OBSERVATIONAL ASTRONOMY – I

Lecture 13

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Spectroscopy

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

Outline

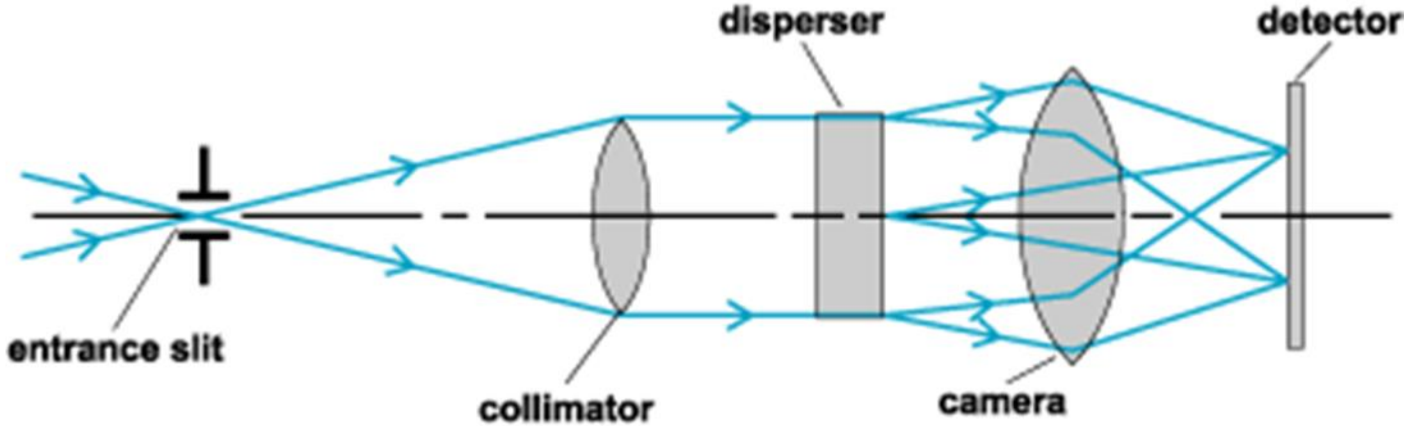
1. General introduction to spectroscopy
2. Practical spectroscopy
3. Spectral reductions (calibration)

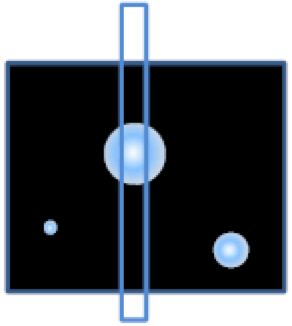
Techniques of Spectroscopy

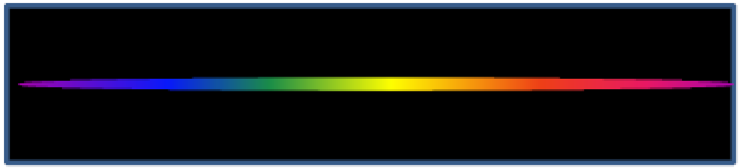
- At X-ray and gamma ray wavelengths detectors have intrinsic energy resolution.
- At lower energies we must use different techniques to separate radiation of different wavelength/energy/frequency spatially.
- These techniques are largely those of interference, so considering radiation as waves.

Spectrometers

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

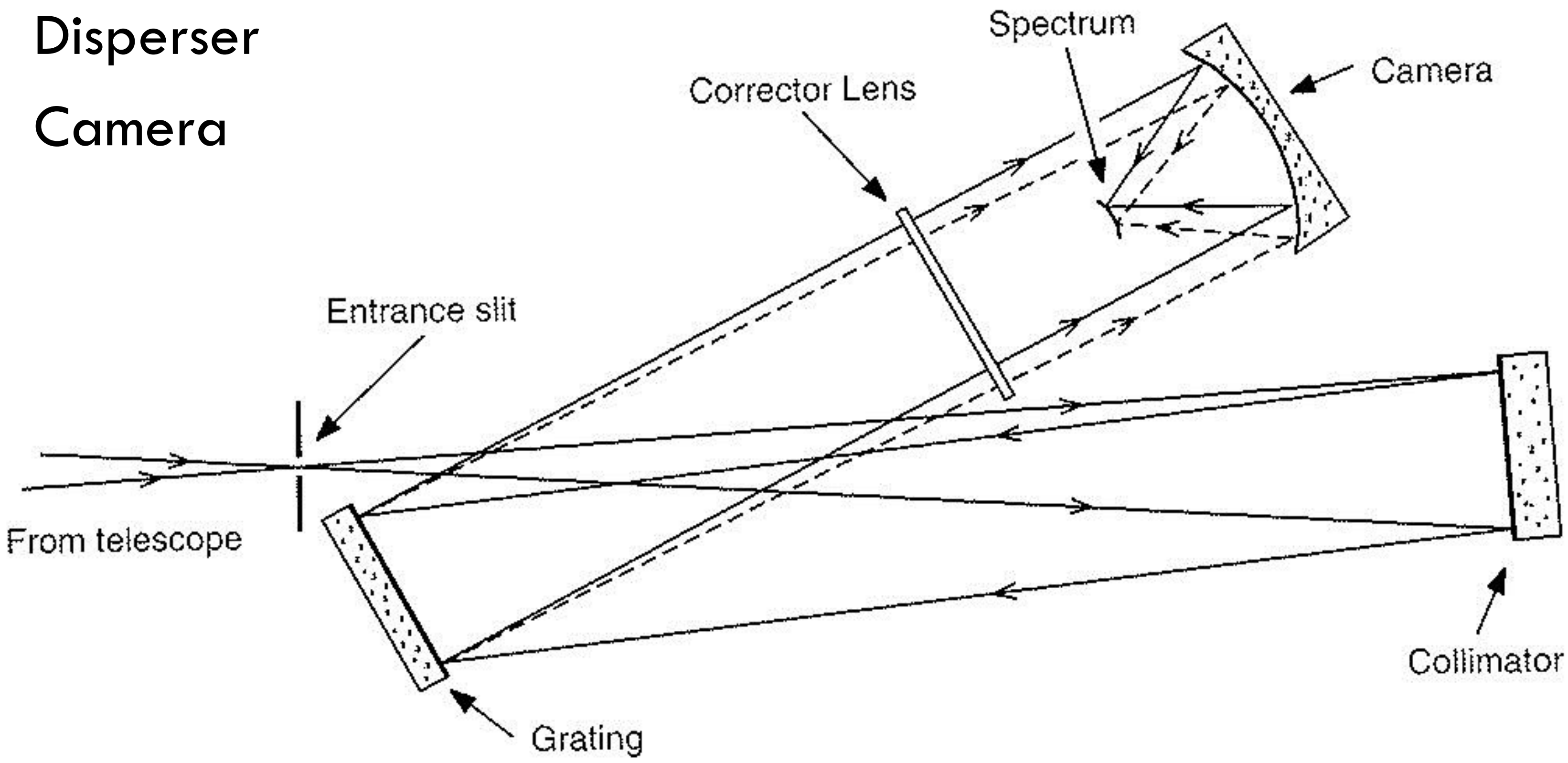






Spectrometers: main elements

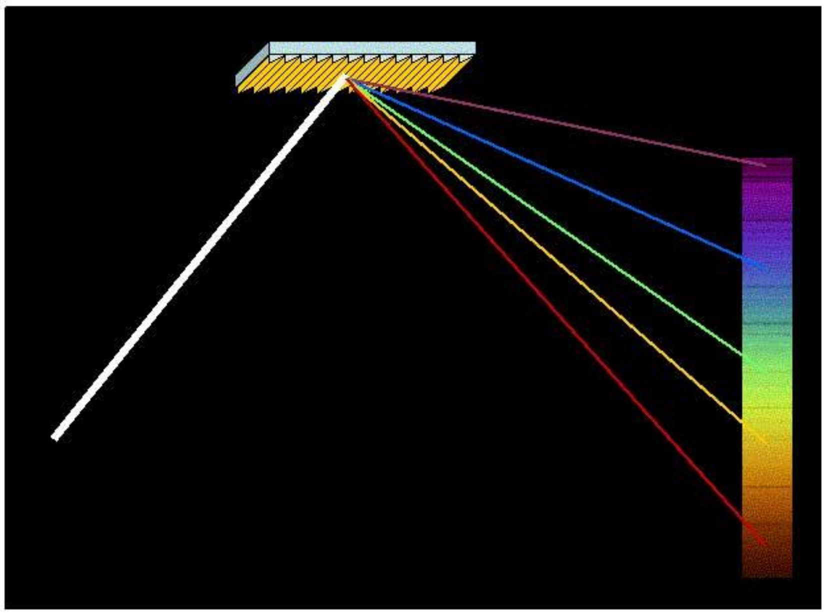
- Entrance apertures at focal plane of telescope
- Collimator
- Disperser
- Camera

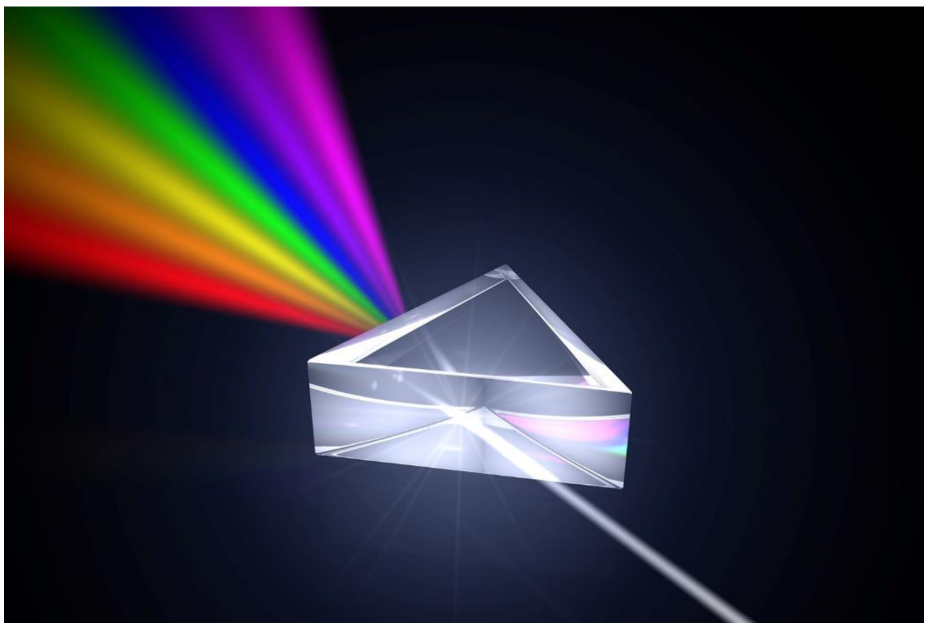


Spectrometers: main elements

- **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 disk depending on the design and application. A narrower slit improves resolution $\sim 2 - 10\times$.
- **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





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

- 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

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

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

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.

Diffraction Grating

- The two patterns are given by:

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

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

where *a* is the linear width of the apertures (assumed rectangular) and *d* is the linear separation between them. We assume normal incidence of the incoming light here.

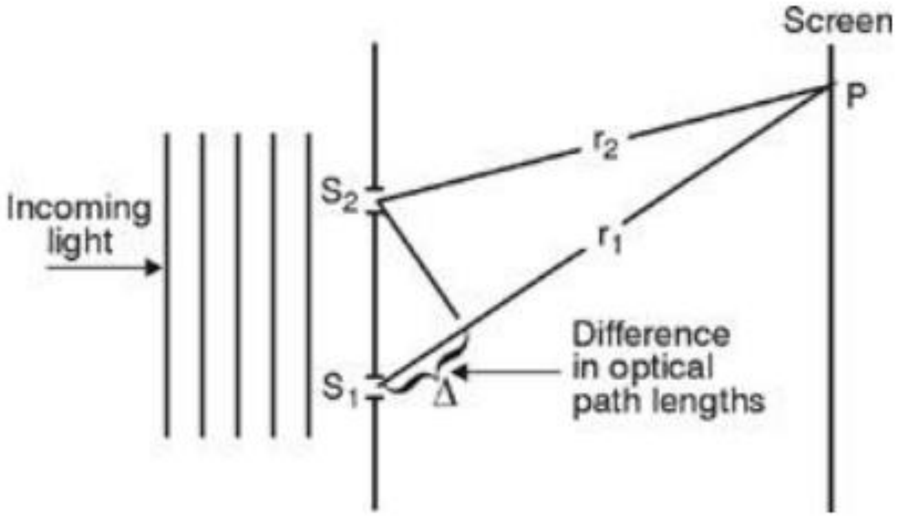
Diffraction Grating

- Consider monochromatic light. Maxima ("orders") in the multislit pattern occur for $\delta = n$, where n is any integer. This implies the path difference Δ between adjacent slits will be n wavelengths

$$\Delta = d \sin i + d \sin \theta$$

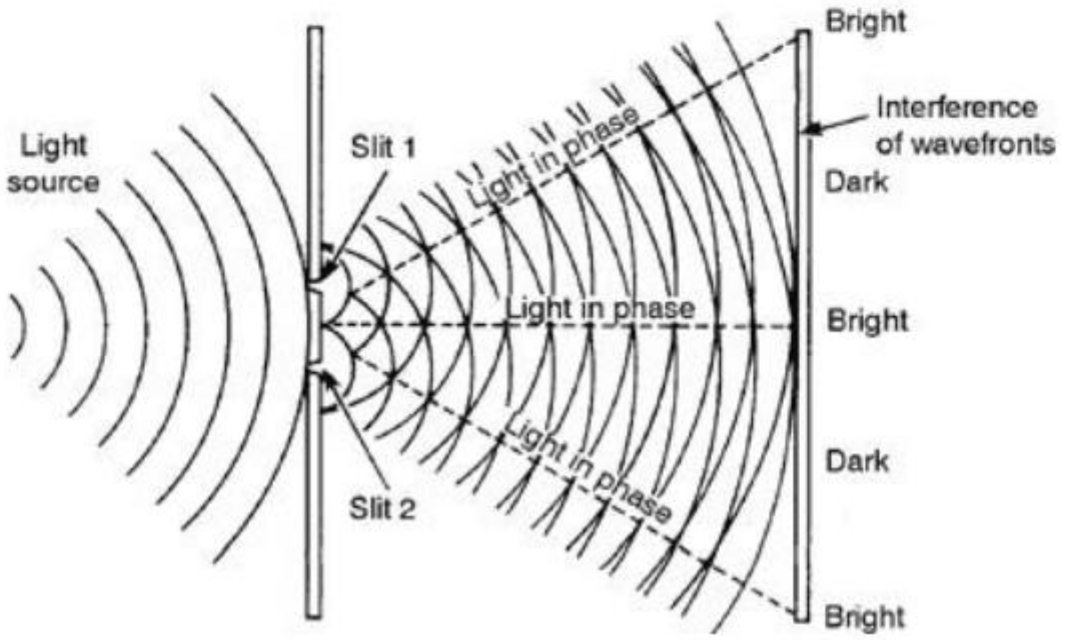
i – is the angle of incidence

θ – is the angle of diffraction



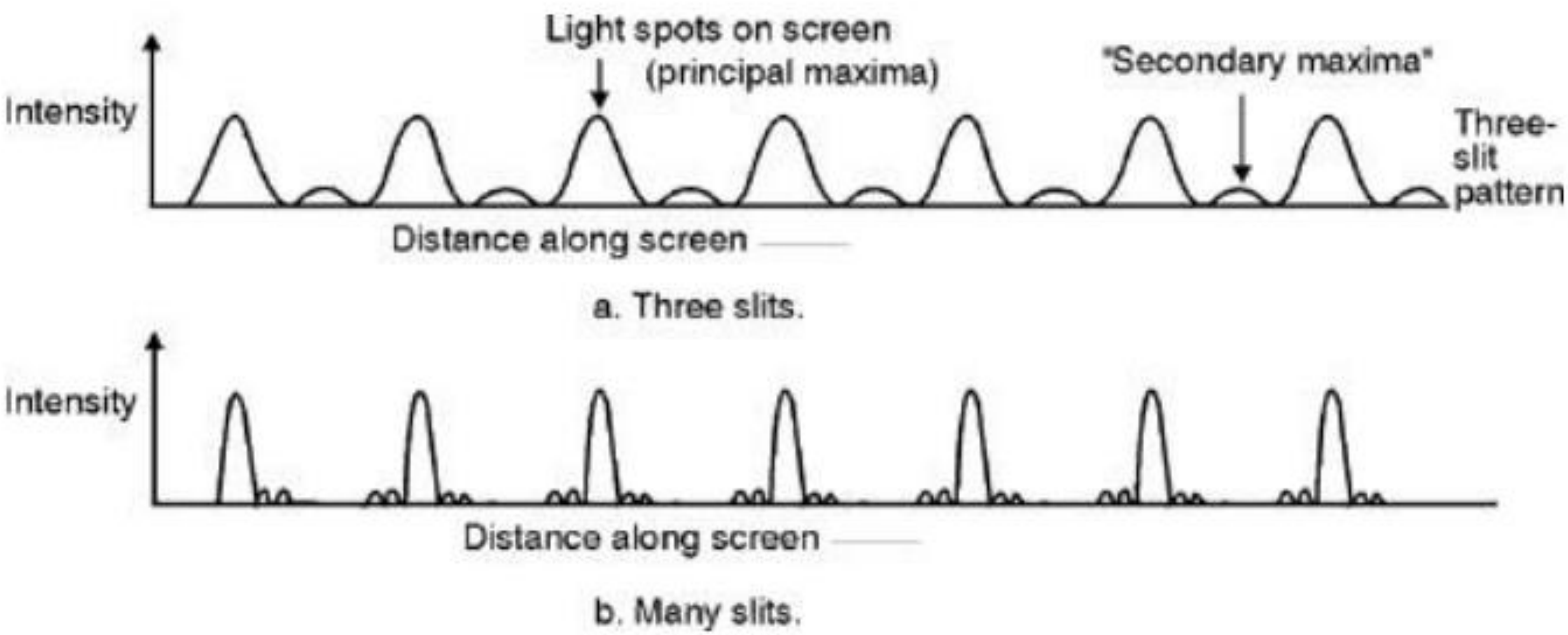
Diffraction Grating

- This produces constructive interference. Maxima in the output intensity occur at a sequence of angles $\sin \theta_n = n \lambda / d$.



Diffraction Grating

- 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.



Diffraction Grating

- Principal maxima are given by the general grating equation:

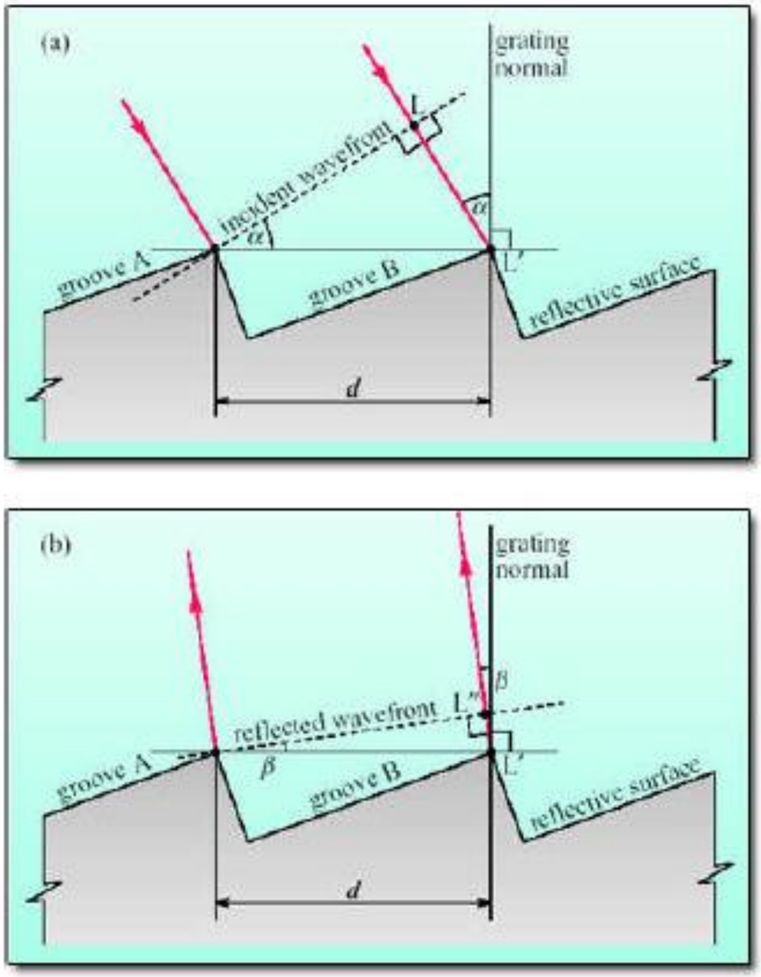
  $$n\,\lambda = d\,(\sin\alpha + \sin\beta)$$

  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

- 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).

Resolving power & Spectral resolution

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

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

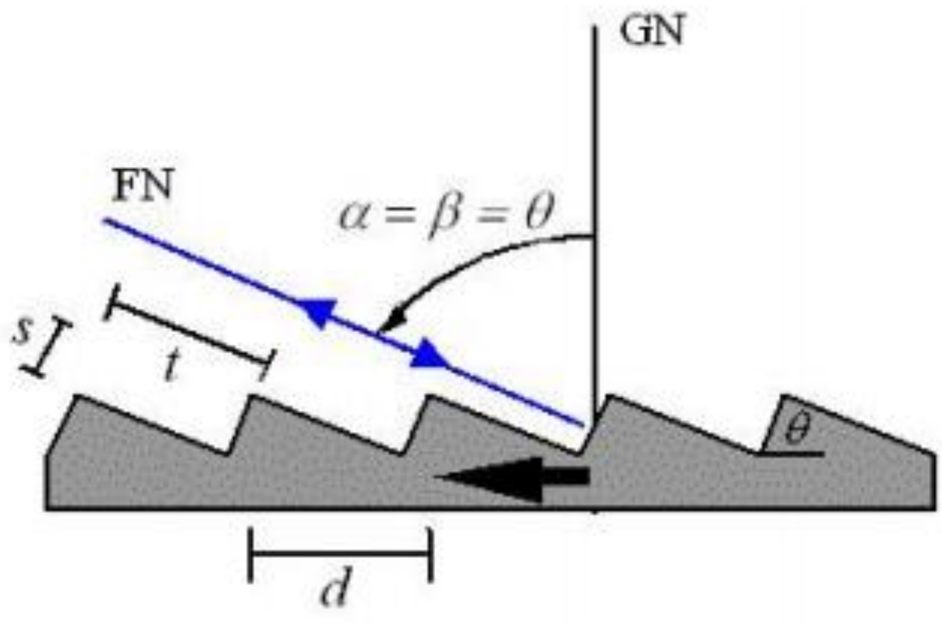
  it depends both on the order *n* and on the total number *N* of slits illuminated on the grating.
- Astronomers often use the word "dispersion" to refer to dλ/dx in the spectrograph focal plane, usually quoted in Å per mm. It is inversely related to the resolving power, so lower values correspond to higher resolving power.

Which resolving power to use for your observations?

- 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

- "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

- 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, $\lambda_1 = 10000Å$, $\lambda_2 = 5000Å$, and $\lambda_3 = 3330Å$ are coincident.

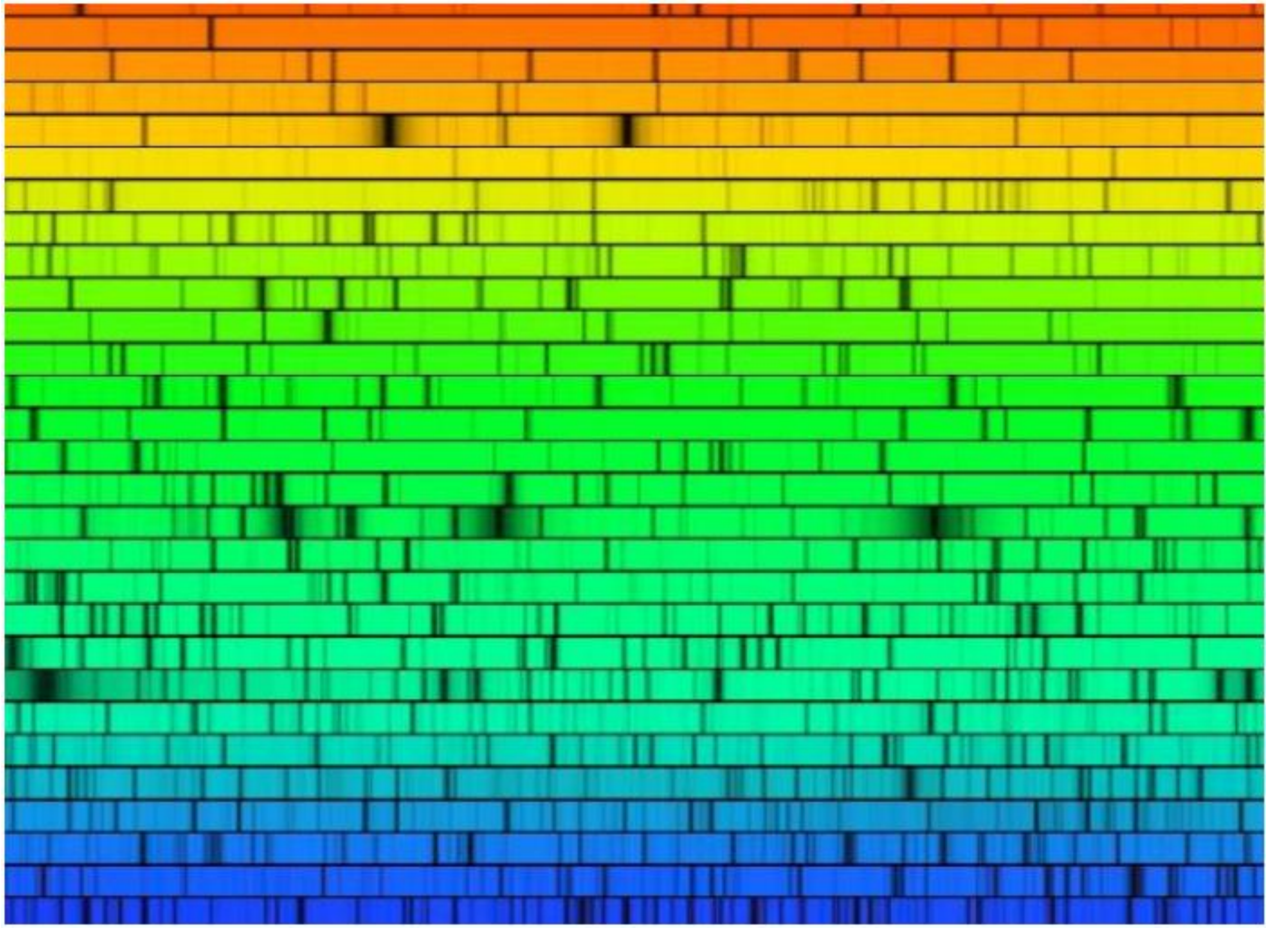
<u>Solution</u>: Use "order separating" filters to block out the unwanted orders,
(through this becomes difficult for large n).

Echelle gratings

- 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

High resolution, optical band solar spectrum



Transmission gratings and 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. Such a device is called a “grism".
- The advantage of a grism is that it can be placed in a filter wheel and treated like another filter.

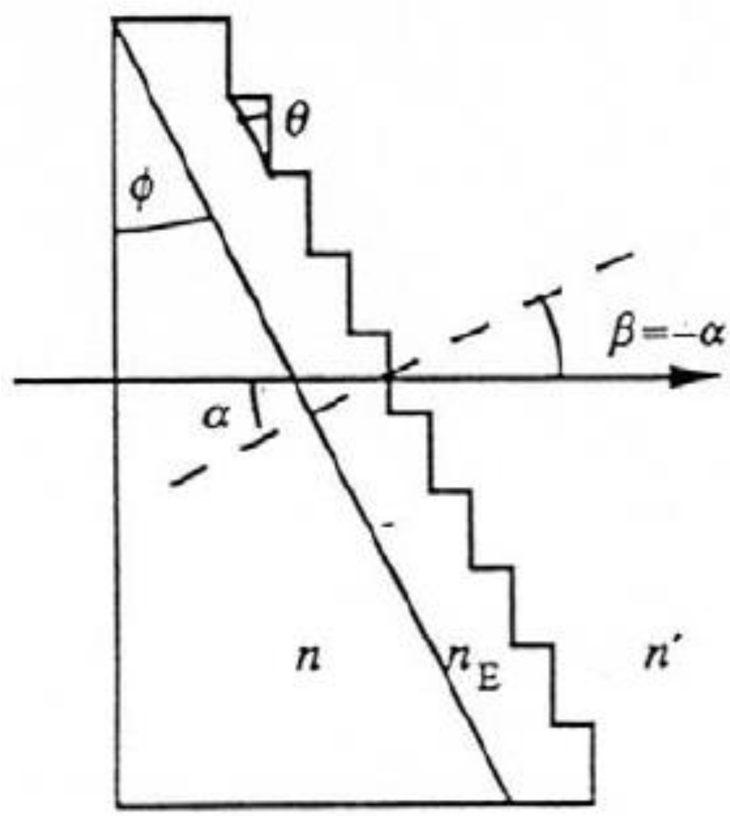
Grisms

- The basic relationships required to design a grism are

$$m\,\lambda_c T = (n-1)\sin\varphi$$

$$R = \frac{EFL}{2\,dpix}(n-1)\tan\varphi$$

where λ_c is the central wavelength, T(=1/d) is the number of lines per millimeter of the grating; n is the refractive index of the prism material; φ is the prism apex angle; EFL is the effective focal length of the camera system and d_{pix} is the pixel size. Resolving powers (two pixels) of R ~ 500 – 2000 are practical.



Practical spectroscopy

Practical spectroscopy

- The purposes of spectroscopy are:
  - To measure accurate wavelengths of emission and absorption lines.
  - To measure the relative strengths of emission lines.
  - To measure equivalent widths of absorption lines.
  - To measure the spectral energy distribution of the continuum radiation.

Practical spectroscopy

- Science goals must come first:
  - What are the resolution and S/N requirements?
  - Is there a restriction on exposure time?
  - Decide on the best compromise between these constraints, you will soon enough run out of photons.
- Identify a slit-width/disperser combination that provides the required dispersion and sampling.
  - Seeing or slit-width limited?
- Work out calibrations required
  - Always try to take cal data through the same/similar lightpath.

Slit-filling effects

- A slit-limited setup ensures that the slit is always illuminated uniformly [provided the object is centered]
- A partially illuminated slit (because image quality is better than the slit-width) may introduce shifts in the projected spectrum as different areas of the slit are illuminated as a function of time
- This will lead to shifts in both the spatial and dispersion direction of the spectrum when comparing to calibration data that are obtained with a fully illuminated slit
  Not good if you are after accurate radial velocities!

Atmospheric dispersion

- Differential atmospheric refraction will deflect a source by an amount that is dependent on wavelength
  - [the index of refraction is a function of wavelength]
- A point source position on the sky is dependent on wavelength!
- The displacement is towards the zenith and larger for shorter wavelengths
- This obviously affects acquisition and slit-angle strategies when obtaining spectroscopy

Atmospheric dispersion

- Index of refraction: n(λ,T,p,f)
  - wavelength, temperature, pressure, water vapour
- Angle displacement: $\Delta R = R(\lambda_1) - R(\lambda_2) \propto \Delta n(\Delta\lambda) \tan z$

zenith angle (airmass)

- Some example shifts (") relative to image at 5000Å:

airmass	3000Å	4000Å	6000Å	10000Å
1.00	0.00	0.00	0.00	0.00
1.25	1.59	0.48	-0.25	-0.61
2.00	3.67	1.10	-0.58	-1.40

Atmospheric dispersion

- Make sure you acquire the target at a wavelength relevant for your spectral range
- Differential refraction will mean differential slit-losses: can only centre object at one λ
- If the slit is vertical (relative to horizon/ zenith line), differential refraction will occur purely along the slit
- This means that the slit P.A. (sky angle) must change with time. The vertical P.A.is the *parallactic* angle