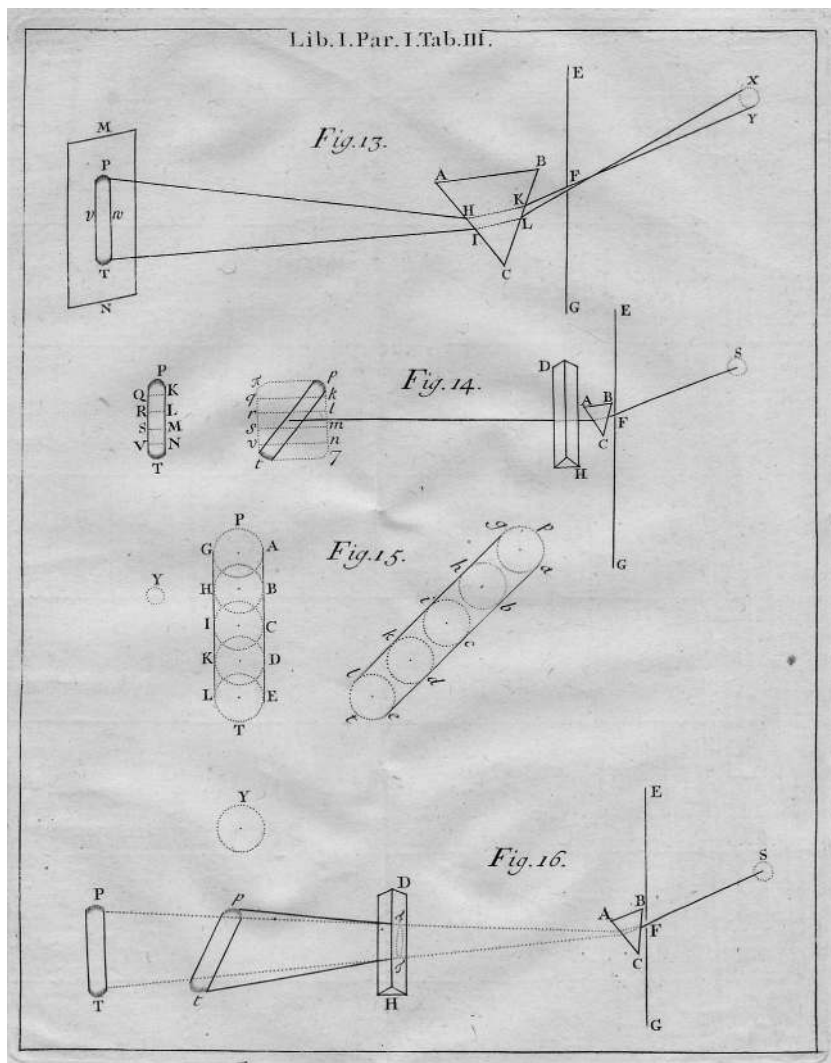


Figure 1.2. Optical arrangements used by Isaac Newton to produce spectra of the Sun, as published and described in *Optice* (Newton, 1740).

spot of sunlight on the wall of his experiment chamber by means of a hole in the sunlit shutter at the opposite side of the room. He then placed one or several prisms into this quasi-parallel light beam. As illustrated by his drawings (reproduced in Figure 1.2), the result was a solar spectrum. However, the size of the beam (with a diameter of approximately one inch) severely limited the

spectral resolution<sup>1</sup> of Newton's spectra. Therefore, although Newton could decompose the solar light into its different colors, he could not resolve spectral details, such as absorption lines or bands. Later, Newton used a lens followed by a prism to obtain solar spectra. This improved the efficiency of his simple spectrometer, but now the spectral resolution was limited by the size of the solar image, and the corresponding resolving power was still low.

Solar spectra of higher resolution were observed first by William Wollaston (1766–1828). As Newton did, Wollaston used sunlight entering a darkened chamber. However, Wollaston replaced Newton's circular entrance aperture by a narrow slit, and he observed the slit from some distance by eye through a prism. He saw the same color sequence as observed by Newton, but in addition, Wollaston noticed several dark lines in the spectrum. Obviously, he was the first one to observe an astronomical line spectrum. However, Wollaston did not realize that the dark lines were a property of the solar spectrum. Instead he assumed that light in general consisted of several distinct colors, separated by dark spectral regions.

The breakthrough came in 1814 when Joseph Fraunhofer (1787–1826) observed the solar spectrum with even higher resolution and better efficiency. As did Wollaston, Fraunhofer used sunlight and a narrow slit. However, instead of looking directly at the slit through a prism, Fraunhofer placed a small telescope behind the prism to observe the dispersed light. This arrangement made much more efficient use of the incident light and resulted in a better spectral resolution. Therefore, Fraunhofer saw many more spectral details and was able to identify more than 500 dark lines of the solar spectrum (Fraunhofer, 1817). Because he also observed the spectra of other light sources, he could unambiguously prove that the dark (absorption) lines (which today are called *Fraunhofer lines*) are an intrinsic property of the solar spectrum.

Perhaps even more important was that Fraunhofer obtained some of his observations of the solar spectrum using a diffraction grating instead of a prism. He made this grating himself by means of equally spaced thin wires. As explained in Section 3.3, for a diffraction grating with known grating period there exists a simple relation between the diffraction angle and the wavelength of the diffracted light. As a result, Fraunhofer could directly measure and list the wavelengths of the observed solar absorption lines.

By placing his prism in front of an astronomical telescope, Fraunhofer also succeeded in observing the spectra of several bright stars and of the planet Venus. He found that the spectrum of Venus was identical with the solar spectrum, but that the observed stars showed very different spectra.

<sup>1</sup> For an exact definition of this term, see Section 3.3.

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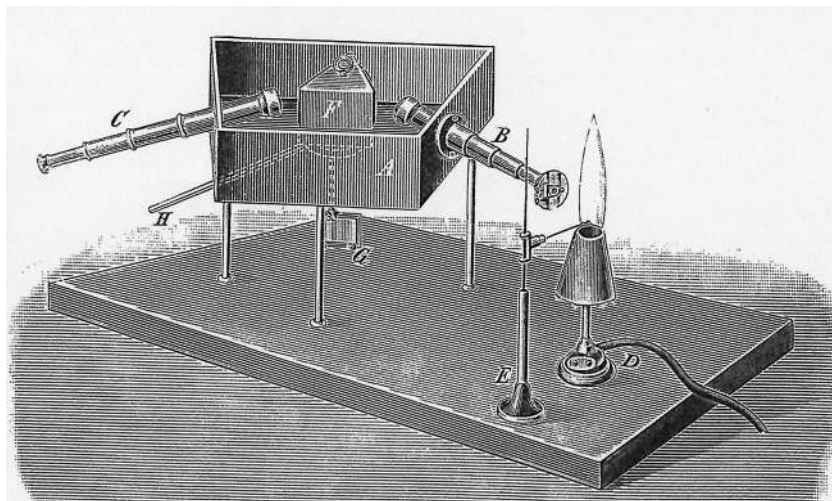


Figure 1.3. The prism spectrometer used in 1859 by G. R. Kirchhoff and R. W. Bunsen to develop spectrum analysis (according to Kayser, 1900). In this arrangement, spectra of various substances were produced by heating corresponding probes in the gas flame D. The light entering the spectrograph slit (at the front end of the tube B) was then collimated to a parallel beam by means of a biconvex lens. The collimated beam was dispersed into its colors by the prism F, and the resulting spectrum was observed visually by means of the small telescope C.

He noted, for instance, that the spectrum of Sirius contained very few lines, which were particularly broad and strong, however. Obviously, by observing Sirius Fraunhofer had, for the first time, seen the broad hydrogen absorption lines that are typical of A-type stellar spectra.

The next important milestone in the development of astronomical spectroscopy took place in 1859 in a chemical laboratory. In that year, the physicist Gustav Kirchhoff (1824–1887) and the chemist Robert Bunsen (1811–1899) invented the method of spectrum analysis. Using the spectrometer reproduced in Figure 1.3, they systematically investigated the line spectra of various chemical elements. Comparing their laboratory results with the solar spectrum, they found that many of the wavelengths and spectral patterns observed in the lab experiments were identical to those reported by Fraunhofer in the solar spectrum. They correctly concluded that the Fraunhofer lines were signatures of the chemical composition of the solar surface layers. Although the technique was initially developed for laboratory measurements, the great potential of spectrum analysis for astronomical research was recognized immediately, and many different astronomers now started observing stellar spectra. They used either Fraunhofer's arrangement (with a large prism in front of a telescope) or

the type of spectrometer used by Kirchhoff and Bunsen (Figure 1.3). In the latter case, the spectrograph slit was placed in the focal plane of a telescope at the position of the stellar image. A slit had the advantage of reaching a better spectral resolution and a lower sky background contribution. Therefore, visual slit spectroscopes soon became the standard spectral instruments in astronomy, until they were replaced by photographic spectrographs. To increase the spectral resolution, instead of a single prism often a train of several consecutive prisms was placed in the parallel beam behind the collimator. Among the many astronomers who (following the work of Fraunhofer, Kirchhoff, and Bunsen) used and improved the technique of visual astronomical spectroscopy were G. B. Donati and Angelo Secchi in Italy, Lewis M. Rutherfurd in the United States, George Airy and William Huggins in the United Kingdom, Jules Janssen in France, and Hermann Carl Vogel in Germany.

## 1.2 The Photographic Era

With the visual spectroscopes, many basic properties of stellar spectra were discovered, and the first spectral classification schemes were developed. However, because the spectra had to be recorded by making drawings and notes at the telescope and by measuring each individual spectral line, visual observations were cumbersome and time consuming. Moreover, only relatively bright stars could be observed by the eye. Therefore, as soon as the new technique of photography was invented in the middle of the nineteenth century, first attempts were made to use photography for recording spectra. Photographic spectra of the Sun were obtained in 1842 by Alexandre-Edmond Becquerel (1820–1898) in France and in 1843 by John W. Draper (1811–1882) in the United States. However, it took another thirty years before John W. Draper's son, Henry Draper (1837–1882), succeeded in obtaining the first usable photographic spectrum of a star in 1872. This success came so late because the early photographic techniques were much less sensitive than the human eye. Even the most sensitive photographic emulsions (developed during the twentieth century) converted only about 1 percent of the incident light into a usable signal. This is about the same fraction as the human eye can detect. However, although their light sensitivity is low, photographic emulsions have the immense advantage of being able to integrate the light over minutes or (depending on the plate properties) even hours. Moreover, in the last quarter of the nineteenth century new types of photographic plates became available, which finally were sufficiently sensitive for recording stellar spectra. As a result, by the end of the nineteenth century photographic plates had become the standard light detectors of astronomy and astronomical spectroscopy.



## 1.2 The Photographic Era

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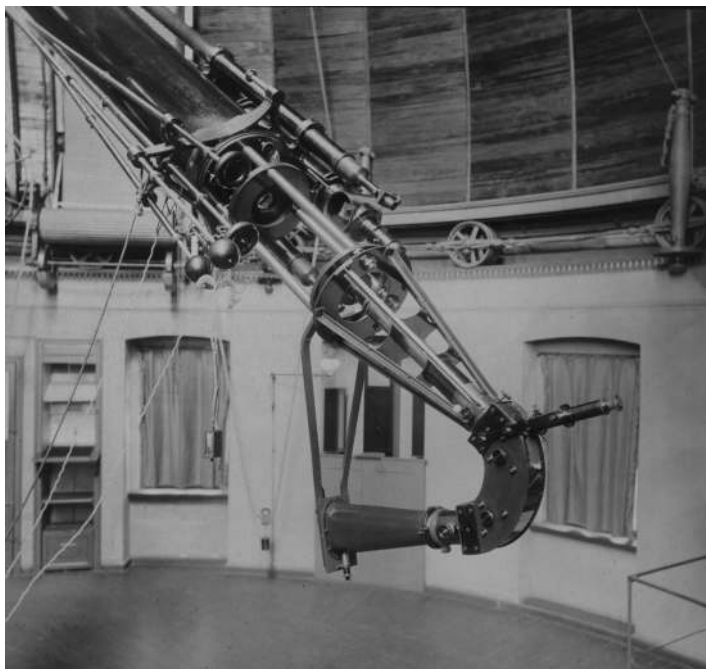


Figure 1.4. The photographic spectrograph that Hermann Carl Vogel installed in 1888 at the 30-cm refractor of the Astrophysical Observatory at Potsdam. The tube extending from the telescope contains the slit and the collimator optics. The curved box houses the prism train. At the lower left end of the prism box, the photographic camera is attached. The small telescope at right was used for adjustments and guiding. Image courtesy Leibniz Institute of Astrophysics, Potsdam.

After Henry Draper's pioneering work, photographic spectroscopy was developed further mainly by William and Margaret Huggins at their private observatory near London, and later by Hermann Carl Vogel (1841–1907) in Potsdam. In 1873, while working at a small private observatory in northern Germany, Vogel had started the first big (still visual) survey of the spectra of all bright stars. He continued this survey (in cooperation with others) when in 1874 he moved to the newly founded Astrophysical Observatory at Potsdam (AOP), where he became the director in 1882. Having learned of the work of Draper and Huggins, Vogel realized that his spectroscopic survey could be improved and accelerated using photographic spectra. His first photographic observations were made in 1887 with an experimental two-prism spectrograph. In 1888, this instrument was replaced by the spectrograph that is shown in Figure 1.4. This instrument, which was built by professional opticians according

to Vogel's design, became the model and prototype of many later photographic spectrometers.

Vogel's instrument (and later photographic spectrographs) still basically followed the optical arrangement of Kirchhoff and Bunsen. However, the small telescope used for observing the spectra visually (C in Figure 1.3) was now replaced by a photographic camera. Moreover, during the twentieth century, for most applications prisms were gradually substituted by diffraction gratings as light-dispersing optical elements.

Relative to prisms, gratings had several important advantages. As explained in Chapter 3, with gratings a much larger range of dispersions can be achieved. Moreover, the dispersion of a grating spectrograph is a linear function of the wavelength, whereas the dispersion of prisms decreases rapidly with increasing wavelength and, for most materials, becomes very small in the red spectral range. Finally, gratings can be used at any wavelength between X-rays and the far infrared (FIR), whereas prisms are restricted to the spectral ranges for which transparent prism materials exist.

As noted earlier, a diffraction grating had been used in 1821 by Joseph Fraunhofer to determine the wavelengths of the solar absorption lines. During the second half of the nineteenth century, grating spectroscopes became the standard tools for solar spectroscopy. Perhaps the best-known examples of the early solar grating spectrometers are the instruments of H. A. Rowland (1848–1901), who, as the (first) professor of physics at the Johns Hopkins University in Baltimore, produced the best diffraction gratings of his time and used them to compile an extensive catalog of the absorption lines of the solar spectrum.

Early attempts to use grating spectroscopes for stellar spectroscopy were much less successful. The reason for these failures was the low efficiency of the first gratings. All early gratings were transmission gratings, where most of the light ended up in the undispersed 0th order. Therefore, they were much less efficient than the prisms of this time. This changed dramatically when blazed reflection gratings (see Chapter 3) became available in 1912. During the following decades, prism and grating spectrographs were still used (and developed) in parallel. After 1935, though, almost all new instruments used diffraction gratings.

Another important new element of astronomical spectrographs were the wide-field Schmidt cameras, which became available after 1930. With their large field and their short focal length, Schmidt cameras were particularly useful in combination with photographic plates as detectors. They soon became the standard cameras for small, efficient low-resolution Cassegrain spectrographs, as well as for the huge stationary coudé-focus instruments that were built for the leading (2- to 5-m) telescopes during the first half of the twentieth century.



## 1.2 The Photographic Era

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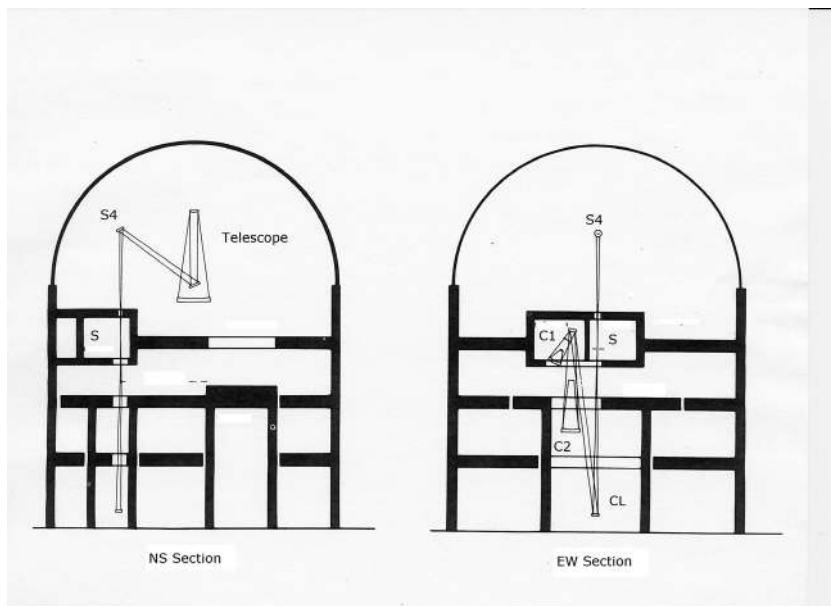


Figure 1.5. Example of a large photographic Coudé spectrograph. The figure shows two cross sections of the building of the 2.2-m telescope of the Calar Alto observatory in southern Spain. The light from the telescope is fed into the spectrograph by means of the stationary mirror S4 on the extension of the (fork-mounted) telescope's polar axis. After passing the spectrograph slit S, the light beam is collimated by the concave mirror CL at the ground floor level of the building, and spectra are recorded by means of a reflection grating (above C1) and one of the two large Schmidt cameras C1 or C2. Note the size of the spectrograph relative to the 2.2-m telescope. Adapted from Bahner and Solf (1972).

An example is the optical layout of the coudé spectrograph of the 2.2-m telescope at the Calar Alto Observatory in Spain, reproduced in Figure 1.5. At the time of its completion, this instrument was one of the most advanced astronomical high-resolution spectrometers. As shown in the figure, such spectrographs sometimes were significantly larger than the telescopes to which they were attached. The large, stationary coudé instruments reached resolving powers of up to 80,000, and the high-quality photographic spectra<sup>2</sup> obtained with these spectrographs formed the basis for the development of the theory of stellar atmospheres. On the other hand, because of light losses in the coudé mirror

<sup>2</sup> In the older astronomical literature, the term *spectrum* was used exclusively for the wavelength or frequency distribution of light, whereas the recording of a spectrum was called a *spectrogram*. Following the present usage in the astronomical literature, both items are called *spectrum* in this book.

trains, losses at the narrow slits used for high-resolution work, and the low sensitivity of the photographic plates, these impressive instruments were (compared with present-day spectrometers) inefficient and restricted to observations of relatively bright targets.

### 1.3 The Impact of Linear Detectors

Although the introduction of photography in the second half of the nineteenth century greatly improved the potential and the performance of spectroscopic instruments, it was obvious from the very beginning that photographic emulsions were not ideal light detectors for scientific applications. One of the drawbacks of photography is the small fraction of the incident light that is actually recorded. In the technical literature, this fraction (defined as the number of light quanta or photons that are detected, divided by the number of light quanta that reach the detector) is called the *quantum efficiency* (QE). As noted already, for photographic emulsions QE is normally below 1 percent. Even more problematic, however, is the highly nonlinear light response of photographic materials. Normal photographic emulsions are completely insensitive to light levels below a certain threshold, independent of the exposure time. At very high light levels, the opaqueness of the developed plate becomes independent of the illumination, or it even decreases again with increasing light intensity (“overexposure” and “solarization” effects). A monotonic relation between the incident light intensity and the opaqueness of the developed and fixed plate exists only in a relatively small intensity range. To make matters worse, this relation depends on the chemicals used, the development time, the age of the plate, the temperature, and various other environmental parameters. To understand these unwelcome properties of photographic plates and the progress that resulted from the new detectors, in the following paragraphs the basic mechanisms of photon detection are briefly summarized in terms of solid-state physics.

#### 1.3.1 Photon Detection

Photography is based on the internal photoeffect in small semiconductor crystals. Its properties can be understood from the energy states of electrons in a semiconductor, which are outlined schematically in Figure 1.6. At zero absolute temperature, all electrons of an ideal semiconductor have energies corresponding to the low valence energy band. At higher temperatures, most electron energies are still within the valence energy band, but some electrons are found