

Observational Astrophysics

10. Spectroscopy

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1 Introduction

Spectroscopy is a type of astronomical observation where one is interested in dispersing the light received from the source to obtain the flux as a function of wavelength. The instrument capable of doing that is the spectrograph or spectrometer. The dispersing element used in such instruments is either a prism or a diffraction grating. Diffraction grating is, most commonly, a plate ruled with very finely spaced, parallel, grooves. Gratings can be either of transmission or reflection types. A recent type of transmission grating is the volume-phase holographic (VPH) grating (Barden et al. 1998, 2000)¹. These gratings are made of some photosensitive material which is processed and imprinted with a periodic modulation of the refractive index. There is also something called “grism”², where a transmission grating is put on one of the sides of a prism.

One can still discuss and understand some of the prism properties using geometrical optics. However, one important effect to understand spectroscopy is the diffraction of light, and for that we need wave optics. I did not separate that topic into different notes, and add some introductory text as part of the recommended reading material below.

Spectrographs can be of many different types. There is the conventional single long-slit spectrograph, the echelle spectrograph, the multi-object types (fed by multi-slits or optical fibers), the ones of integral field, and even the slitless ones. There is also the Fabry-Perot type of instrument, which gives spectral information but one can actually think of it as a tunable narrow-band interferometric filter. With this, you can take a series of images in slightly different wavelengths, by adjusting the constructive and destructive interference.

Finally, we should mention the Fourier transform spectrographs, which make use of different principles. These instruments use interferometry to obtain the spectral information through Fourier transformation.

¹<https://ui.adsabs.harvard.edu/abs/1998SPIE.3355..866B/abstract> and <https://ui.adsabs.harvard.edu/abs/2000PASP..112..809B/abstract>

²The idea was first presented by Bowen & Vaughan (1973), see <https://ui.adsabs.harvard.edu/abs/1973PASP..85..174B/abstract>, and first used by Hoag (1976), see <https://ui.adsabs.harvard.edu/abs/1976PASP...88..860H/abstract>.

2 Read these texts

2.1 Introduction to waves and diffraction

I am providing to everybody the material in this subsection. However, I recommend the reading only if you would like to refresh some basic concepts. You might as well decide that you do not need to read these and jump to the texts in the next subsections.

If you would like to refresh the basic concepts about simple harmonic motion, vibrations, and waves, have a look at Chapter 11 of “Fundamentals of Optics” (Jenkins & White 1976)³.

If you think that you need to cover the basics of diffraction, then the following texts are recommended. The concept of diffraction by a single opening (slit, rectangular or a pinhole) illuminated by a collimated light beam is discussed in Chapter 15 of the same book (Jenkins & White 1976). The case for a double slit is discussed in Chapter 16 and the concepts are then extended to a diffraction grating in Chapter 17. A diffraction grating can be understood as the case of several narrow, parallel slits. Together, these three chapters of Jenkins & White (1976) **have 63 pages**.

2.2 Spectroscopy

If you do not want, or do not need, the introduction above, Chapter 2 of “Spectroscopic Instrumentation: Fundamentals and Guidelines for Astronomers” by Eversberg & Vollmann (2015)⁴, **which has 75 pages**, should give all the fundamentals needed to understand grating spectroscopy (actually, even more than just the fundamentals. It includes also an extensive discussion on prisms, in Sections 2.2 and 2.4, which is perhaps less relevant and could be skipped, but that I leave here for completeness. It also discusses sampling, pixel size, etc). This text also covers some of the same concepts discussed in the Chapters of Jenkins & White (1976), but the approach is different. For some, reading both approaches might be useful and will also help to clarify things.

2.3 Spectrographs

To read about different types of spectrographs (echelle, multi-object, integral field) have a look at Bernstein & Sackett (2013)⁵. This text (**another 32 pages**) will first repeat some of the same basic information on spectroscopy before showing examples of real instruments.

3 Spectroscopy: Summary of concepts

I need to first acknowledge that a lot of the content of these notes is based on the lecture notes of prof. Claudia Mendes de Oliveira, from the University of São Paulo, Brazil, from the course that I

³<https://archive.org/details/fundamentalsofop00jenk>

⁴<https://link.springer.com/book/10.1007/978-3-662-44535-8>

⁵https://link.springer.com/referenceworkentry/10.1007%2F978-94-007-5621-2_15

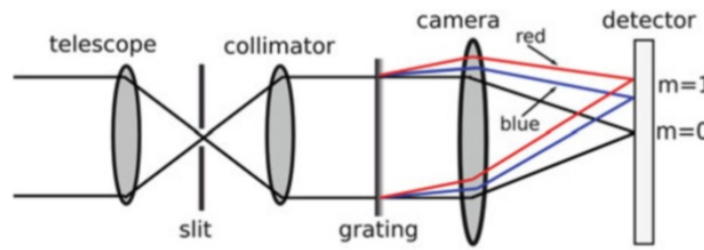


Fig. 5.5 Schematic layout of a typical spectrograph. This is drawn with a transmission grating, to aid clarity; in practice, reflection gratings are nearly always used

Figure 1: Typical scheme of a spectrograph using transmission elements. Credit: Fig 5.5 from Lawrence (2013), see <https://link.springer.com/book/10.1007/978-3-642-39835-3>.

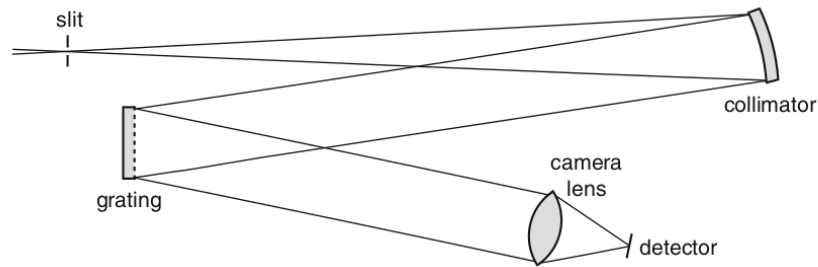


Fig. 2-1
The essential components of an astronomical spectrograph

Figure 2: Typical scheme of a spectrograph using (mostly) reflection elements. Credit: Fig 2.1 from Massey & Hanson (2013), see https://link.springer.com/referenceworkentry/10.1007/978-94-007-5618-2_2.

attended back in 2005 (or 2006).

- The basic design of a spectrograph is shown in Figures 1 and 2 using transmission or reflection elements, respectively. It includes the following components:
 1. (Entrance) Slit (or Fiber): restricts the solid angle of light entering the system to that of the source that you want to observe (plus some sky contamination). Located at the telescope focal plane.
 2. Collimator: collimates the light, so that parallel light is sent to the dispersing element.
 3. Grating: the element that disperses the light.
 4. Camera (is shown as a lens in both examples, but it could be a mirror): images the spectrum onto the detector.
 5. Detector: which will record the spectrum but also needs to be chosen to ensure the correct sampling of the spectra.
- A diffraction grating is the most used “dispersion element” in modern spectrographs. They can rely on transmissive or reflective optics.

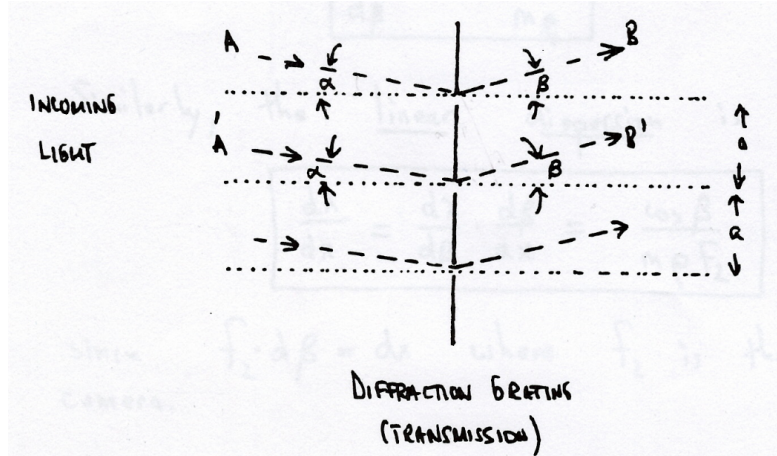


Figure 3: Geometry of a (transmission) grating. Credit: Mendes de Oliveira, C. (IAG/USP).

- Slitless spectroscopy can be achieved by placing a dispersing element directly in front of the telescope (where the beam is still collimated) or at the converging beam, just before the focal plane. The first case is called “objective mode” while the second is called “nonobjective mode”⁶.
- Let’s consider the geometry of a transmission grating as shown in Fig. 3. The path difference between rays AB and A'B' is given by: $a(\sin \alpha + \sin \beta)$; where a is the distance between consecutive slits or grooves in the grating, α is the angle of incidence and β is the angle of refraction (or reflection, for reflective grating), both measured with respect to the normal of the grating surface. Constructive interference will only take place if this path difference is a multiple “ m ” of the wavelength “ λ ” of the incoming light. This condition is written as:

$$m \lambda = a(\sin \alpha + \sin \beta), \quad (1)$$

which is the so-called grating equation.

- From the grating equation, $1/a$ (or ρ) is the ruling density of the grating (usually given in lines per mm).
- In the grating equation, m is called the spectral order.
- Now, let’s consider two monochromatic sources of light with wavelengths λ_1 and λ_2 , where $\lambda_2 > \lambda_1$, going through the system. For a given order m , and the same incidence angle α , the constructive interference for λ_2 will take place only for a larger angle β . This means that the same order for the two wavelengths will be slightly shifted from each other. That’s how you get the spectrum, the interference peaks corresponding to the same order for each wavelength are separated from each other.
- If instead of only two wavelengths there is a continuum, then each wavelength will end up slightly separated from the others (when the same order is considered).

⁶The name first introduced by Hoag & Schroeder (1970), see <https://ui.adsabs.harvard.edu/abs/1970PASP...82.1141H/abstract> but the idea seems to have been first implemented by James Edward Keeler (https://link.springer.com/referenceworkentry/10.1007/978-1-4419-9917-7_746), director of the Lick Observatory in 1900, see Palmer (1903) in <https://ui.adsabs.harvard.edu/abs/1903LicOB...2...46P/abstract>.

- The exception is order $m = 0$. Order 0 for all wavelengths will fall on the same place, so in order 0 there is no spectral dispersion.
- Now consider the following, let's call the spacing between consecutive orders for λ_1 as Δ_1 while for λ_2 it is Δ_2 . For λ_1 , order 0 is at the origin, order 1 at Δ_1 , order 2 at $2\Delta_1$, and so on. The same for λ_2 , i.e. order 0 is at the same origin, order 1 at Δ_2 , order 2 at $2\Delta_2$, and so on. The difference in position between orders 1 of the two wavelengths is $d_1 = \Delta_2 - \Delta_1$. The difference in position between orders 2 of the two wavelengths is $d_2 = 2\Delta_2 - 2\Delta_1 = 2(\Delta_2 - \Delta_1) = 2d_1$. The difference in position between orders 3 will be $3d_1$, and so on. In other words, the higher the order we are looking at, the more separated are the two wavelengths.
- Eventually, however, different orders for different wavelengths might start to overlap. For example, let's think that we are shining visible light onto the grating, with wavelength range between 4000 and 7000 Å. If we take order 3 for 7000 Å, the grating equation would be written as: $3 \times 7000 = a(\sin\alpha + \sin\beta)$. With a and α the same for all wavelengths. The same combination, or the same β , will happen for order 4 of light with 5250 Å (i.e., $4 \times 5250 = 3 \times 7000$).
- The angular dispersion can be obtained by differentiating the grating equation with respect to the wavelength:

$$\frac{d\beta}{d\lambda} = \frac{m\rho}{\cos\beta}, \quad (2)$$

or

$$\frac{d\beta}{d\lambda} = \frac{(\sin\alpha + \sin\beta)}{\lambda \cos\beta}, \quad (3)$$

if we exchange $m\rho$ using the grating equation.

- Equation 2 shows that for a given $d\lambda$, the angular separation $d\beta$ increases with increasing order. In addition, increasing the ruling density (ρ) also results in increasing the angular separation $d\beta$, for a given $d\lambda$ and order.
 - Now, let's recall about the plate scale or image scale of a lens. A small shift in angle, $d\beta$, results in a linear shift, dx , in the focal plane where $d\beta/dx = 1/f$ and f is focal length of the lens. So to get the linear dispersion of the grating, we just need to introduce the focal length of the camera:
- $$\frac{d\beta}{d\lambda} \frac{dx}{d\beta} = \frac{dx}{d\lambda} = \frac{m\rho f}{\cos\beta}. \quad (4)$$
- In the case where the dispersing element is placed in the converging beam (and there is no camera), the linear dispersion will be given by the angular dispersion times the distance “ s ” between the dispersing element and the focal plane.
 - The “plate factor” is the reciprocal of the linear dispersion defined above, and is usually given as Å/mm or Å/pixel.
 - The “intensity distribution” of the light that has been diffracted by a grating is given by:

$$I = A_0^2 \frac{\sin^2 \theta}{\theta^2} \frac{\sin^2 N\gamma}{\sin^2 \gamma}, \quad (5)$$

where

$$\gamma = \frac{\pi a (\sin \alpha + \sin \beta)}{\lambda},$$

$$\theta = \frac{\pi b (\sin \alpha + \sin \beta)}{\lambda},$$

N is the number of grooves or slits in the grating, a = distance between grooves, b = width of a single slit or groove, α is the angle of incidence, β the angle of refraction/reflection (both defined in Fig. 3), and A_0^2 is the maximum intensity at the center of the diffraction pattern (and A_0 itself is the amplitude). You will mostly find the definitions of γ and θ above without the incidence angle α . This just means one is assuming from the onset that $\alpha = 0$, i.e. light is shining on the grating vertically.

- 2γ gives the phase difference between the center of two adjacent slits.
- θ above is the phase difference between the edge and the center of one slit.
- The factor $\frac{\sin^2 N\gamma}{\sin^2 \gamma}$ is said to represent the interference term of a grating with N slits or grooves. An example of the pattern created by this factor is shown in Fig. 5.
- The factor $\frac{\sin^2 \theta}{\theta^2}$ comes from the diffraction pattern created by a single slit of width b and is called the “blaze function”. It modulates the interference pattern of each single wavelength. An example of the modulation by this factor is shown in Fig. 6.
- The intensity maximum happens when θ approaches zero (and $\sin \theta \sim \theta$ so that $\sin^2 \theta / \theta^2$ approaches one). The case where θ approaches zero is the case where there is no phase difference in the light passing through the different regions of a slit. For simplicity, let's consider the case where $\alpha = 0$. In this case, the condition happens when $\beta = 0$. And using the grating equation this will correspond to order 0. So the blaze function, i.e. the modulating pattern created by a single slit, peaks at the position of order 0. This position will coincide with order 0 for the interference term of N slits (as in Figure 6). All this means that most of the light is lost in order 0 where there is no spectral dispersion.
- Fortunately, there is a way around this, which is better illustrated using a reflection grating, see Figure 2.24 from Eversberg & Vollmann (2015). By introducing an angle on the grooves of the grating, one can shift the peak of the blaze function to coincide with another order of the interference term of N slits. This angle is called the “blaze angle” of the grating and the grating is said to be blazed. (Note here that the angles α and β , important for the interference pattern and measured with respect to the normal to the grating surface, are not affected by the blazing of the grating. However, now the surface that is reflecting the light inside each groove is tilted. The angles needed to compute the blaze function are no longer the same α and β and need to be adjusted.)
- However, if you will remember the case of two wavelengths λ_1 and λ_2 above, their first orders are slightly shifted from each other. So when the blaze angle of the grating is decided, one is also deciding which wavelength will benefit the most from the shift in the maximum of the intensity pattern. This wavelength of maximum efficiency is called the “blaze wavelength” of the grating.
- There is a specific way to setup the spectrograph by choosing the blaze angle of the grating in a way that the diffraction and incidence angle are nearly the same. This is called the

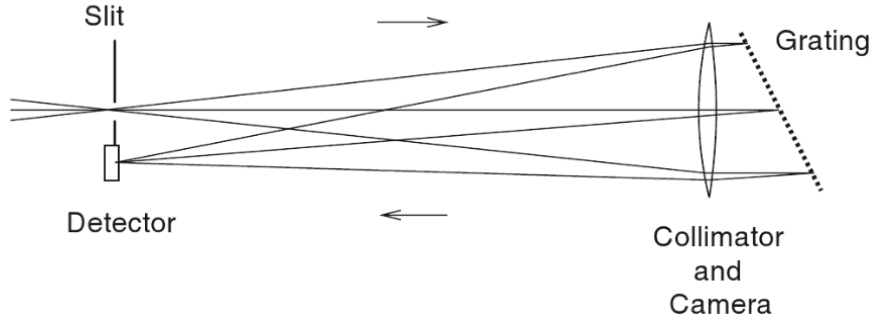


Figure 4.12. Schematic light path in a Littrow spectrometer.

Figure 4: Littrow configuration. Credit: Figure 14.2 of Appenzeller (2012), see a preview of the book [here](#).

“Littrow⁷ configuration”, see Fig. 4. In this configuration, the same optical element works as collimator and camera. The dispersed beam thus returns almost in the same direction of the input beam. Any optical aberration introduced by the collimator is compensated when the beam returns. Blazed reflection gratings are most efficient when used at their blaze angle, so the Littrow configuration also gives the best possible efficiency from the use of the specific grating.

- The (chromatic) resolving power (R) is the ability of a spectrograph to discriminate wavelengths. This is expressed as the ration $\lambda/\Delta\lambda$. Following Rayleigh’s criterion, we can consider that wavelengths λ and $\lambda + \Delta\lambda$ are resolved when the maximum of interference pattern of order m of one wavelength is located at the same place as the minimum of the pattern of the other wavelength for the same order. Doing that, we can find that

$$R = mN = m\rho W, \quad (6)$$

where m is the order, N is the number of grooves of the grating (which can also be expressed as the groove density ρ times the size W of the grating). In practice, Equation 6 gives only the theoretical maximum resolution of the grating. The actual resolution will be limited by the size of the image on the detector (either the image of the entrance slit, or the diffraction limit of the telescope, whichever is bigger).

- We can also substitute m using the grating equation and obtain:

$$R = \frac{Na(\sin \alpha + \sin \beta)}{\lambda} = \frac{W(\sin \alpha + \sin \beta)}{\lambda}, \quad (7)$$

where looking at Fig. 7, we can see that the numerator of Eq. 7 is the total path difference between the marginal rays spanning the grating width.

⁷Named after the Austrian astronomer Otto von Littrow, see Kerschbaum & Müller (2009) in <https://ui.adsabs.harvard.edu/abs/2009AN...330..574K/abstract> for some biographical information. His design was first presented in Littrow (1863), see <https://play.google.com/books/reader?id=0445AAAAcAAJ&pg=GBS.PP2&hl=en> for the original in German.

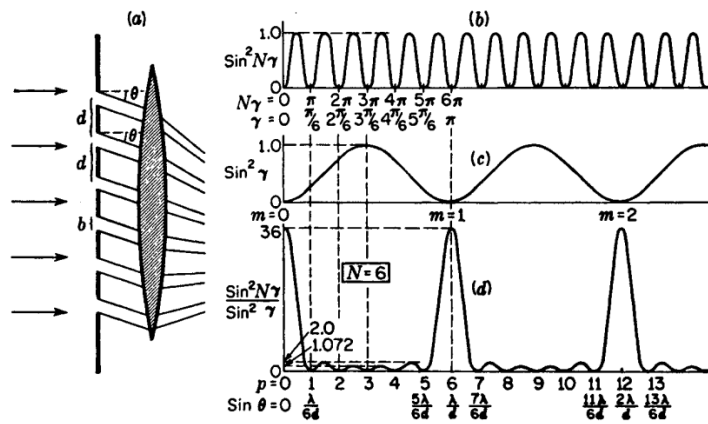


Figure 5: Intensity pattern by a grating with 6 narrow slits. Credit: Figure 17C of Jenkins & White (1976).

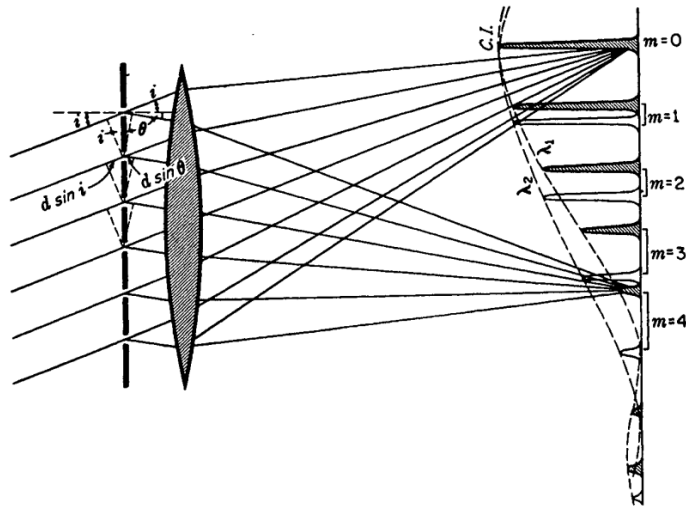


Figure 6: Intensity pattern produced by a grating with several slits, for two wavelengths where each is modulated by its own blaze function. Credit: Figure 17E of Jenkins & White (1976).

- Figure 7 is also useful to see the beam magnification caused by the grating, $M = d_1/d_2 = \cos\alpha/\cos\beta$.
- Another way to think about the resolution is to consider the size of the images at wavelengths λ and $\Delta\lambda$ on the detector. The wavelengths can only be distinguished (resolved) if the sizes are separated by Rayleigh's criterion. What we are imaging at the detector is either the seeing disk or the entrance slit (the smaller of the two). So our limit of resolution $\Delta\lambda$ can be written as $\Delta\lambda = w' \frac{d\lambda}{dx}$, where w' the width of the slit image and $\frac{d\lambda}{dx}$ is the plate factor (the reciprocal of the linear dispersion).
- Let's consider the entrance slit with width w and image with width w' . The sizes are related by $w' = Mw f_{\text{cam}}/f_{\text{col}}$, where M is the magnification, f_{cam} is the focal length of the camera, and f_{col} is the focal length of the collimator.
- Combining the above we can write:

$$\Delta\lambda = w' \frac{d\lambda}{dx} = w' \frac{\cos\beta}{m\rho f_{\text{cam}}} = w \frac{d_1}{d_2} \frac{f_{\text{cam}}}{f_{\text{col}}} \frac{\cos\beta}{m\rho f_{\text{cam}}} = w \frac{d_1 \cos\beta}{d_2 f_{\text{col}} m\rho}, \quad (8)$$

where we can still see from Fig. 7 that $d_2 = W \cos\beta$ (where W is the grating size), so that

$$\Delta\lambda = \frac{wd_1}{m\rho f_{\text{col}}W} = \frac{w}{m\rho F_{\text{col}}W}, \quad (9)$$

where we introduce that the focal ratio of the collimator is $F_{\text{col}} = f_{\text{col}}/d_1$.

- So that finally the resolving power R can be written as:

$$R = \frac{\lambda}{\Delta\lambda} = \frac{\lambda m\rho F_{\text{col}}W}{w}, \quad (10)$$

where we see that the physical parameters of the setup are important to determine the resolution of the spectrograph (to recall, F_{col} is the focal ratio of the collimator, ρ is the line density of the grating, W is the length size of the grating, m is the order, and w is the physical width of the entrance slit).

- Usually, the width of the entrance slit is not expressed in physical units (e.g., mm) but in angular units (e.g., arcsec). One is related to the other by the focal length of the telescope, $w = s f_{\text{tel}}$. The focal ratio of the collimator is the same focal ratio of the telescope, $f_{\text{tel}}/d_{\text{tel}} = f_{\text{col}}/d_{\text{col}}$, so that we can write $w/F_{\text{col}} = s d_{\text{tel}}$. And using this in Eq. 10 we have:

$$R = \frac{\lambda m\rho W}{s d_{\text{tel}}} \quad (11)$$

- We can see something interesting from Eq. 11. If you take one spectrograph and put it in a larger telescope, keeping the same projected slit width on the sky, you will get smaller resolving power for the same order and same wavelength. To get the same resolving power in a larger telescope, we need a larger spectrograph (i.e., larger illuminated size of the grating W , with a larger collimator to have a larger beam).
- So let's compare the resolving power that we get from Equations 6 (the maximum possible with a grating) and 11 (limited by the entrance slit size). Let's work in order $m = 1$, at wavelength $\lambda = 5000 \text{ \AA}$, with a grating that has $\rho = 1200 \text{ lines/mm}$ used with an angle of α

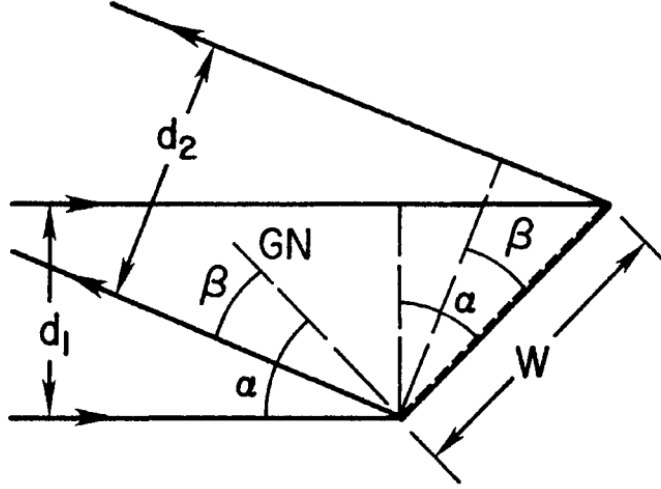


Figure 7: Geometry for the magnification of the beam that illuminates the grating. Credit: Figure 13.3 of Schroeder (2000), see <https://www.sciencedirect.com/book/9780126298109/astronomical-optics>.

= 20° , a collimator of 100mm, a telescope of $d_{\text{tel}} = 8$ m, and a slit with angular size $s = 0.5$ arcsec. For the maximum resolving power we get:

$$R_{\text{max}} = m\rho W = 1 * 1200 * 103.5 \sim 124\,200, \quad (12)$$

where $W = d_{\text{col}}/\cos\beta$ (see Fig. 7) and we obtain β using the grating equation. While from the slit width we would get:

$$R = \frac{\lambda m \rho W}{s d_{\text{tel}}} = \frac{5000\text{e-}7 * 1 * 1200 * 103.5}{((0.5/(3600)) * (\pi/180)) * 8\text{e}3} \sim 3200, \quad (13)$$

where we converted the slit width given in arcsec to radians.

- To approach the theoretical maximum resolution, the factor λ/sd_{del} has to approach unit. This will naturally happen when $\lambda \sim 19\mu\text{m}$, in the infrared, where we are operating at the diffraction limit of the system.

4 Spectrographs: Summary of concepts

- The so-called high-resolution spectrographs usually obtain large resolving power using echelle⁸ gratings, which are blazed to large angles ($\sim 60\text{-}75^\circ$). With this, the maximum of the blaze function is transferred to high orders (50-100). In such configuration, the echelle gratings actually only need to have modest groove density (30-300 lines/mm).
- It will happen, however, that the orders will physically overlap; there is essentially no shift in their central position, even though they cover somewhat different wavelength ranges (there

⁸From the French word *échelle*, meaning ladder.

is also some overlap in the wavelength coverage). To separate the orders, one uses a second dispersing element (a prism or another grating) to separate the light in the direction perpendicular to the orders (the so-called “cross disperser”). Such an arrangement will actually makes optimal use of the whole area of a rectangular detector. One will then get high-resolution together with large wavelength coverage. An example of echelle spectrum is given in Fig. 9.

- If we look back to Fig. 5, we see that the blaze function maximum was at order 0, and the intensity strongly decreased for the higher orders. In the echelle case, as all orders are at the same geometrical center, they will all be imaged with the highest possible efficiency.
- Several of such echelle spectrographs also incorporate a dichroic or beam splitter. This is an optical device that can split the beam, sending different wavelength ranges to different directions (for example, reflecting a certain wavelength while allowing the rest to cross it). This is useful to create separated “arms or channels” in the instrument. Each arm can then be optimized for the different wavelength ranges (e.g., with a grating that has high efficiency in the blue and another that has high efficiency in the red).
- There are a few interesting properties of echelle spectrographs to remember:
 1. The product of central wavelength and order number is a constant (see Section 5.5 of Eversberg & Vollmann 2015). In higher orders we observe shorter wavelengths.
 2. The “free spectral range” (FSR) is the wavelength range of a given order which does not overlap with the wavelength range of an adjacent order. It is given by $FSR = \lambda/m$ (see Section 5.6 of Eversberg & Vollmann 2015). The free spectral range decreases at higher orders.
 3. The blaze function curvature in the echelle case is much steeper than that of gratings working in lower orders, see Section 5.14 of Eversberg & Vollmann (2015) and their Figure 5.14 (reproduced here as Fig. 10).
 4. The spectral lines end up slightly tilted with respect to the normal direction of the order (see Section 5.7 of Eversberg & Vollmann 2015).
- You might come across the term “echellete” grating. They have smaller blaze angles than echelle gratings and are used in lower orders ($m = 5-20$).
- Another way to increase resolution is using image slicers⁹. We saw that we would like to make the slit as thin as possible to obtain higher resolving power. But if the slit is much thinner than the seeing disk, then a lot of light from the object is being lost (what is called “slit losses”). The image slicer is an arrangement of mirrors, in the focal plane, that breaks the seeing disk into slices and rearranges them along the slit (see one example in Fig. 8). You will then get a separated spectrum for each slice.
- In many cases, the astronomer will be interested in taking spectra of several objects that are actually located in the same field of view (e.g., several galaxies in a galaxy cluster; globular clusters in a galaxy; individual stars in a nearby galaxy; individual stars in a stellar cluster; a survey of stars in a given field). It would be a big waste of time and resources to take

⁹First described by Bowen (1938), see <https://ui.adsabs.harvard.edu/abs/1938ApJ...88..113B/abstract>.

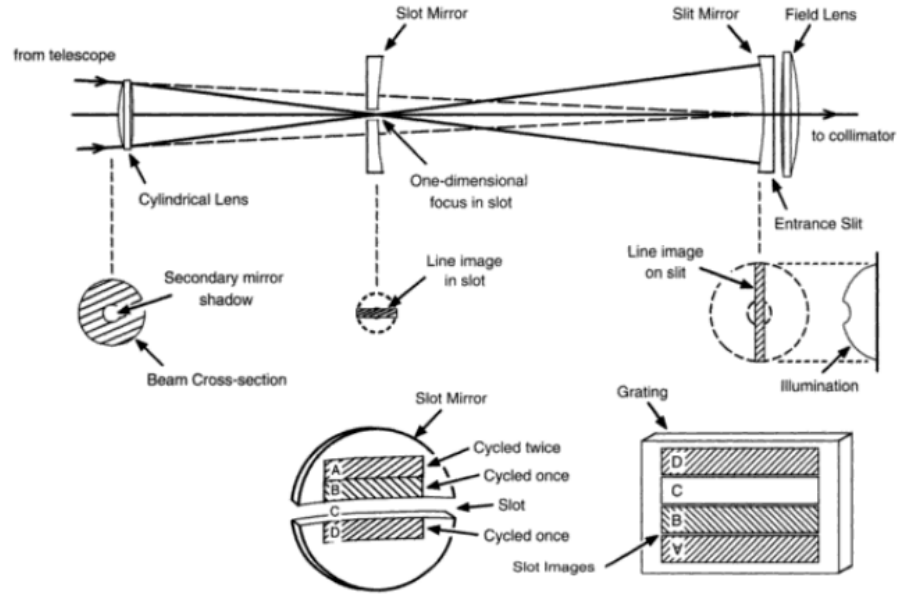


Fig. 12.4. The optical layout of the Richardson slicer has a slot mirror and the slit mirror separated by their (same) radius of curvature, i.e., two focal lengths. Each mirror has an aperture through the center, the slot in the slot mirror, and the slit in the slit mirror (in the plane of the figure). The cylindrical lens collapses the incoming beam to a line image in the slot. A second line image is formed on the slit. Images (A, B, D) of the slot (C) are shown on the

Figure 8: The Richardson image slicer. Credit: Fig. 12.4 from Gray (2005), see a preview of the book [here](#).



Figure 9: Spectrum of QSO HE2217-2818 (U -magnitude = 16.5), on the CCD, obtained with the UVES spectrograph at the VLT. It covers the wavelength interval between 330 - 450 nm (from the bottom to the top). Credit: ESO (see <https://www.eso.org/public/images/eso9944d/>).

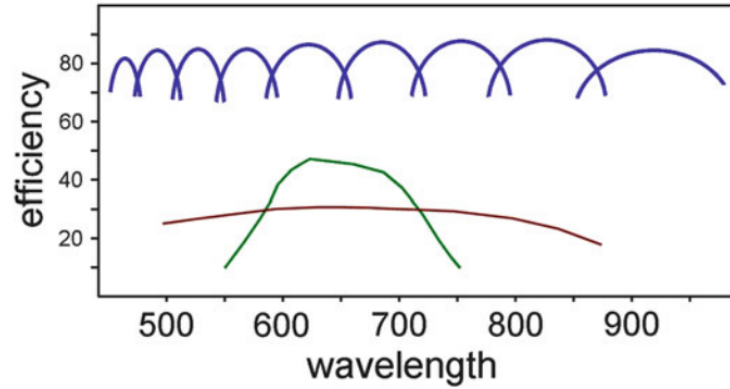


Fig. 5.14 Basic efficiency comparison between a holographic grating (*red*), a blazed grating (*green*) and an echelle grating (*blue*) over the entire visible spectrum. The echelle grating works close to the Blaze angle at all wavelengths and has a superior efficiency compared to the other two grating types. The green curve may well show a different form with respect to the efficiency. The width of all single echelle order efficiencies reflects the corresponding order length

Figure 10: Blaze function comparison. Credit: Fig. 5.14 of Eversberg & Vollmann (2015).

one individual long slit spectrum at a time (using only part of your detector). The solution for this are the multi-object spectrographs (MOS) which are essentially of two types, the multi-slit and the multi-fiber spectrographs.

- For the multi-slit case, instead of having a single slit in the focal plane, one introduces a custom-made multi-slit mask. You will need to know the position of each object to high precision. A machine will then be used to cut “slitlets” (small slits) in a plate (or mask).
- Note that the slitlets on the mask should not be too close in the “dispersion direction”, or you will end up with overlapping spectra. In the production of the mask, you need to consider the size that each spectrum will have on the detector (see Fig. 11).
- In addition, the slit size has to be long enough to include some sky region, for the sky subtraction during data reduction.
- Note also that if the slitlet is not centered in the field of view, then the corresponding spectrum will not be centered in the detector. The edges of the spectrum might end up falling outside of the detector area.
- Custom-made slit masks are however not reusable for another observing field. Also, how would you introduce a custom-made mask for a MOS in a space telescope? A recently developed alternative is the “microshutter array technology” (Li et al. 2017)¹⁰. The array functions as a programmable slit mask. It has several shutters and the user can decide to open only those that coincide with objects of interest in the field. This technology has been implemented for NIRSpec¹¹, the Near-Infrared Spectrograph on the JWST, which will allow obtaining spectra for up to 200 objects at the same time.

¹⁰<https://ui.adsabs.harvard.edu/abs/2017JMM%26M...16b5501L/abstract>

¹¹<https://sci.esa.int/web/jwst/-/45694-nirspec-the-near-infrared-spectrograph>

- In the case of a multi-fiber spectrograph there are no slits, the light of each object is collected by an optical fiber positioned in the field. One will then need a complex machine to position the fibers with high precision over the field. There are different options on how to do that (see Smith et al. 2004, for a discussion)¹²:
 1. Plug plates: the concept is similar to slit masks, in the sense that holes need to be drilled on a plate. The difference is that a fiber is then (manually) inserted in each hole, to collect the light and send it to the spectrograph. As with the slit mask, each new observing field will require the production of a new plate. This was the system used in the Sloan Digital Sky Survey (Owen et al. 1994)¹³.
 2. Robotic buttons positioner: in this case, individual fibers, parked outside the field plate, are grabbed by a robotic arm and positioned inside the field. They can be held in place magnetically onto the field plate. Some care is needed during positioning to avoid collisions and of course there is a limit of how close fibers can be positioned. This is the system used by the OzPoz multi-fiber positioner (Gillingham et al. 2000)¹⁴ of the FLAMES facility at the VLT. With Ozpoz, it can take up to 15 minutes to configure all the fibers over the field.
 3. Densely populated field: several fiber positioning units are pre-distributed to cover the entire plate field. Each unit can position the fiber within a limited patrol field and the positioning can mostly be done in parallel (although there is overlap among individual patrol fields and the possibility of collision needs to be monitored). This is the solution adopted for the upcoming MOONS instrument for the VLT (Montgomery et al. 2016)¹⁵.
- For input to the spectrograph, the fibers can be arranged in line so that on the detector the same wavelength range will be obtained for each object.
- On the down side, the aperture of the fiber is fixed and it might not match the seeing disk, causing variable sky contamination. For sky background correction, a few fibers have to be allocated to sky positions. But this means the sky correction will not be local, like it is possible with slits.
- The fibers will also introduce some light attenuation, as they do not transmit 100% of the light entering them. The transmission is wavelength dependent, and light loss is particularly strong in blue wavelengths.
- Integral field spectrographs are another way to obtain several spectra in the same observing field. In this case however, you do not have the freedom of positioning individual fibers, but they are densely packed in a bundle. This is an optimal arrangement to obtain spectra of different regions of extended objects, maintaining the spatial information. The resulting data is often thought as a 3D data cube (wavelength and two spatial positions).
- Alternatively to a fiber bundle, the integral field unit can be made of an array of lenslets creating separated images that are then fed to the spectrograph. Image slicers can also be used to slice the field.

¹²<https://ui.adsabs.harvard.edu/abs/2004SPIE.5495..348S/abstract>

¹³<https://ui.adsabs.harvard.edu/abs/1994SPIE.2198..1100/abstract>

¹⁴<https://ui.adsabs.harvard.edu/abs/2000SPIE.4008..914G/abstract>

¹⁵<https://ui.adsabs.harvard.edu/abs/2016SPIE.9908E..95M/abstract>

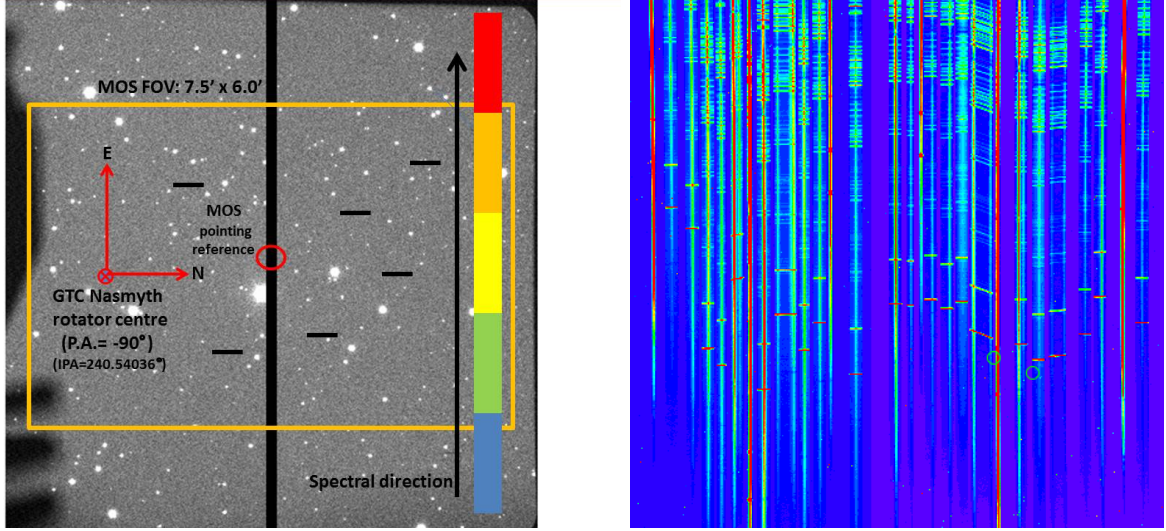


Figure 11: Example of slits positioned over an observing field and of spectra (not of the same field though) obtained with the OSIRIS instrument at the GTC. Each slit will produce one spectrum in the indicated spectral direction (left panel). Two slits that share the same x-axis position would produce overlapping spectra in the image of the right panel. Credit: Gran Telescopio Canarias, see <http://www.gtc.iac.es/instruments/osiris/osirisMOS.php>.

5 Additional reading

If you are interested in more information about echelle spectroscopy, have a look at Chapter 5 of Eversberg & Vollmann (2015). For those interested in image slicers, Chapter 9 of Eversberg & Vollmann (2015) is dedicated to this topic and gives several examples used in real instruments.

We did not cover Fabry-Perot and Fourier transform spectrographs. A first reading of these types of spectroscopy could be Section 8.3.4 and 8.3.5 of Léna et al. (2012)¹⁶.

The article by Moiseev (2021)¹⁷ discusses a Fabry-Perot instrument at the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences instrument at the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences. It could be useful for those interested, also for finding further relevant references.

The book “Fourier Transform Spectrometry” by Davis et al. (2001)¹⁸ could be useful, although it is general and not focused on astronomical use.

References

Appenzeller, I. 2012, Introduction to astronomical spectroscopy, Vol. 9 (Cambridge University Press)

¹⁶<https://link.springer.com/book/10.1007%2F978-3-642-21815-6>

¹⁷<https://ui.adsabs.harvard.edu/abs/2021AstBu..76..316M/abstract>

¹⁸<https://www.sciencedirect.com/book/9780120425105/fourier-transform-spectrometry>

- Barden, S. C., Arns, J. A., & Colburn, W. S. 1998, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 3355, Optical Astronomical Instrumentation, ed. S. D’Odorico, 866–876
- Barden, S. C., Arns, J. A., Colburn, W. S., & Williams, J. B. 2000, *PASP*, 112, 809
- Bernstein, R. A. & Shectman, S. A. 2013, *Astronomical Spectrographs*, ed. T. D. Oswalt & I. S. McLean, 587
- Bowen, I. S. 1938, *ApJ*, 88, 113
- Bowen, I. S. & Vaughan, A. H., J. 1973, *PASP*, 85, 174
- Davis, S. P., Abrams, M. C., & Brault, J. W. 2001, *Fourier transform spectrometry* (Elsevier)
- Eversberg, T. & Vollmann, K. 2015, *Spectroscopic Instrumentation: Fundamentals and Guidelines for Astronomers*
- Gillingham, P. R., Miziarski, S., & Klauser, U. 2000, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4008, Optical and IR Telescope Instrumentation and Detectors, ed. M. Iye & A. F. Moorwood, 914–921
- Gray, D. F. 2005, *The observation and analysis of stellar photospheres* (Cambridge University Press)
- Hoag, A. A. 1976, *PASP*, 88, 860
- Hoag, A. A. & Schroeder, D. J. 1970, *PASP*, 82, 1141
- Jenkins, F. A. & White, H. E. 1976, *Fundamentals of Optics* 4th edition
- Kerschbaum, F. & Müller, I. 2009, *Astronomische Nachrichten*, 330, 574
- Lawrence, A. 2013, *Astronomical Measurement: A Concise Guide* (Springer Science & Business Media)
- Léna, P., Rouan, D., Lebrun, F., Mignard, F., & Pelat, D. 2012, *Observational astrophysics* (Springer Science & Business Media)
- Li, M. J., Brown, A.-D., Burns, D. E., et al. 2017, *Journal of Micro/Nanolithography, MEMS, and MOEMS*, 16, 025501
- Littrow, O. v. 1863, *Sitzungsberichte der Kaizerlichen Akademie der Wissenschaften mathem.-naturwiss. Klasse XLVII. Band*, 26
- Massey, P. & Hanson, M. M. 2013, *Astronomical Spectroscopy*, ed. T. D. Oswalt & H. E. Bond, 35
- Moiseev, A. V. 2021, *Astrophysical Bulletin*, 76, 316
- Montgomery, D., Atkinson, D., Beard, S., et al. 2016, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9908, Ground-based and Airborne Instrumentation for Astronomy VI, ed. C. J. Evans, L. Simard, & H. Takami, 990895
- Owen, R. E., Siegmund, W. A., Limmongkol, S., & Hull, C. L. 1994, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 2198, Instrumentation in Astronomy VIII, ed. D. L. Crawford & E. R. Craine, 110–114

Palmer, H. K. 1903, Lick Observatory Bulletin, 2, 46

Schroeder, D. J. 2000, Astronomical optics, 2nd edition (Elsevier)

Smith, G., Brzeski, J., Miziarski, S., et al. 2004, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 5495, Astronomical Structures and Mechanisms Technology, ed. J. Antebi & D. Lemke, 348–359