



OBSERVATIONAL ASTRONOMY

FALL 2026

Lecture 13

Vitaly Neustroev

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Spectroscopy

Spectral analysis is the source of most of our astrophysical knowledge.

Outline

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1. General introduction to spectroscopy
2. Practical spectroscopy
3. Spectral reductions (calibration)

Techniques of Spectroscopy

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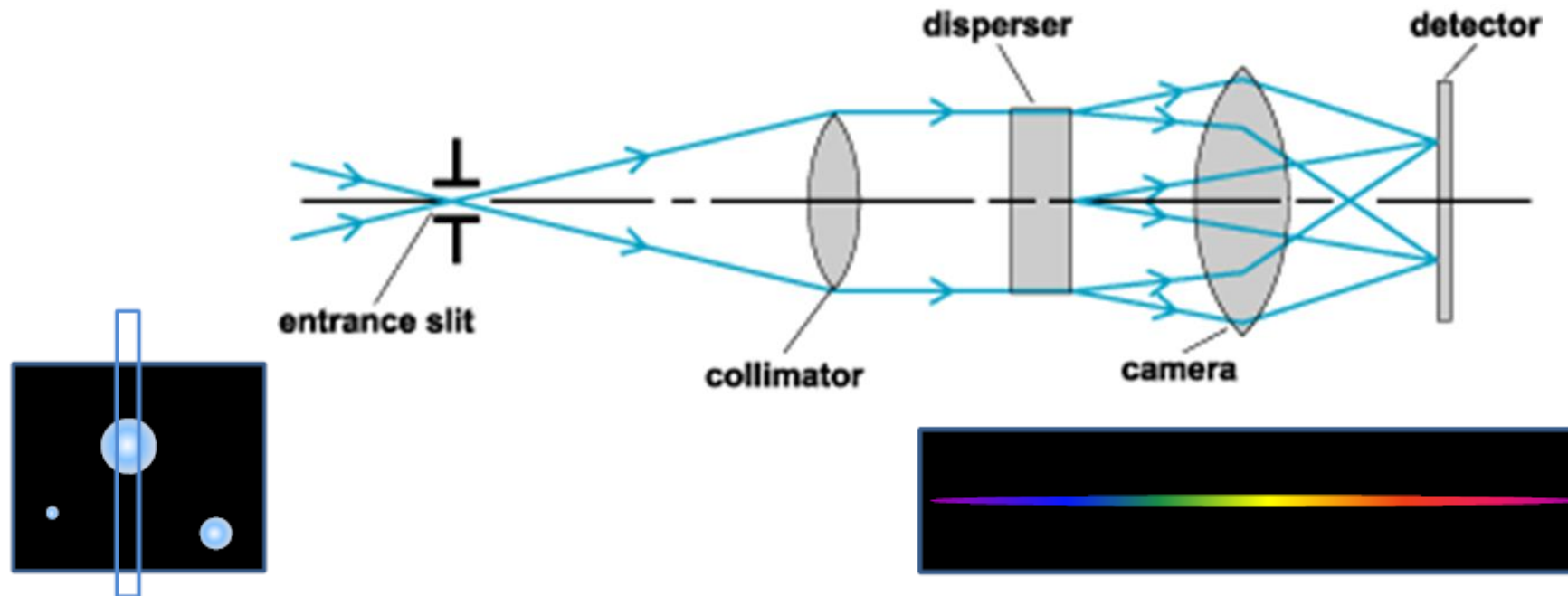
Spectroscopy (**spectrophotometry**) is the most informative technique of light analysis, that measures how much light an object produces at various wavelengths of light.

- At X-ray and gamma ray wavelengths detectors have intrinsic energy resolution.
- At lower energies we must use different techniques to separate radiation of different wavelength/energy/frequency spatially.
- These techniques are largely those of interference, so considering radiation as waves.

Spectrometers

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- All spectrometers have essentially the same basic design, but many different implementations are possible depending on the constraints and choice of spectral disperser.



Spectrometers: main elements

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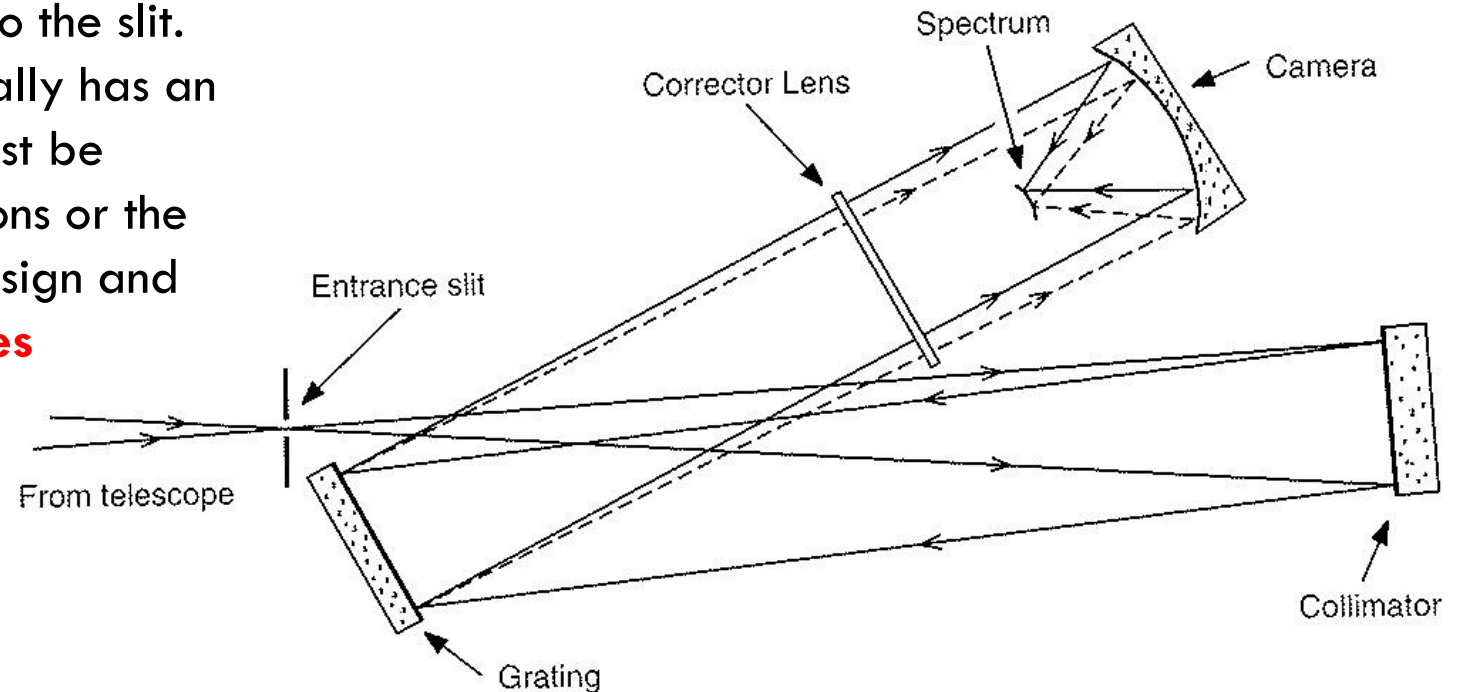
□ Entrance aperture:

The image of a target is focused onto the slit. The slit is in the **focal plane**, and usually has an **adjustable width w** . The slit width must be matched to either the seeing conditions or the diffraction disc depending on the design and application. A narrower slit **improves** resolution $\sim 1/w \times$.



□ Collimator: makes the rays parallel

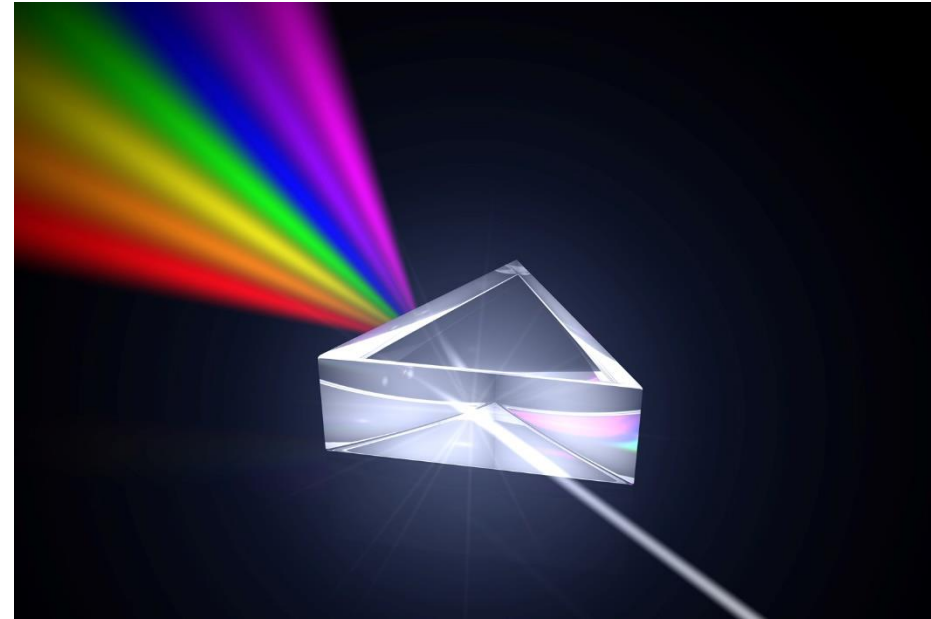
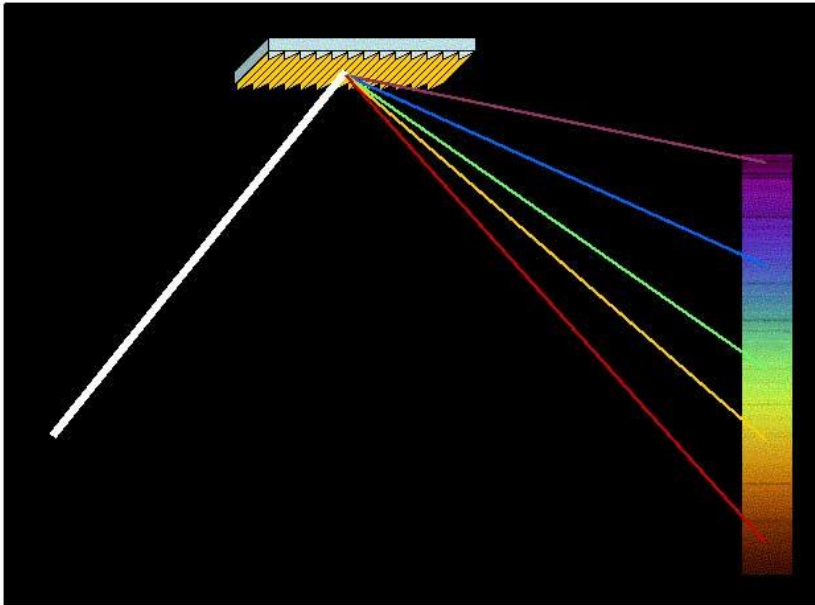
□ Disperser disperses the light into colours: grating or prism, usually on rotating stage so can adjust central wavelength.



□ Camera: to re-focus parallel output beam from disperser onto focal plane of detector (CCD)

Disperser: Grating vs Prism

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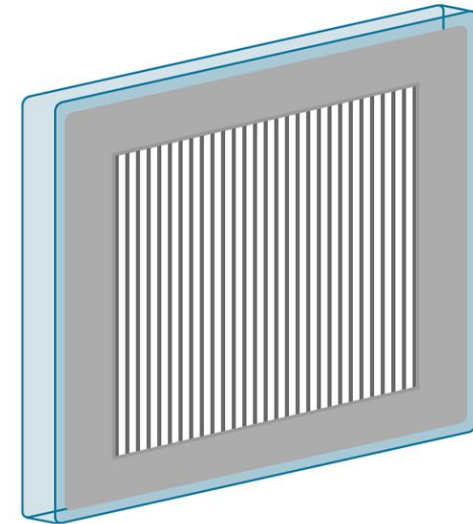


Resolution of a prism is low compared to what is possible with a grating, therefore **grating is usually the primary dispersive element in a modern spectrograph.**

Diffraction Grating (1)

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- A diffraction grating is a set of multiple, identical slits (**transmitting** or **reflecting**) separated by a distance comparable to the wavelength of light.
- Each slit can be considered as radiating secondary waves (Huygens' secondary wavelets).
- The amplitude at any point on the image side of the slit can be calculated by summing the amplitude contributed by each set of secondary wavelets.



Diffraction Grating (2)

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- The theory of Fraunhofer diffraction from a plane grating predicts that the diffracted light is distributed as:

$$I(\theta) = I_0 f_1 f_2,$$

where I is the output intensity leaving the grating in direction ϑ with respect to the normal,

I_0 is the input intensity at the grating,
 f_1 is the diffraction pattern for a single grating slit, and

f_2 is the pattern for a set of N identical apertures.

- The two patterns are given by:

$$f_1 = \frac{\sin^2(\pi\alpha)}{(\pi\alpha)^2}, \quad \alpha = \frac{a \sin \theta}{\lambda}$$

$$f_2 = \frac{\sin^2(N\pi\delta)}{\sin^2(\pi\delta)}, \quad \delta = \frac{d \sin \theta}{\lambda}$$

where a is the linear width of the apertures (assumed rectangular) and d is the linear separation between them (the groove spacing).

Here, we assume **normal incidence** of the incoming light.

Diffraction Grating (3)

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- Consider monochromatic light.
- Principal maxima (“orders”) in the multi-slit pattern occur for $\delta = n$, where n is any integer, i.e. $\sin(\pi\delta)=0$.

$$f_2 = \frac{\sin^2(N\pi\delta)}{\sin^2(\pi\delta)}$$

- Indeed,

$$\lim_{\beta \rightarrow \pm n\pi} \frac{\sin(N\beta)}{\sin(\beta)} = \lim_{\beta \rightarrow \pm n\pi} \frac{\frac{d}{d\beta}(\sin(N\beta))}{\frac{d}{d\beta}(\sin(\beta))} = \lim_{\beta \rightarrow \pm n\pi} \frac{N \cos(N\beta)}{\cos \beta} = N \lim_{\beta \rightarrow \pm n\pi} \frac{\cos(N\beta)}{\cos \beta} = N$$

L'Hôpital's rule 

$$\lim_{x \rightarrow c} \frac{f(x)}{g(x)} = \lim_{x \rightarrow c} \frac{f'(x)}{g'(x)}$$

- Thus, the condition for principal maxima $\sin(\pi\delta)=0$

Diffraction Grating (4)

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- Consider monochromatic light.
- Principal maxima (“orders”) in the multi-slit pattern occur for $\delta = n\lambda$, where n is any integer.

This implies the path difference Δ between adjacent slits will be n wavelengths:

Using the law of cosines,

$$r_1^2 = r^2 + \left(\frac{d}{2}\right)^2 - dr \cos\left(\frac{\pi}{2} - \theta\right) = r^2 + \left(\frac{d}{2}\right)^2 - dr \sin \theta$$

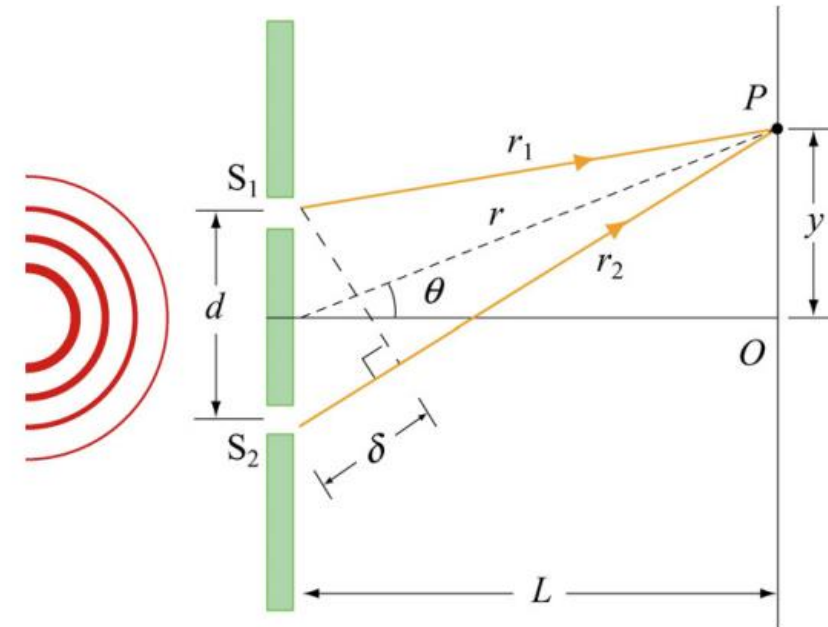
$$r_2^2 = r^2 + \left(\frac{d}{2}\right)^2 - dr \cos\left(\frac{\pi}{2} + \theta\right) = r^2 + \left(\frac{d}{2}\right)^2 + dr \sin \theta$$

Subtracting

$$r_2^2 - r_1^2 = (r_2 + r_1)(r_2 - r_1) = 2dr \sin \theta$$

If $L \gg d$, i.e. the distance to the screen is much greater than the distance between the slits):

$$\delta = r_2 - r_1 \approx d \sin \theta$$



Diffraction Grating (5)

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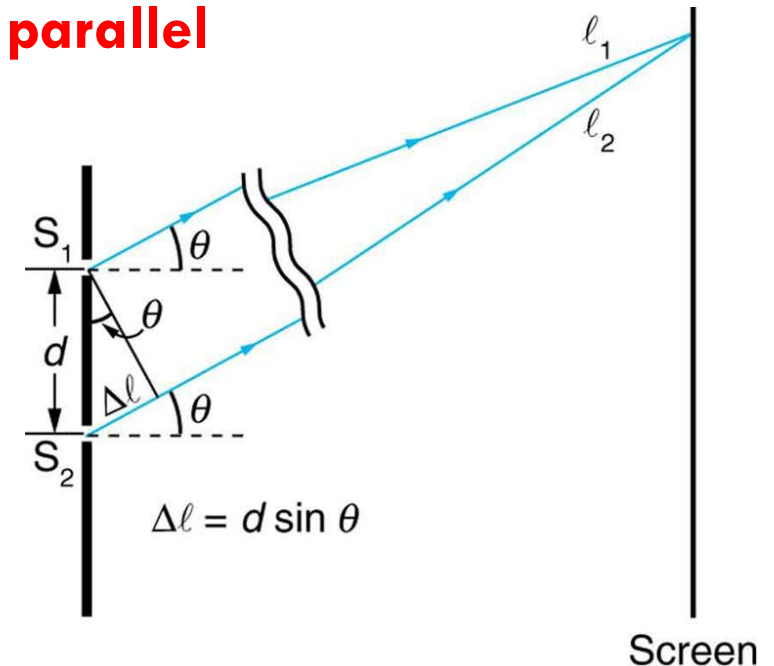
- Consider monochromatic light.
- Principal maxima (“orders”) in the multi-slit pattern occur for $\delta = n$, where n is any integer.

This implies the path difference Δ between adjacent slits will be n wavelengths.

If $L \gg d$, the two rays are essentially treated as being **parallel**

$$\Delta = \Delta l = d \sin \vartheta$$

ϑ – is the angle of diffraction



Diffraction Grating (6)

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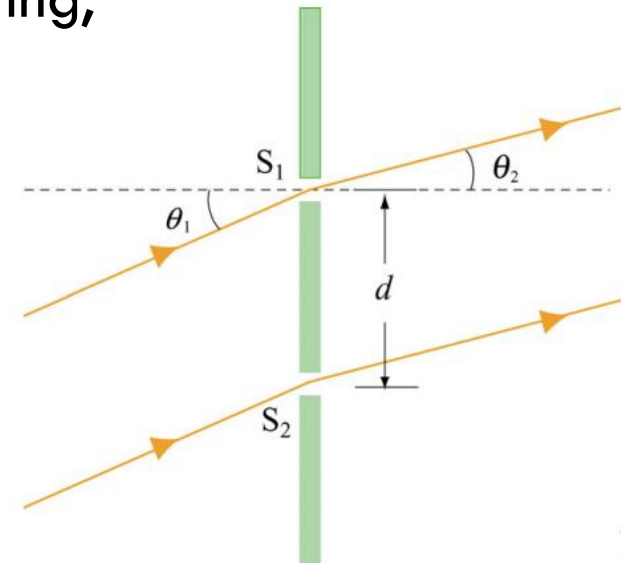
- Consider monochromatic light.
- Principal maxima (“orders”) in the multi-slit pattern occur for $\delta = n$, where n is any integer.

If the normal to the plane of the apertures is at an angle ϑ_1 to the incoming radiation, which corresponds to the often utilized inclined grating, then

$$\Delta = d \sin \vartheta_1 + d \sin \vartheta_2$$

ϑ_1 – is the angle of incidence

ϑ_2 – is the angle of diffraction

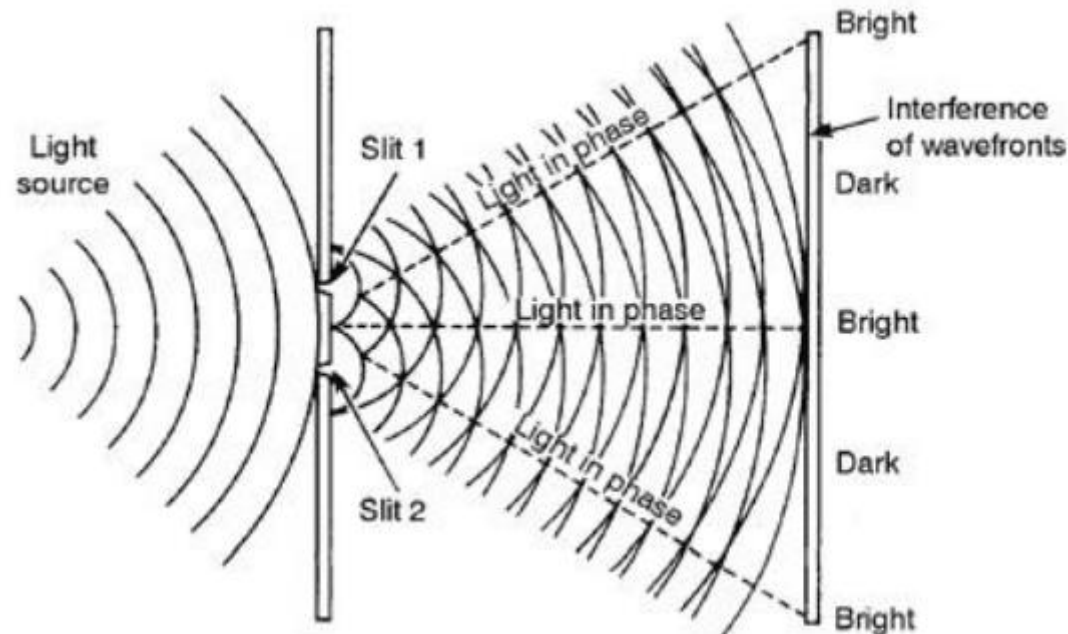


Diffraction Grating (7)

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- Thus, if the path difference Δ between adjacent slits is n wavelengths, this will produce constructive interference. Maxima in the output intensity occur at a sequence of angles $\sin \theta_n = n\lambda/d$.

$$\delta = n\lambda = \frac{d \sin \theta}{\lambda}$$



Diffraction Grating (8)

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- Principal maxima are given by the general grating equation:

$$n \lambda = d (\sin \alpha + \sin \beta)$$

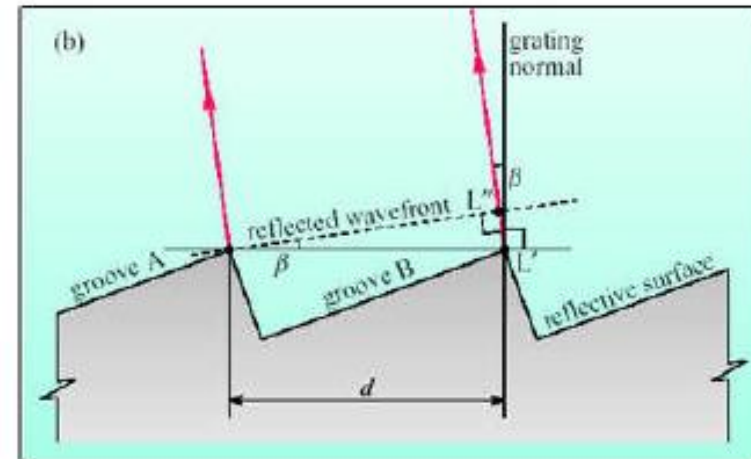
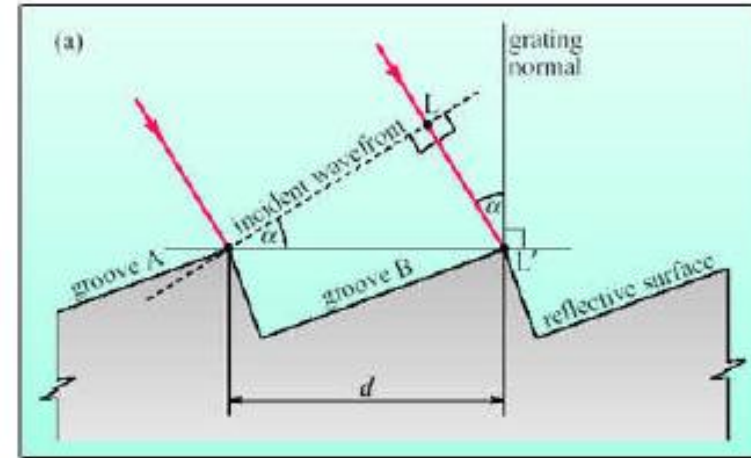
n is an integer representing the order in which the grating is being used.

n is called **the order of diffraction**.

d – the groove spacing.

α – is the angle of incidence

β – is the angle of diffraction



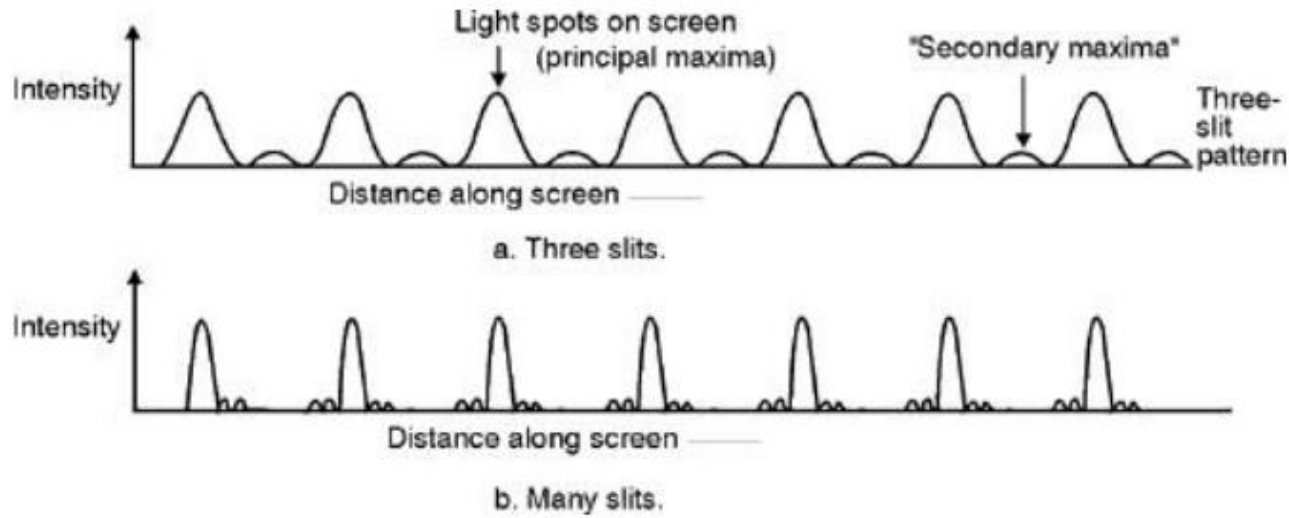
Diffraction Grating (9)

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- The single slit diffraction pattern modifies this by affecting the heights of the maxima, the strongest maximum is that at $n = 0$.
- This maximum is of **no** use to us, because it does not provide any discrimination in wavelength, it is at the same angle for any λ .
- Gratings are designed to concentrate radiation in orders with $n \neq 0$ (note that positive and negative n are equivalent).

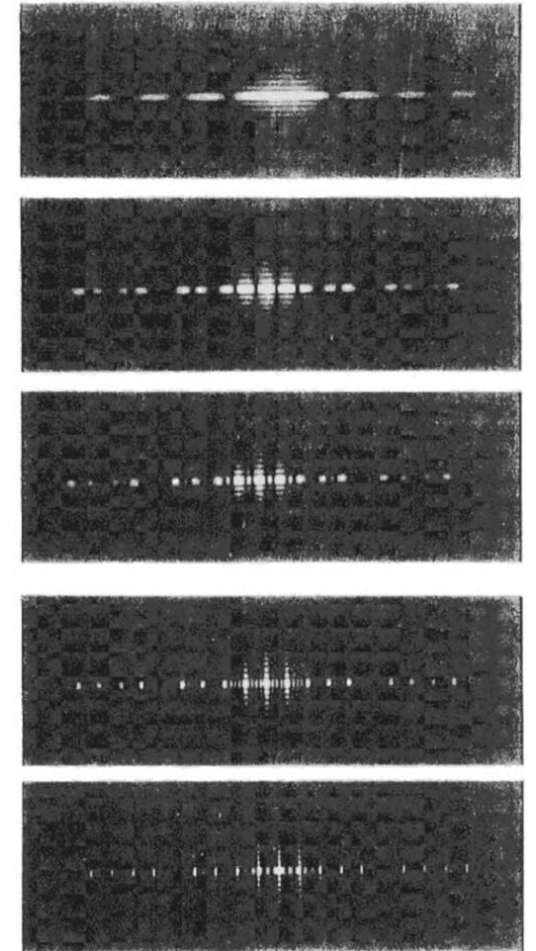
Diffraction Grating (10)

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The monochromatic multi-slit pattern for 3 slits and a large number of slits. Each peak corresponds to a particular order. The addition of slits **increases the sharpness and brightness** of the peaks **but leaves the locations** of the orders unchanged.

The monochromatic multi-slit pattern for 1 slit (top), 2, 3, 5, and 10 slits (bottom).



Credit: Kitchin C. R.

Resolving power & Spectral resolution

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- Spectral resolution for order n is determined by the wavelength shift needed to place the diffraction pattern maximum for $\lambda + \delta\lambda$ on the first minimum in the pattern for λ . The **resolving power** is

$$R = \frac{\lambda}{\delta\lambda} = nN$$



it depends both on the order n and on the total number N of slits illuminated on the grating.

- Astronomers often use the word “dispersion” to refer to $d\lambda/dx$ in the spectrograph focal plane, usually quoted in $\text{\AA per mm}$, or $\text{\AA per pix}$. It is inversely related to the resolving power, so lower values correspond to higher resolving power.

Which resolving power to use for your observations?

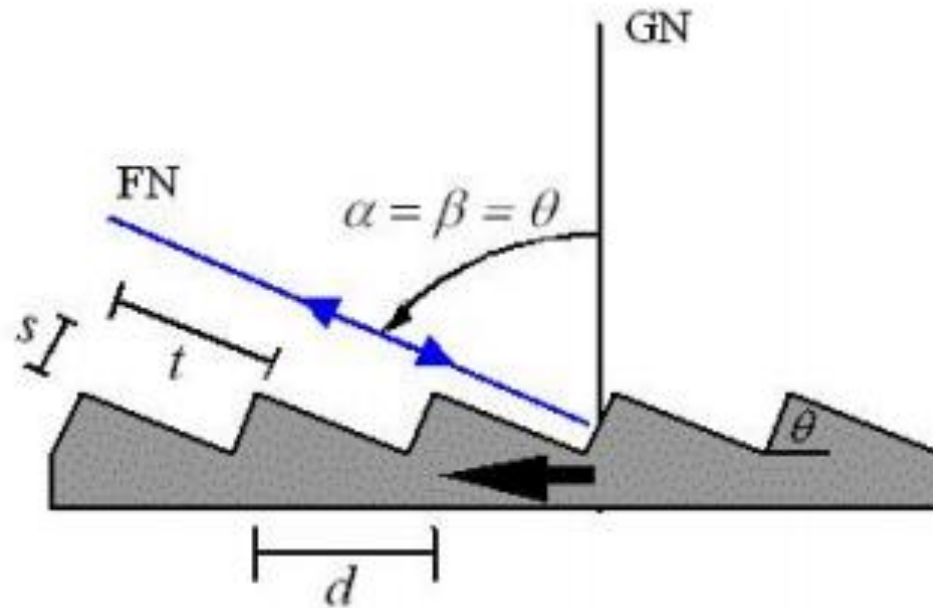
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- Always „the larger the better“ is not the answer.
- High resolution needs a lot of photons, so to get any signal one needs a bright source and/or a large telescope.
- Also, in some cases there is no need for high resolution. If the process you want to study produces velocities of 1000 km/s, there is not much point studying it with resolution of 1 km/s.
- Still, with high resolution you might discover surprising things about your object.

Diffraction Grating: Resolution

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- “Echelle” gratings reach very high resolutions by operating at large $n \sim 50 - 100$ and angle of incidence $\alpha \sim 90^\circ$. Yield $R > 10^5$.



Order overlap

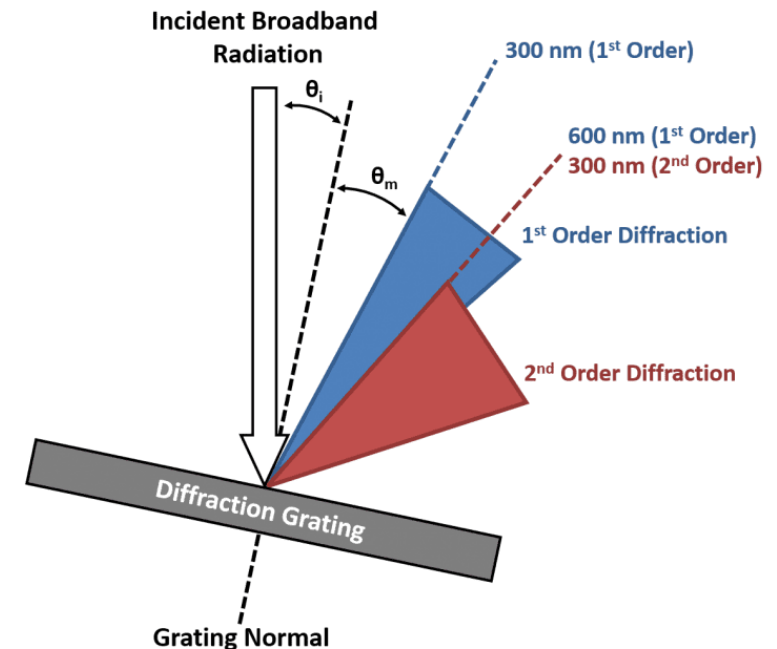
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- Red light of a given order is spatially coincident with blue light from a higher order. Wavelength λ_m in order m is superposed on light from wavelength λ_n in order n if

$$\lambda_m = \frac{n\lambda_n}{m}$$

For instance, $\lambda_1 = 10000\text{\AA}$, $\lambda_2 = 5000\text{\AA}$,
and $\lambda_3 = 3330\text{\AA}$ are coincident.

Solution: Use “order separating” filters to block out the unwanted orders, (through this becomes difficult for large n).



Echelle gratings (1)

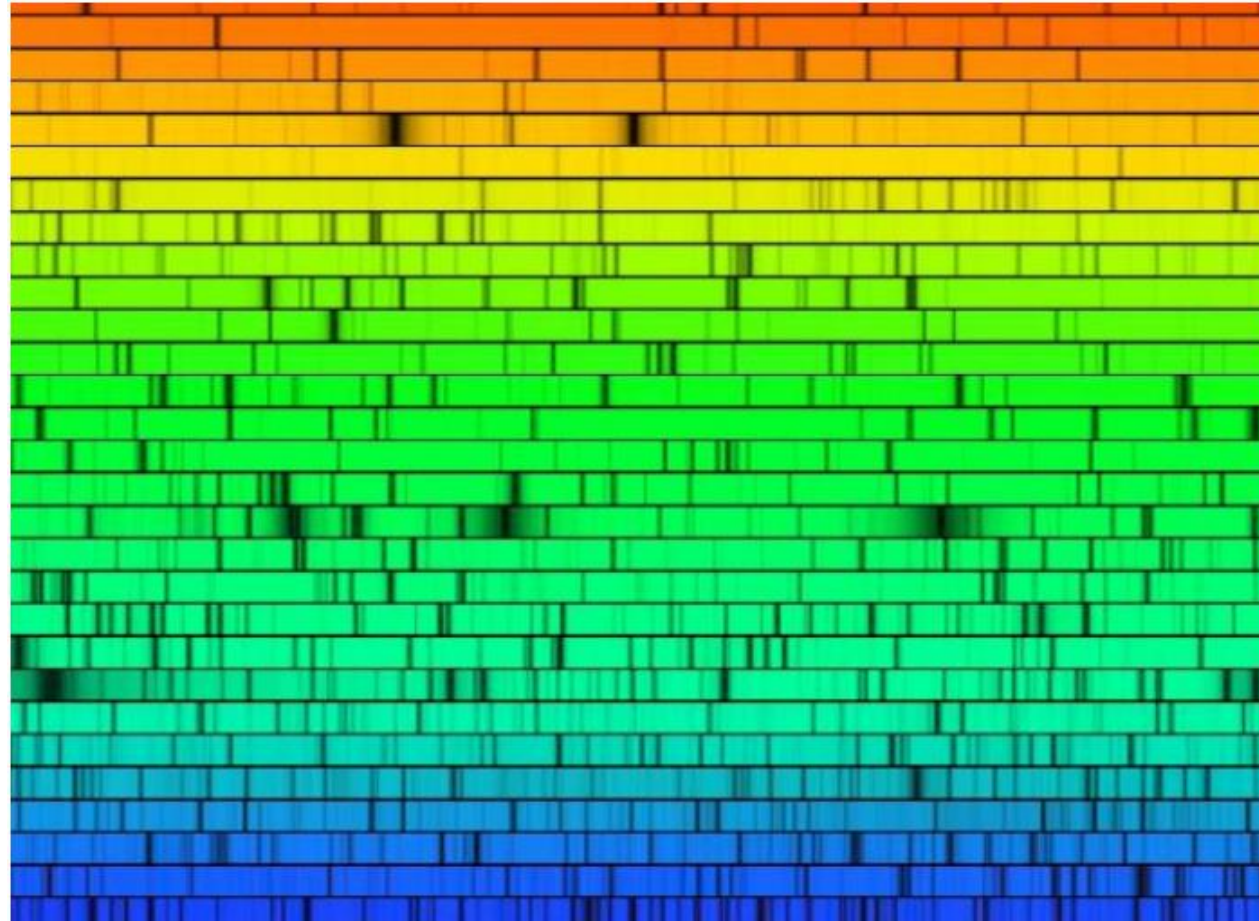
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- Order overlap is much worse, because adjacent orders differ in wavelength by small amounts (e.g. Order 6 @ 500nm is coincident with order 5 @ 600nm, order 7 @ 429nm, order 8 @ 375nm etc)
- Must separate these orders by **cross-dispersion**, usually dispersing with a prism at right angles to the grating dispersion.
- Echelle spectrum consists of a number of spectral orders arranged side by side on the detector.
- Echelles can only be used for point sources (stars and quasars) or for small objects, otherwise the light from different orders still overlaps.

Echelle gratings (2)

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High resolution,
optical band solar
spectrum

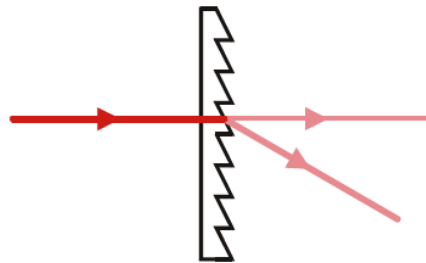


Transmission gratings and grisms

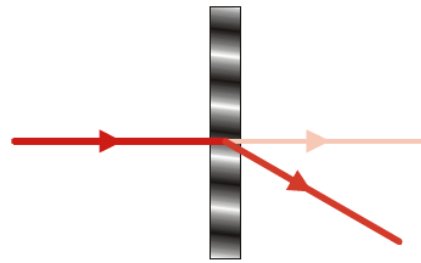
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There are different versions of transmission gratings:

- Transmission grating
- Volume Phase Holographic Gratings: **VPH** - use modulations of the index of refraction rather than surface structures to produce dispersion. **High efficiency**.

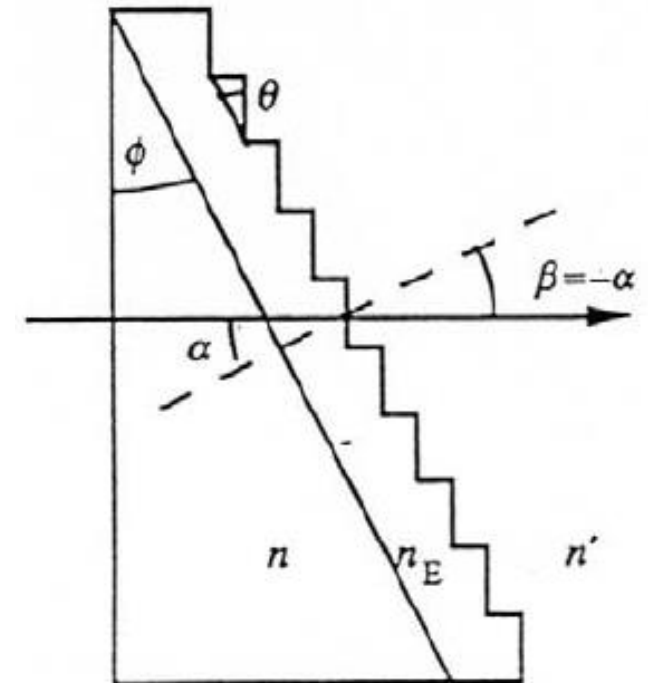


Relief Diffraction Grating



VPH Diffraction Grating

- **Grisms** - a very popular way to convert a camera into a spectrograph is to deposit a transmission grating on the hypotenuse of a right-angled prism and use the deviation of the prism to bring the first order of diffraction on axis.
 - The advantage of a grism is that it can be placed in a filter wheel and treated like another filter. Resolving powers of $R \sim 500 - 2000$ are practical.



Spectrometer Throughput

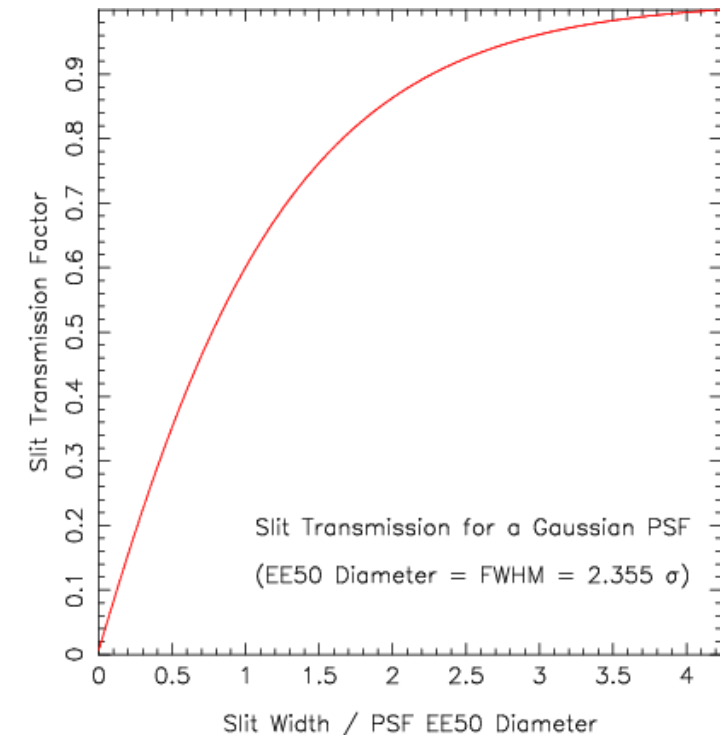
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- Spectrometer throughput ranges from a few percent to ~50%. The losses accumulate fast. Dispersing elements are usually a big hit, then the losses at multiple surfaces go like $(\text{transmission})^n$ where n is the number of surfaces in the collimator and camera elements (n can be pretty big)

$$0.98^8 \cdot 0.7 \cdot 0.8 = 0.47$$

Camera/collimator
with 8 surfaces grating ccd

- Another throughput issue: slit losses can be very significant!



ALFOSC at the NOT telescope

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- UV-optical imaging, low resolution spectroscopy and polarimetry
- 2048x2048 CCD (0.19"/pixel)
- 6.4'x6.4' field of view (FOV)
- Large selection of broad, intermediate and narrow band filters
- Several grisms:
 - ▣ $R \sim 200-10,000$ (typically 1000)
 - ▣ Velocity resolution 30-1500 km/s
- Multi Object Spectroscopy with masks
- Imaging polarimetry and spectropolarimetry
- Spectroscopy of objects brighter than $R \sim 20$
- Imaging of objects brighter than $R \sim 23.5$