Optical/IR Observational Astronomy

Spectroscopy

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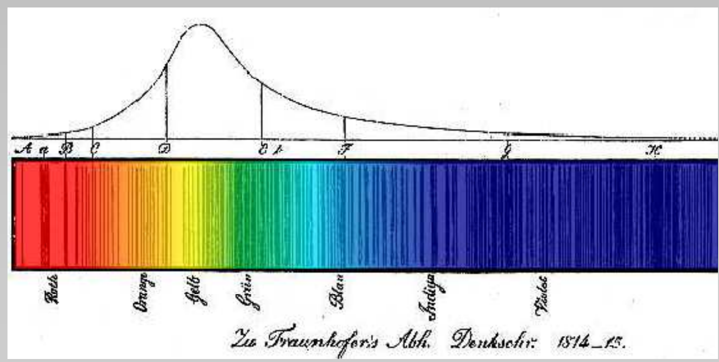
Background

Spectroscopy is really just *monochromatic* photometry

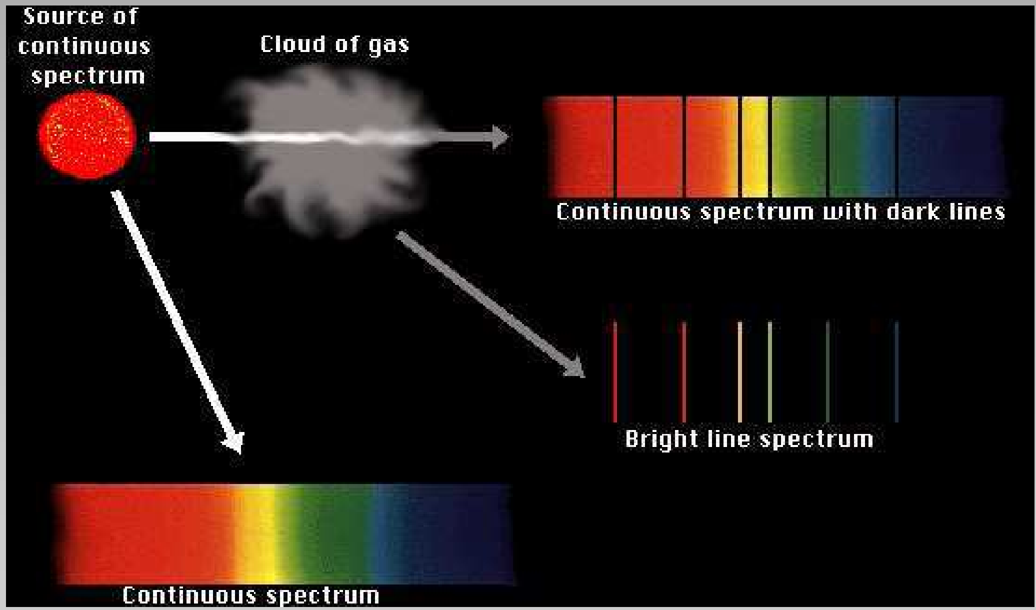
History

- 1637 Descartes explained the origin of the rainbow.
- 1666 Newton's classic experiments on the nature of colour.
- 1752 Melvil discovered the yellow "D lines" emitted by sodium vapour.
- 1802 Wollaston discovered dark lines in the spectrum of the Sun.
- 1814 Fraunhofer used a small theodolite telescope to examine stellar spectra and found similar lines as in the solar spectrum.
  - He catalogued the features as A, B, C, ... etc,
  - some which persist to the present day – the sodium "D" lines, the "G" band (CN - cyanogen).



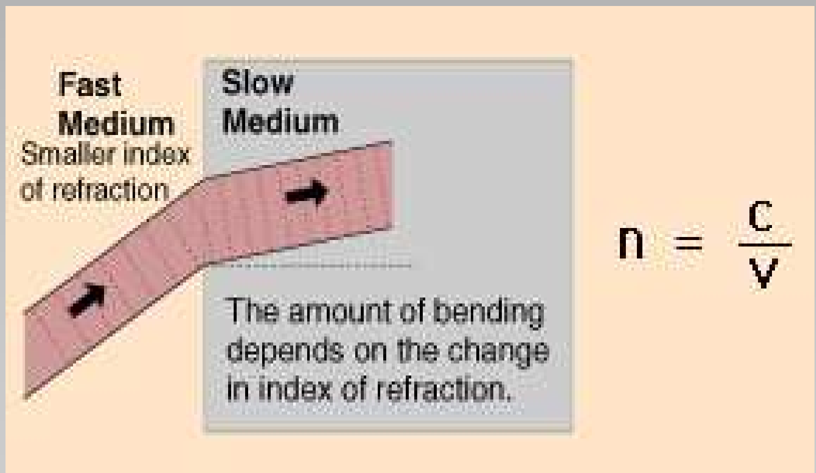
Background

- 1859 Kirchhoff & Bunsen experiments established that a heated surface emits a continuous (Planck or "black body") spectrum
  - a heated low pressure gas emits an emission spectrum with discrete lines at wavelengths characteristic of the gas; and a cool low pressure
    - » **Examples include planetary nebula & HII (ionized hydrogen) region**
  - gas in front of a hot source absorbs at those same characteristic wavelengths.
    - » **Examples include the photospheres of stars (black bodies with absorbing "atmospheres"**



How to disperse light?

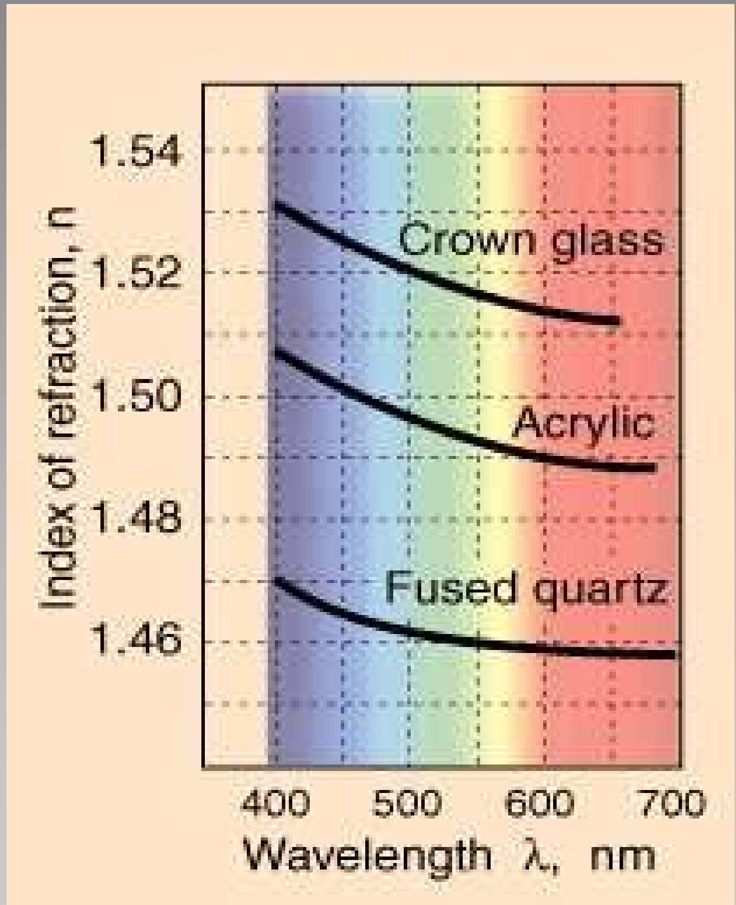
- **First achieved with glass prisms**
  - **Highly transparent**
- **Made from material with higher *index of refraction* than air**
  - **Bends the lights**
- **Made from material with wavelength dependent index of refraction**
  - ***Disperses* light**
  - **Degree of bending is *wavelength dependent***



Index of refraction, *n*, is ratio of speed of light in vacuum compared to speed of light in the material

Index of Refraction

- **Non-linear with wavelength**
  - **Degree of *dispersion* also non-linear**
- **Original spectrographs used *prisms***
  - **Continued well into 20th C**
- **But, problems with prisms….**
  - **They cannot achieve very high dispersion, therefore can't do *high resolution* (R = $\lambda/\Delta\lambda$) spectroscopy**
  - **They're quite "lossy":**
    - » **reflection losses at air-glass surfaces (4% per surface for uncoated prisms)**
    - » **Absorption losses in the glass, particularly in the UV**
  - **Temperature changes can cause index changes**
    - $\Rightarrow$ **Dispersion changes and line shifts**



Dispersion Formula for Prisms

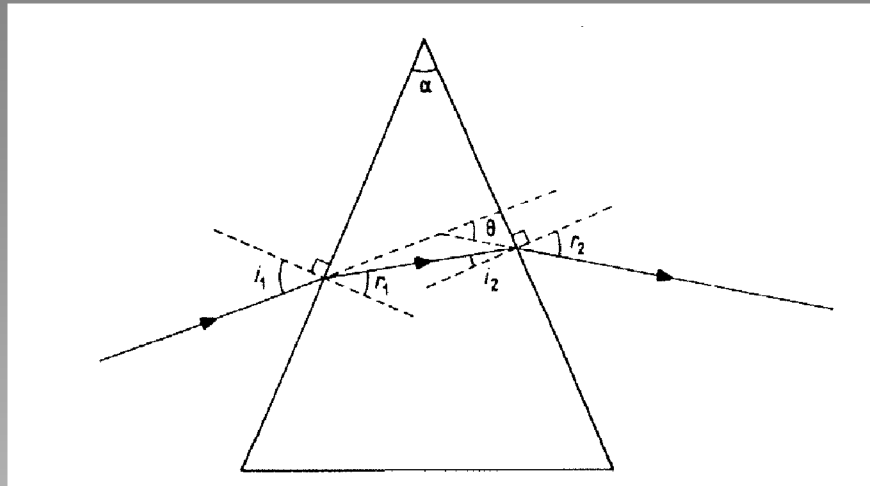
- **Just apply Snell's law**

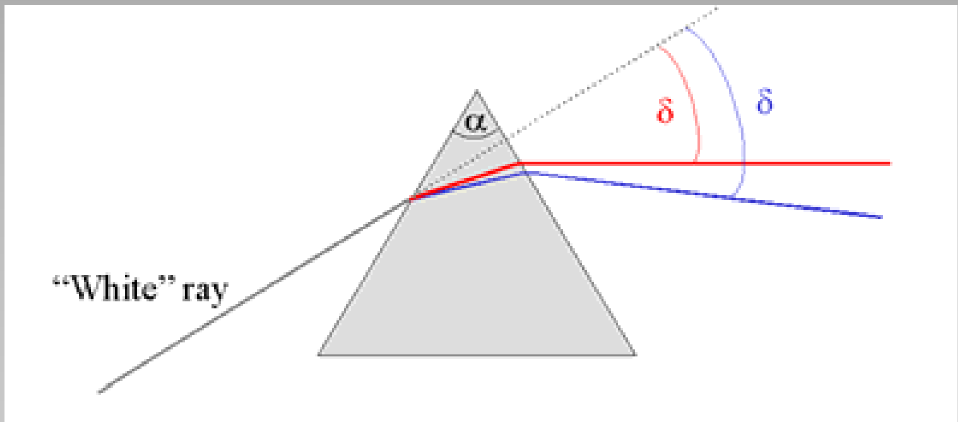
  $n_1 \sin i = n_2 \sin r$

  – *From air-to-glass ($n_1 = 1$, $n_2 = 1.5$)*

  $\Rightarrow n_2 = \sin i / \sin r$

- **Geometry for generalized case**





- **Deviation is:**

  $\delta = i + r - \alpha$

- **Dispersion is simply:**

  $\Delta\theta/\Delta\lambda = d\delta/d\lambda$

More on Prisms

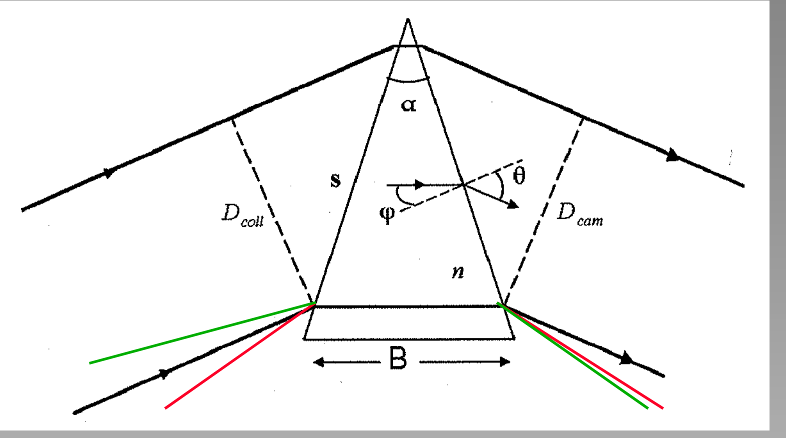
- **Prisms**
  - **Used in *minimum deviation* condition**
  - **Symmetrical**
    - » **Beam width constant**
    - $\Rightarrow$ **No astigmatism**
  - **From trig:**

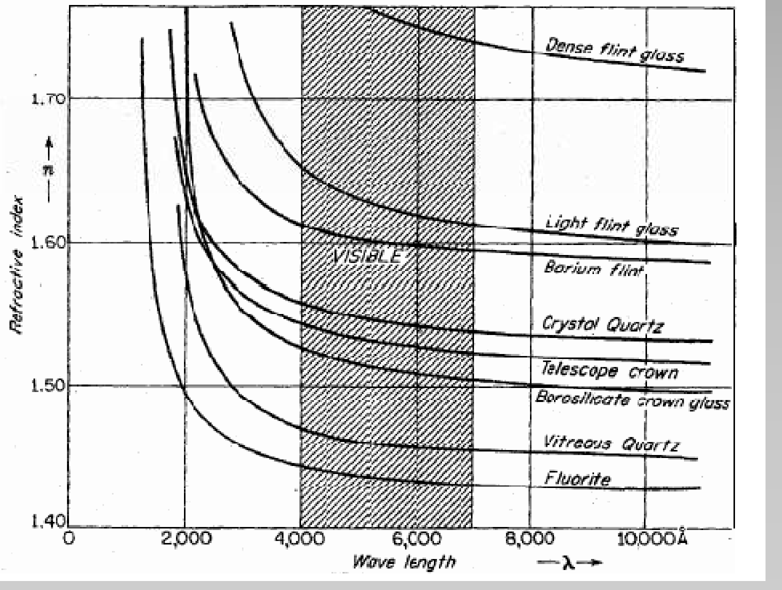
$$\frac{d\theta}{d\lambda} = \frac{d\theta}{dn}\frac{dn}{d\lambda} = \frac{B}{D_{\mathrm{cam}}}\frac{dn}{d\lambda} = \frac{2\ sin\ (\alpha/2)}{cos\ \theta}\cdot\frac{dn}{d\lambda}$$

  - **So dispersion depends on**
    - » **Apex angle of prism**
    - » **Emergent angle of diffraction**
    - » **Index of refraction dependency on λ**
  - **Spectral resolution is given as:**

R = $\lambda / \Delta\lambda = B\ dn/d\lambda$ ***(slitless)***

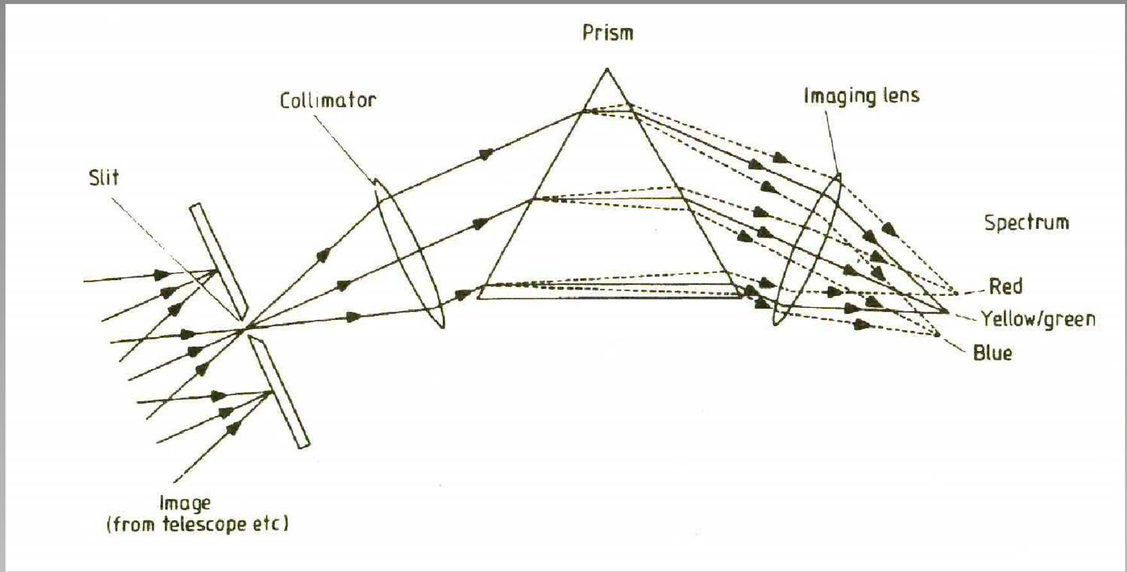
(higher resolution in blue compared to red)



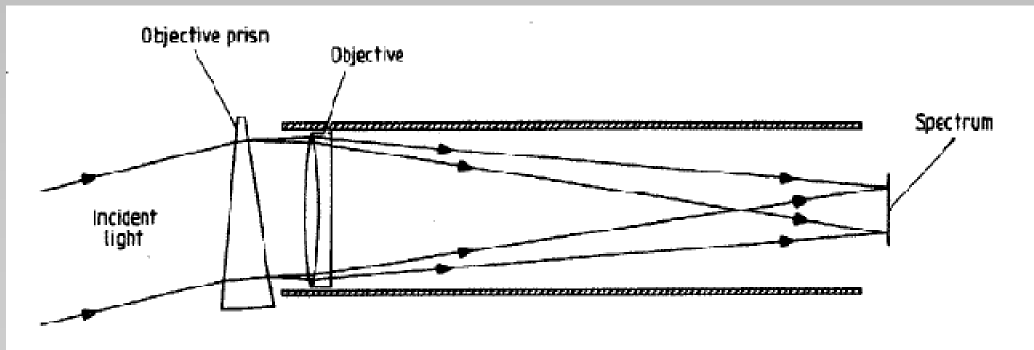


Prism Spectrographs

- **This is basis of all prism spectrographs**

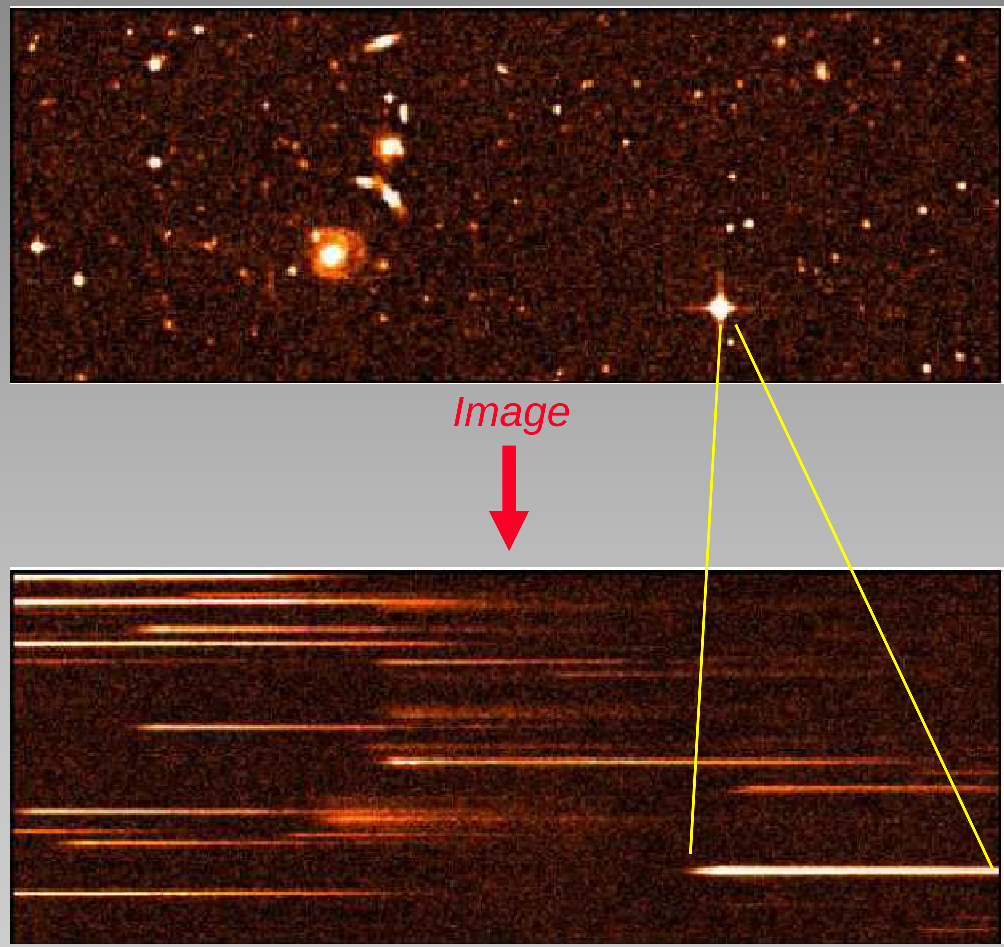


- **First used as *objective prisms***
  - **Prisms placed at telescope aperture**



Objective Prism Surveys

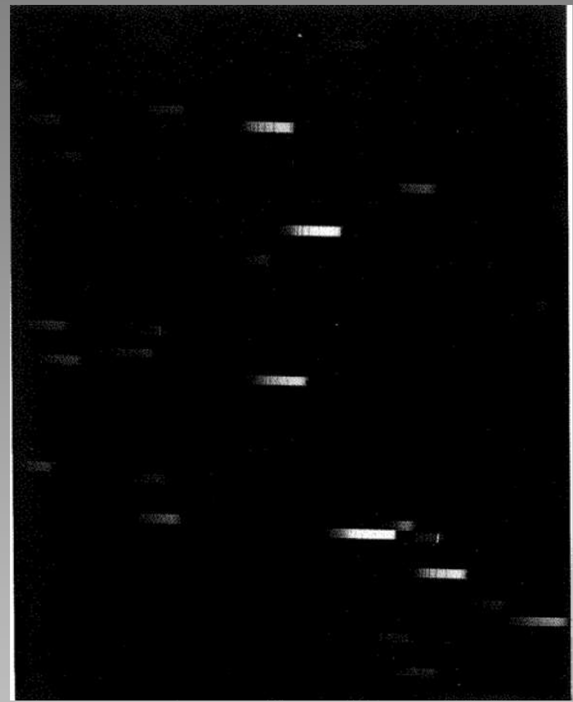
- Used to ***disperse*** images on the sky
- Create multiple ***low resolution*** spectra
- Resolution determined by the ***prism dispersion***, ***detector resolution*** and ***seeing***
- First done with ***photographic plates***
  - e.g. on the Cape Observatory McLean refractor

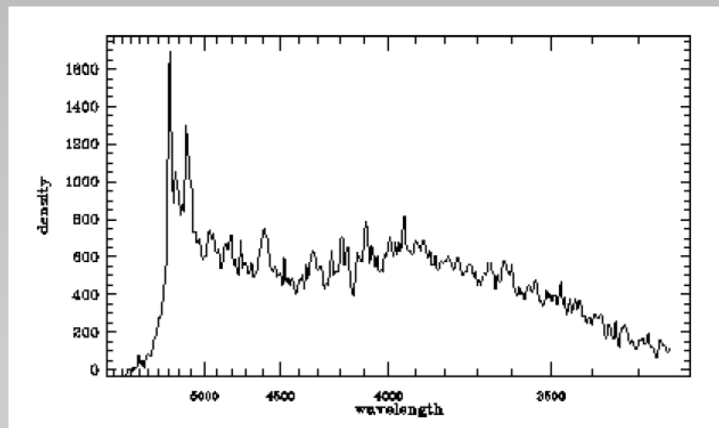


Spectrogram (dispersed image)

Objective Prisms

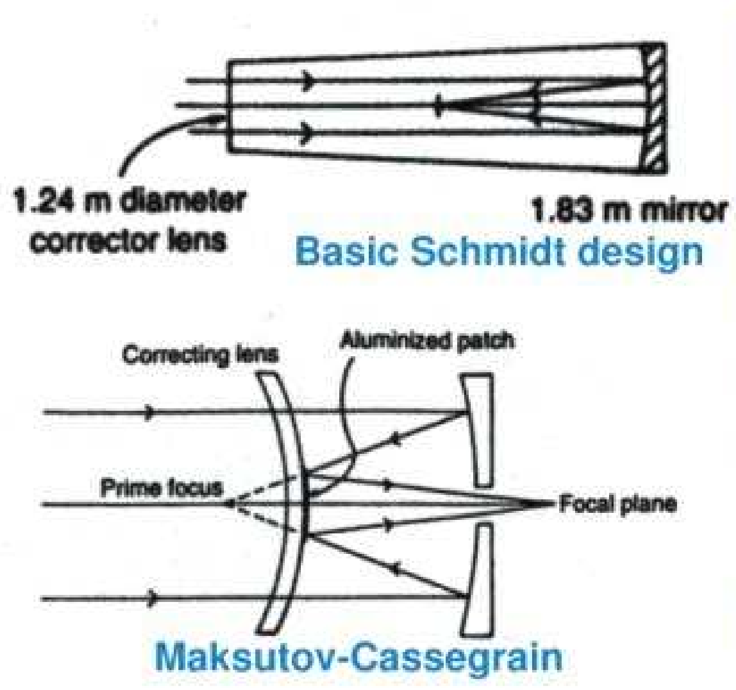
- **Spectra widened by trailing telescope in direction perpendicular to dispersion**
  - **Easier to see features by eye (first techniques)**
- **First catalogue of stellar spectra done at Harvard College Observatory by Annie Cannon**
  - **Laboriously catalogued 250,000 stars, by eye!**





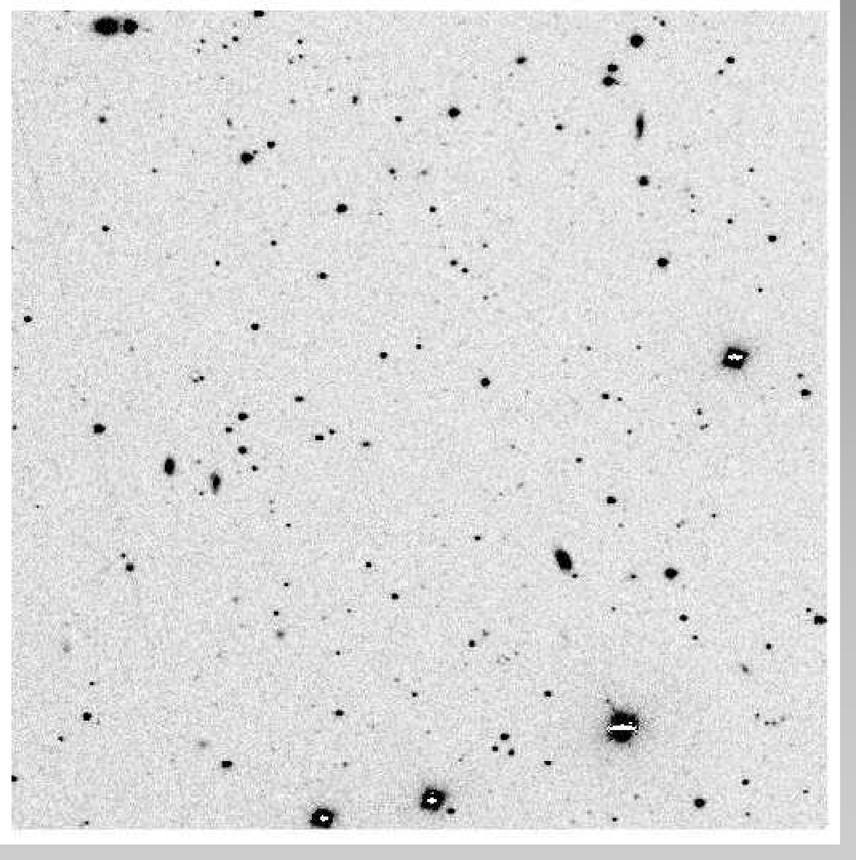
Objective Prisms Surveys

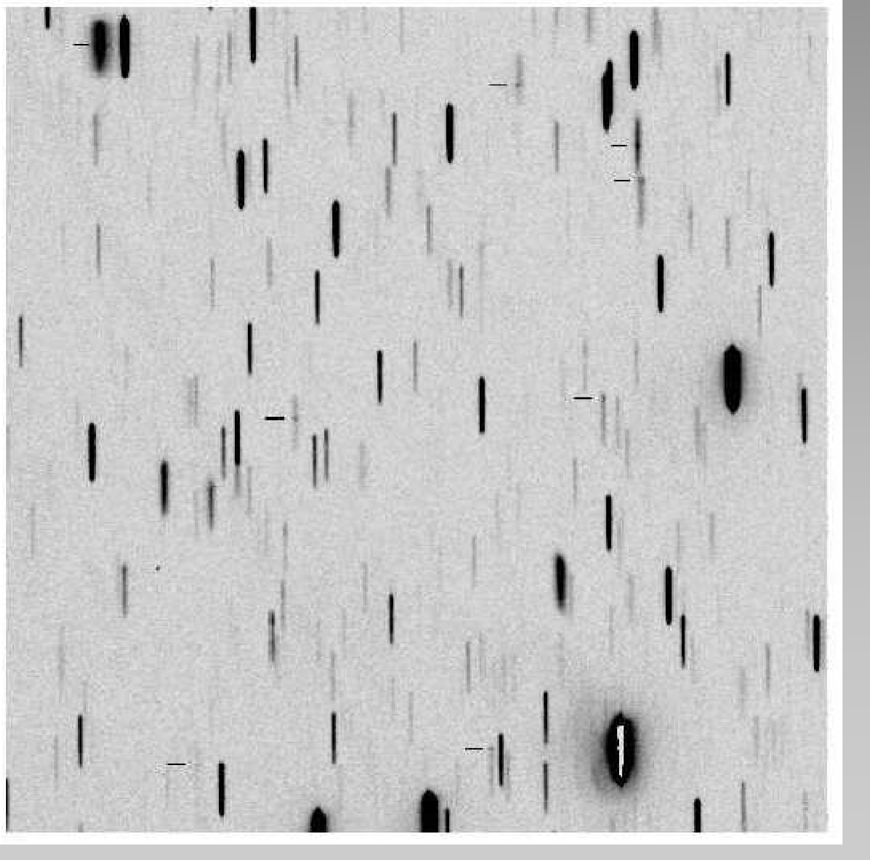
- **Combined with Schmidt telescope, objective prisms could be used to spectroscopically survey large areas of sky**
- ***Multiplex advantage:*** **area coverage *and* wavelength information**



Example of Objective Prisms Spectra

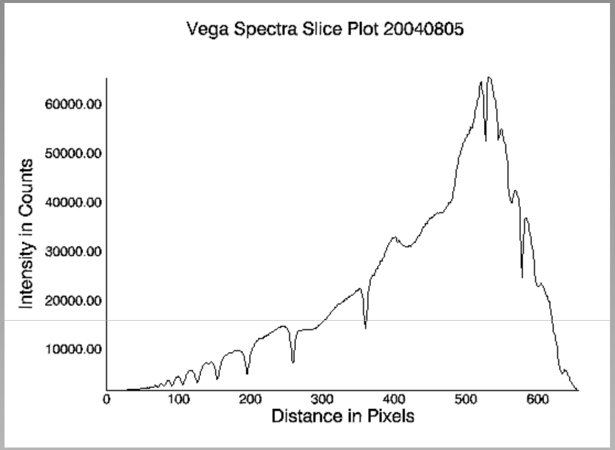
- **Search for emission line objects**
  - **e.g. star formation in galaxies**

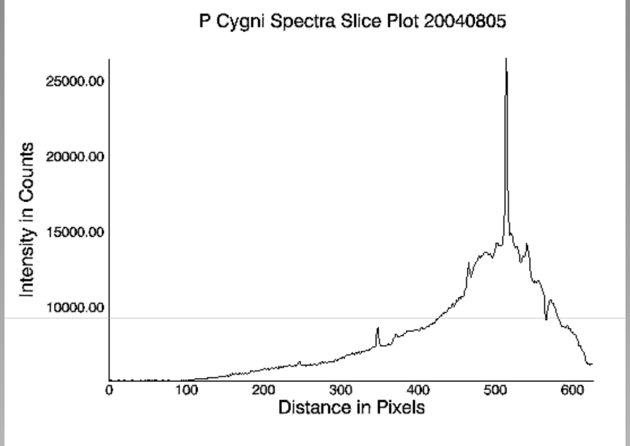


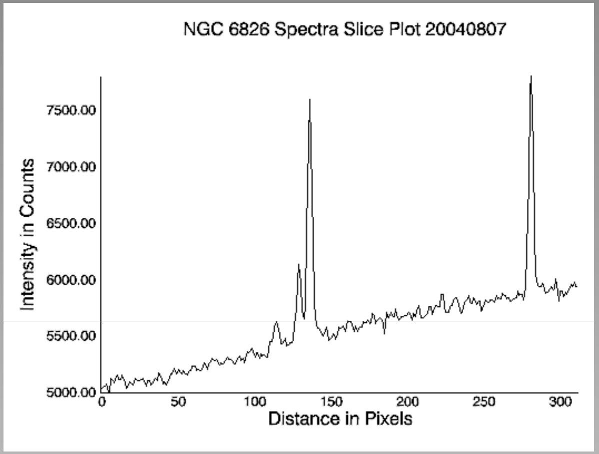


Example of Objective Prisms Spectra

- **Spectral classification**

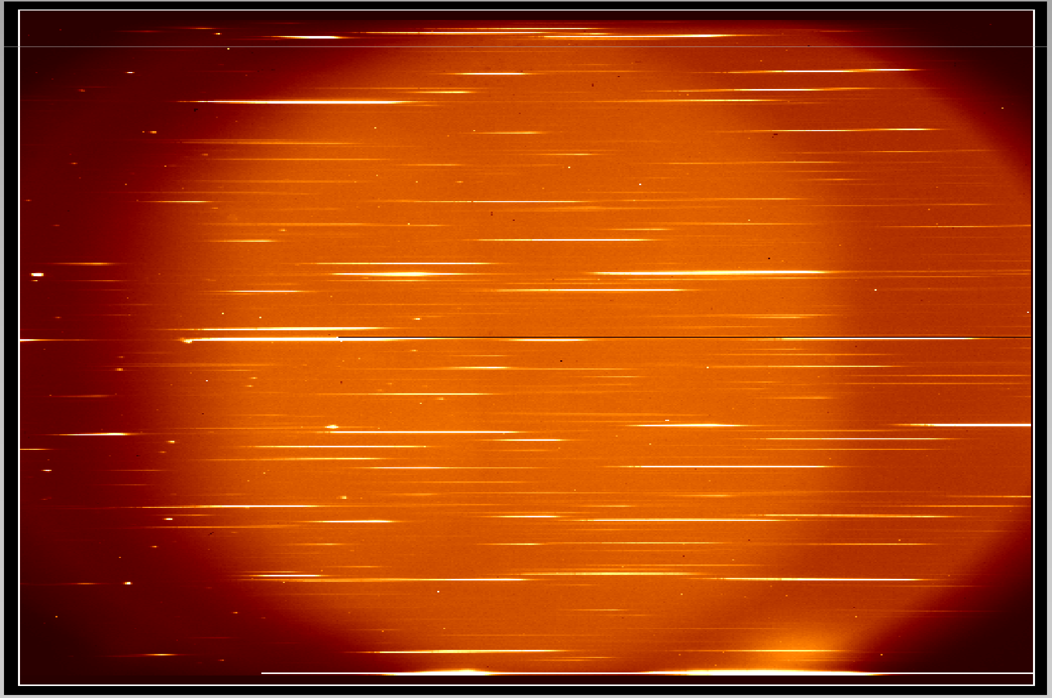


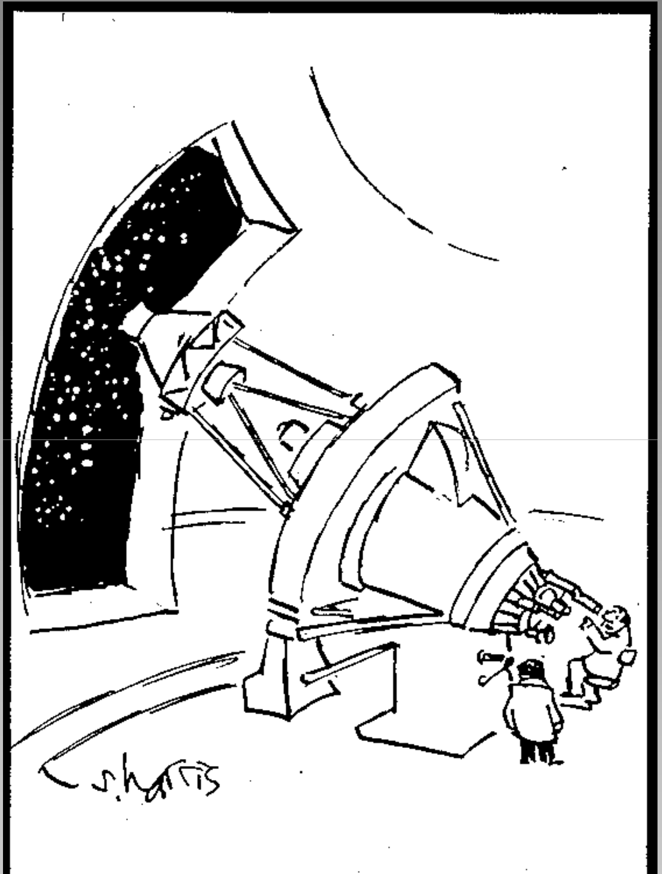




Problems with Objective Prisms

- Low spectral resolution
- Spectra are smeared
- Overlapping objects in a dense field
- Non- linear dispersion
- Generally only for relatively bright objects





"Actually they all look alike to me."

Diffraction Gratings

- Uses the ***wave properties*** of light
- Interference fringes

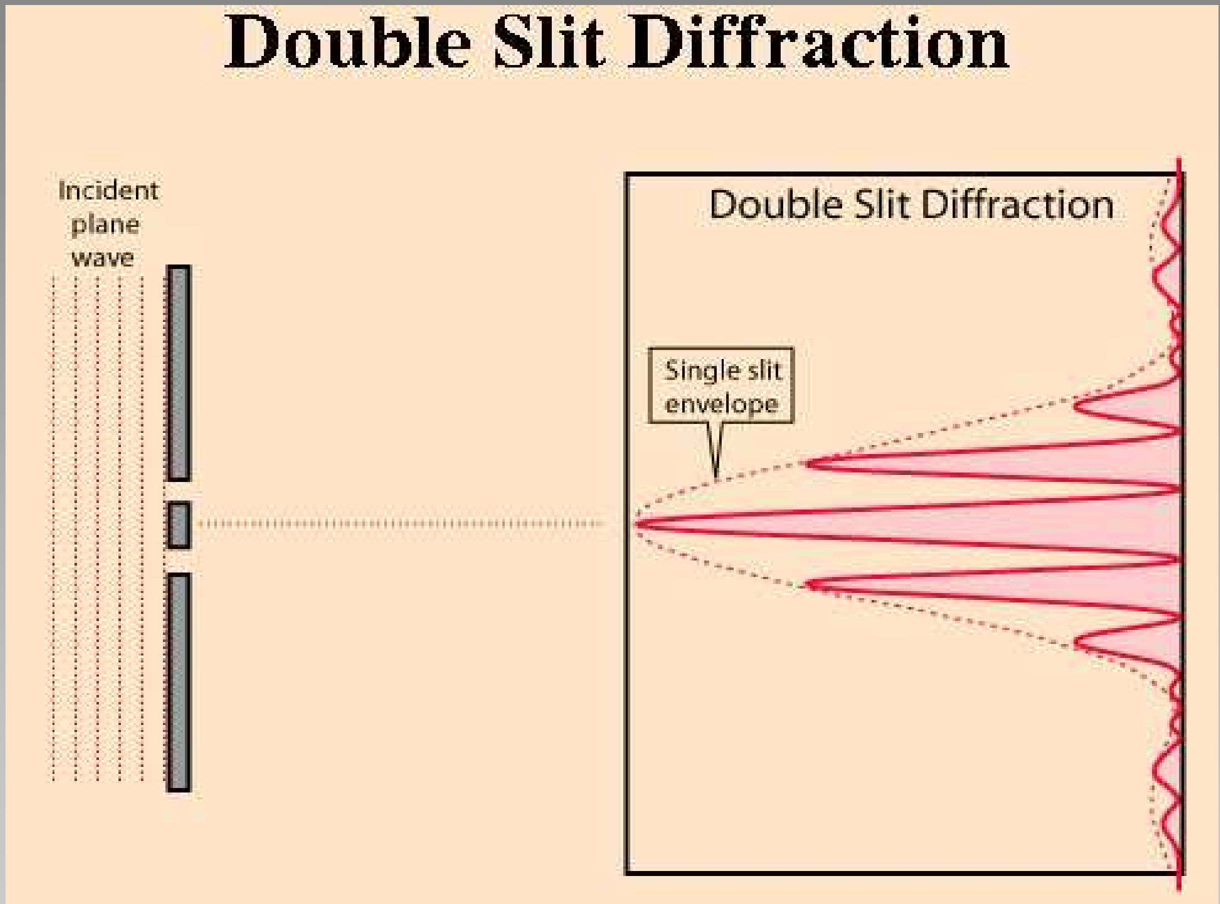
- Interference from ***periodic structures***
  - Equally spaced grooves
  - Either in reflection or transmission

Diffraction Gratings

For constructive interference:

$$m\,\lambda \;\simeq\; d\;sin\,\theta$$

For multiple slits, fringes become narrower



Diffraction Gratings: Grating Equation

- **Constructive interference occurs when the *path difference* between two diffracted waves differs by an *integral* number of wavelength**

$$m\,\lambda = d(\sin\alpha \pm \sin\beta)$$

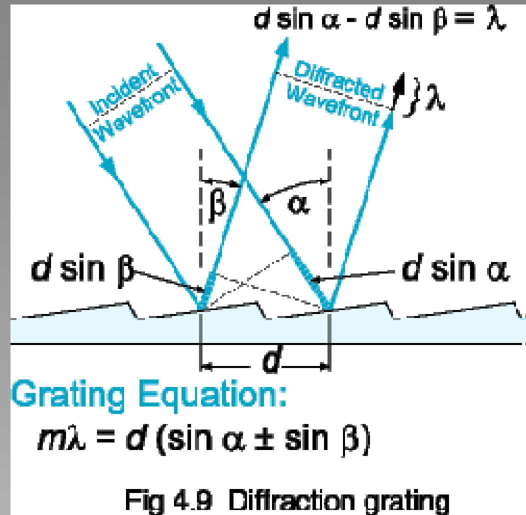


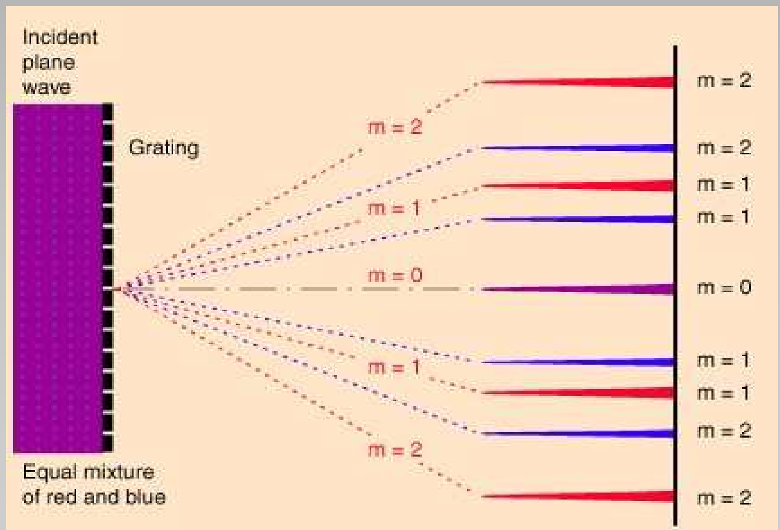
Fig 4.9 Diffraction grating

- **Dispersion given as**

$$\frac{\Delta\beta}{\Delta\lambda} = \frac{m}{d\cos\beta}$$

  - **Proportional to order, *m***
  - **Inversely proportional to spacing, *d* (proportional to line density, *l = 1/d)* *e.g. 300 l/mm grating is lower resolution than 1200 l/mm***

$$m\,\lambda = d(\sin\alpha - \sin\beta)$$

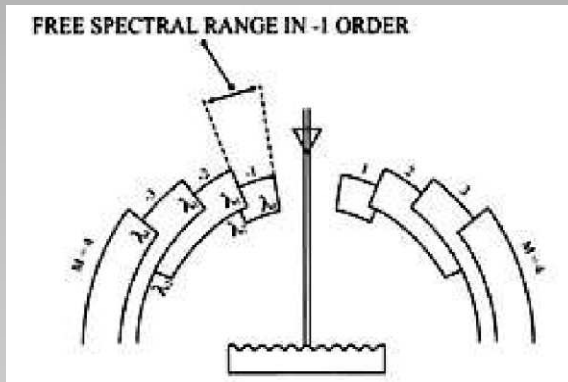


Diffraction Gratings: Free Spectral Range

- For a given ***diffraction angle*** different ***orders*** can overlap, satisfying the condition:

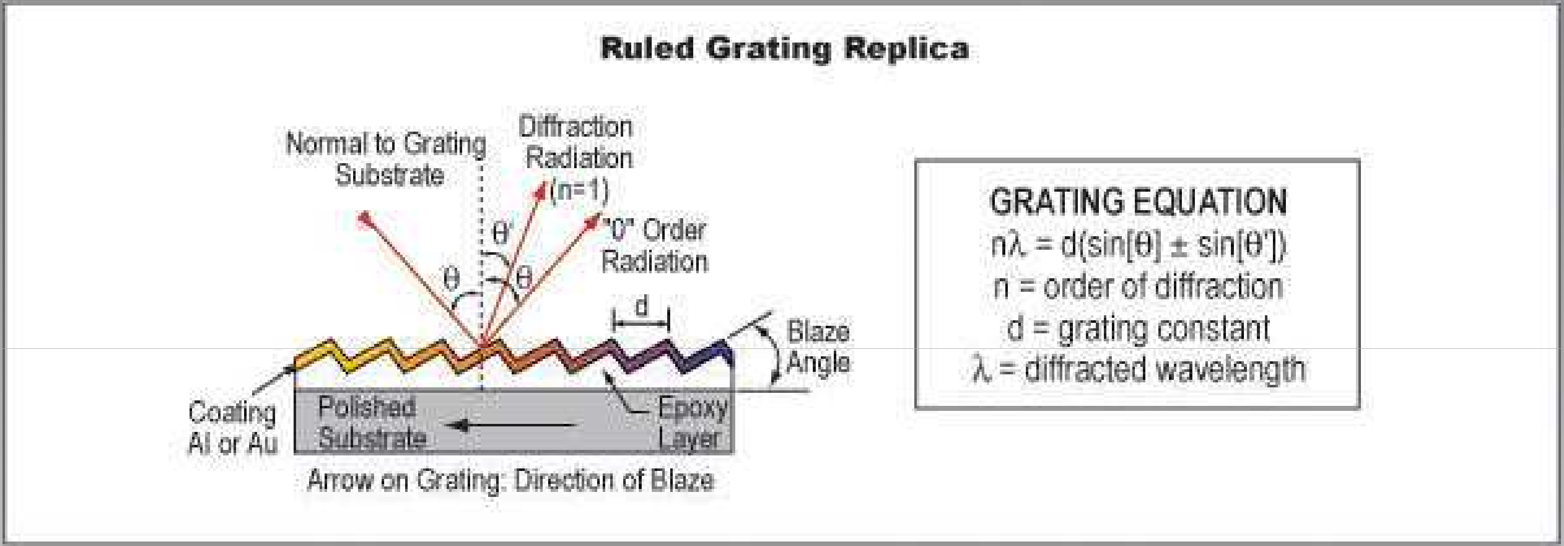
$$m\,\lambda \;=\; 2\,m\,\frac{\lambda}{2} \;=\; 3\,m\,\frac{\lambda}{3}.....$$

- So a first order (m = 1) diffracted wavelength at 800 nm overlaps with the second order (m=2) diffracted wavelength at 400 nm and third order (m=3) diffracted wavelength at 266.7 nm
- Typically we use order separating filters if detectors are sensitive to these higher order diffracted wavelengths
- ***Free Spectral Range*** is that part of a spectrum free of overlapping orders
- More of an issues for gratings designed to work at ***high orders*** (e.g. echelle gratings)



Grating Blaze

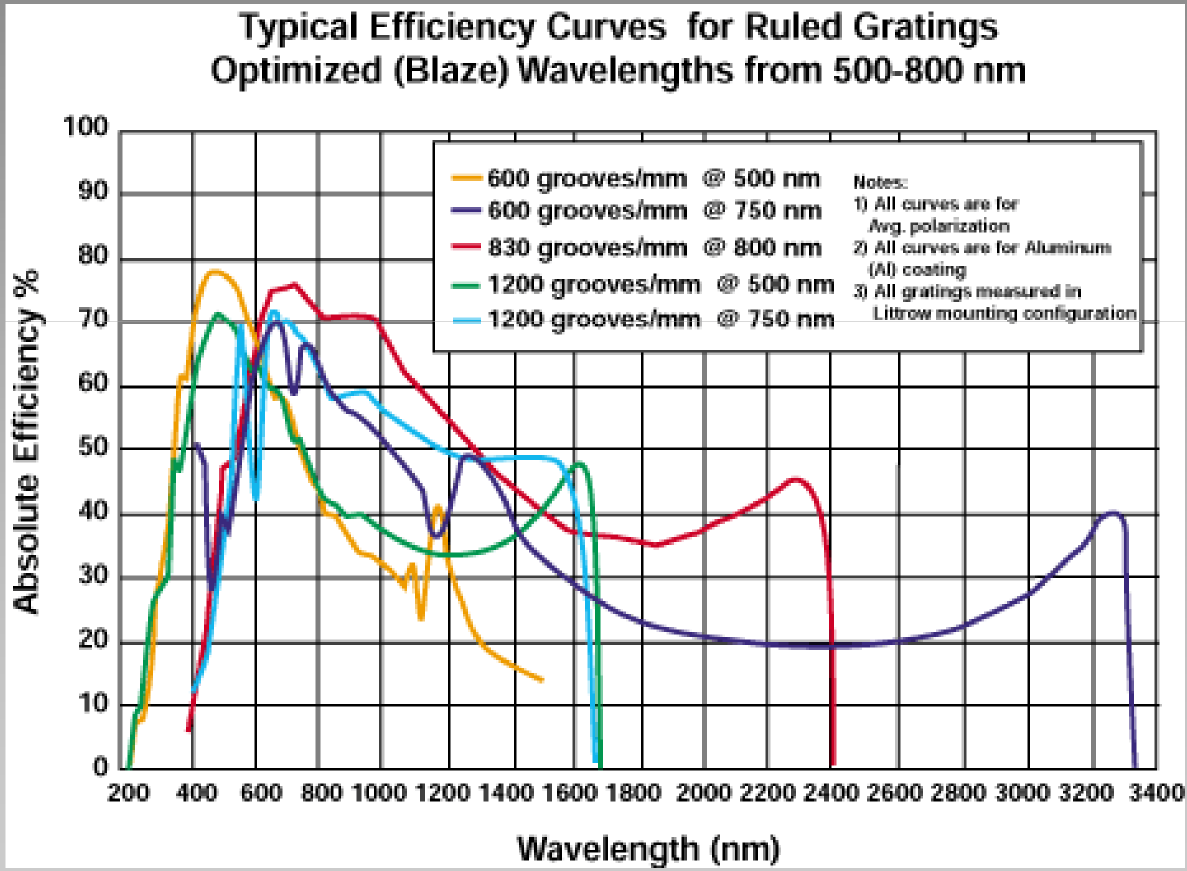
- The tilt angle of the grating ***facets*** with respect to grating surface normal



- Most efficient angle, since diffraction at the blaze angle obeys reflection condition of $i = r$
- Diffraction efficiency drops off moving away from the blaze angle/wavelength

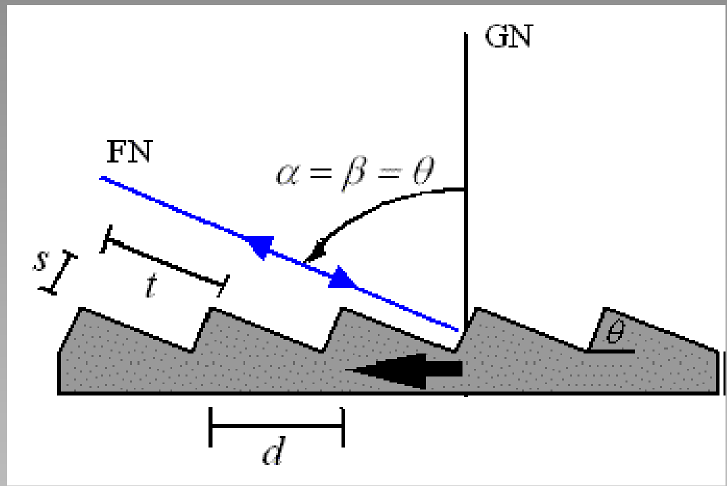
Grating Efficiencies

- **Grating efficiency drops off moving away from blaze wavelength:**



Echelle Gratings

- High resolution gratings avhieved by making the ***blaze condition*** (highest efficiency) satisfied and ***high orders*** (e.g. *m* = 50 – 100)



- High orders overlap, so need to separate them
  - Cross dispersion with another low resolution grating or prism

Echelle Gratings: Cross Dispersion

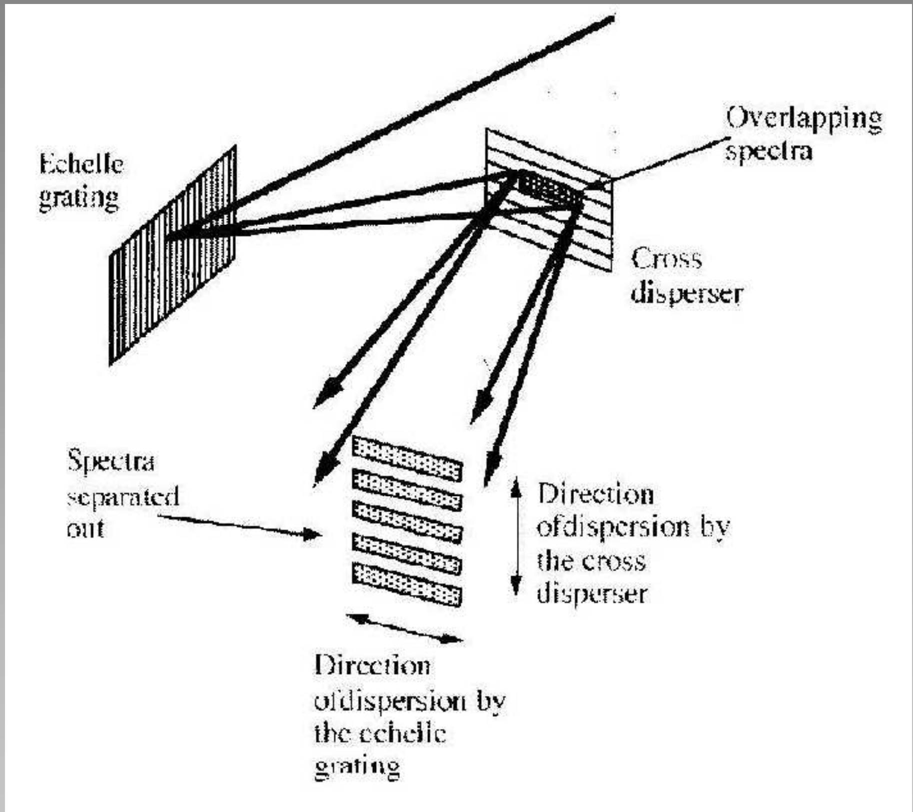
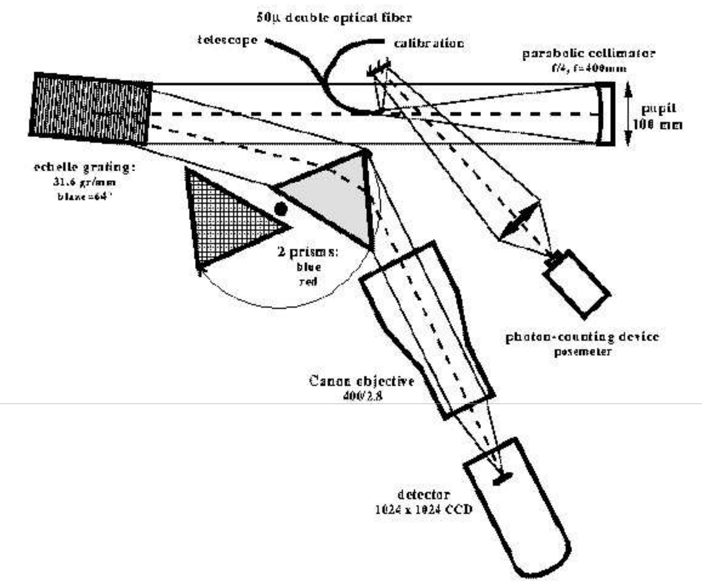


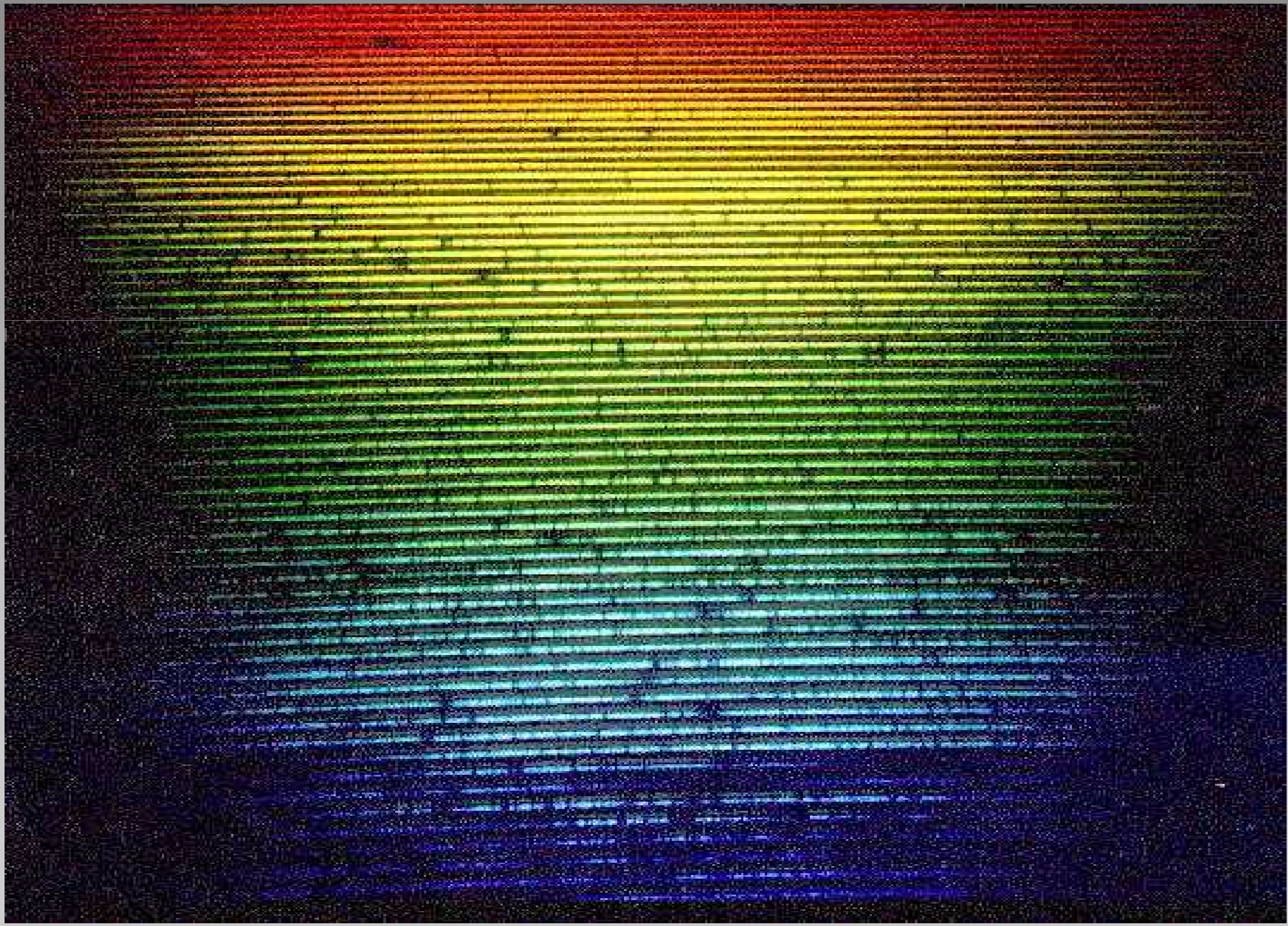
Figure 8.9 Schematic view of an echelle grating and a cross disperser.



GIRAFFE **spectrograph (1.9-m SAAO)**

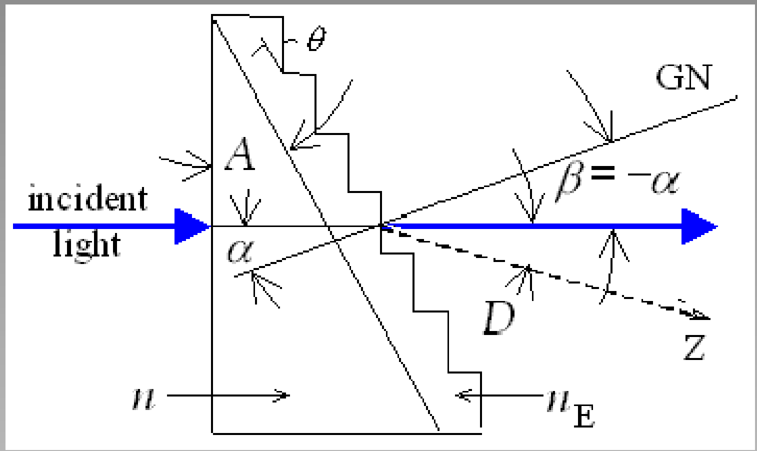
Echelle Gratings

- High resolution echellograms



Grisms

- Uses properties of both ***gratings*** and ***prisms***



- **Useful for high efficiency & low resolution**
- **Can keep the diffracted rays "straight through" (no deviation angle)**

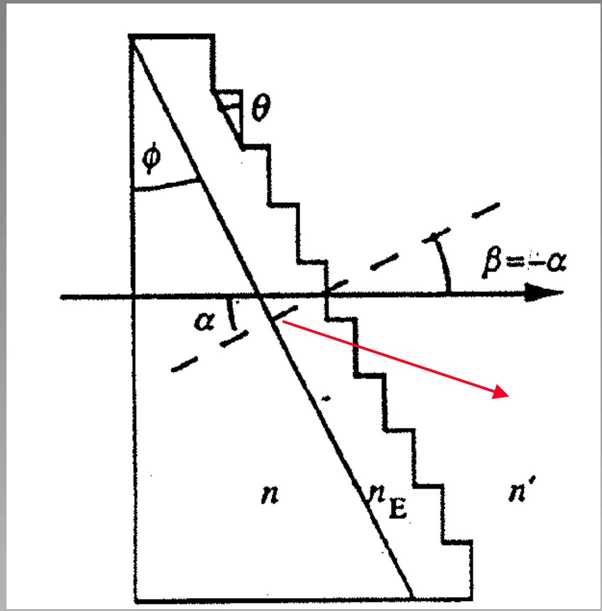
Grisms

- Gratings
  - All things comes from the basic grating equation:

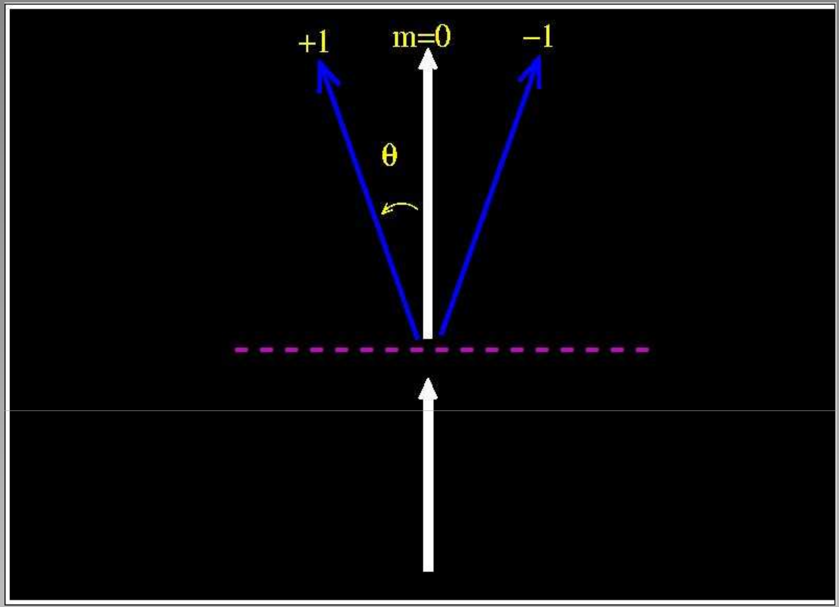
$$m\,\lambda = d(\sin\alpha \pm \sin\beta)$$

- Grisms (combined grating+prism)
  - Blaze angle (facet angle to normal) = incidence angle (*on grating)*
  - Normal incidence on prism face
  - Blaze angle = angle of refraction of prism
  - Resolution given as:

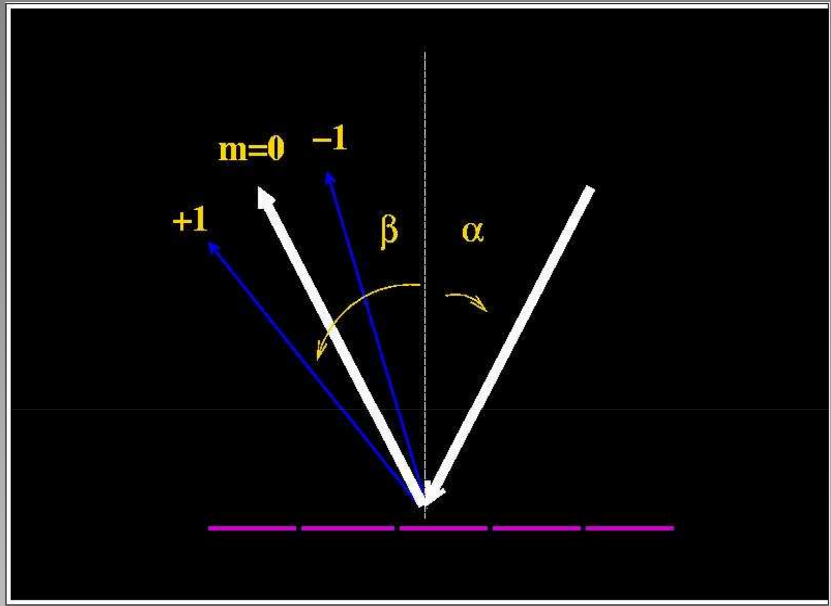
$$R \propto (n-1)\tan\varphi$$



Review of Reflection Gratings



Transmission Grating



Reflection Grating

$$\sin \theta = m \cdot n \cdot \lambda$$

$$\sin \alpha + \sin \beta = m \cdot n \cdot \lambda$$

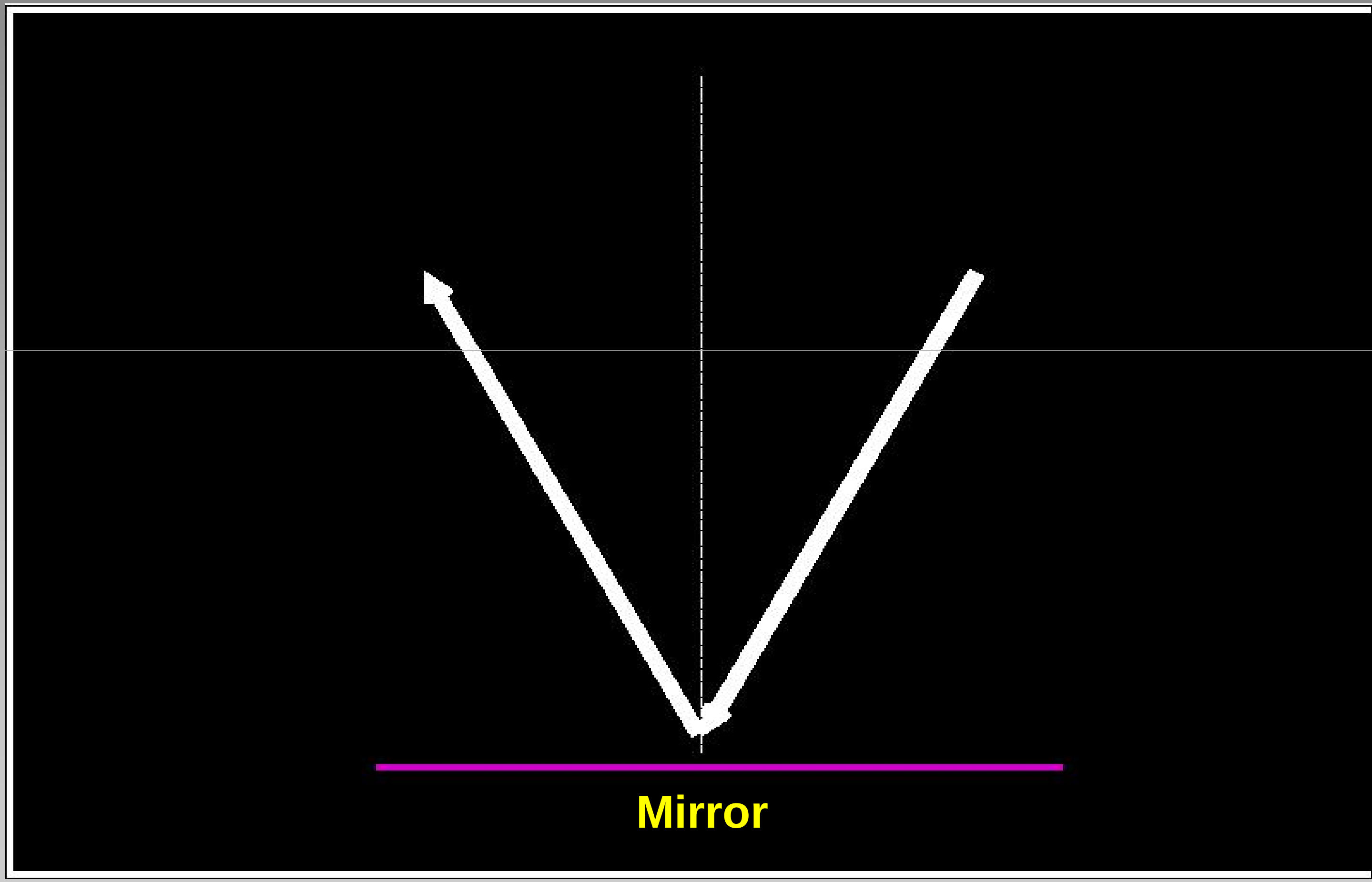
***n* = groove density (grooves or lines / mm)**

***m* = spectral order number (m = 1, 2, 3 …)**

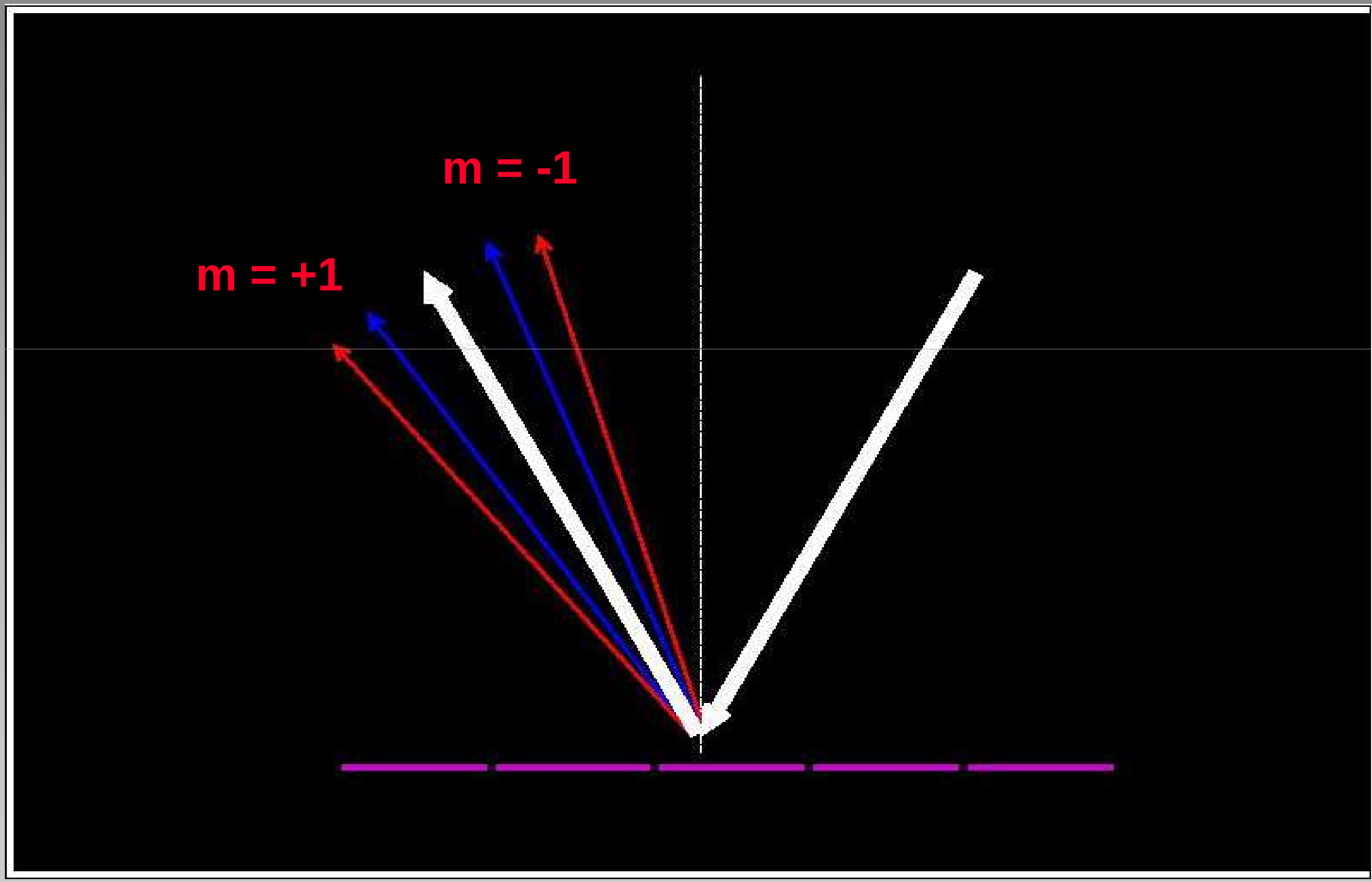
α = angle of incidence (independent of λ)

***B* = angle of diffraction (λ dependent)**

Reflection Gratings

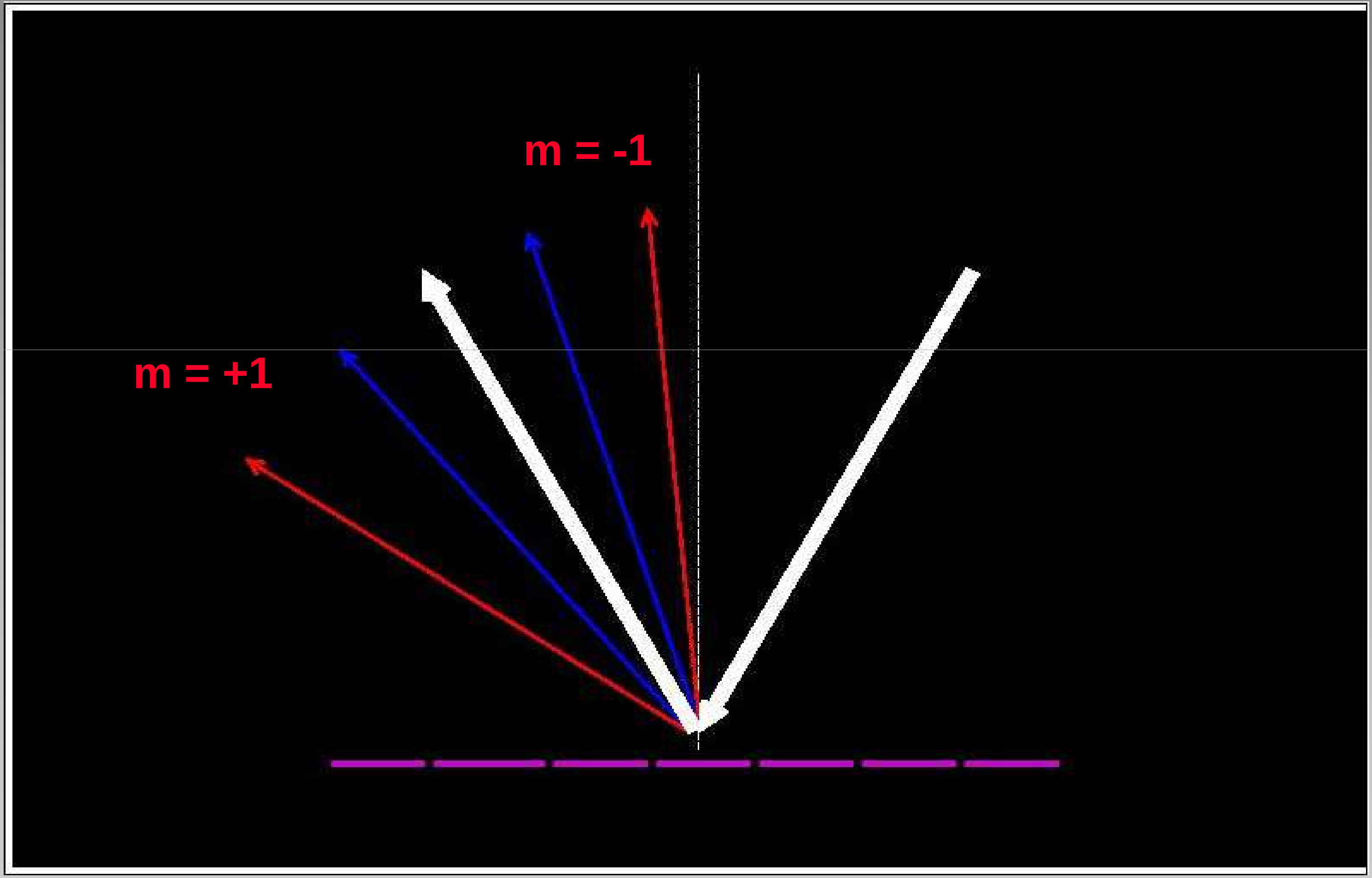


Spectroscopy



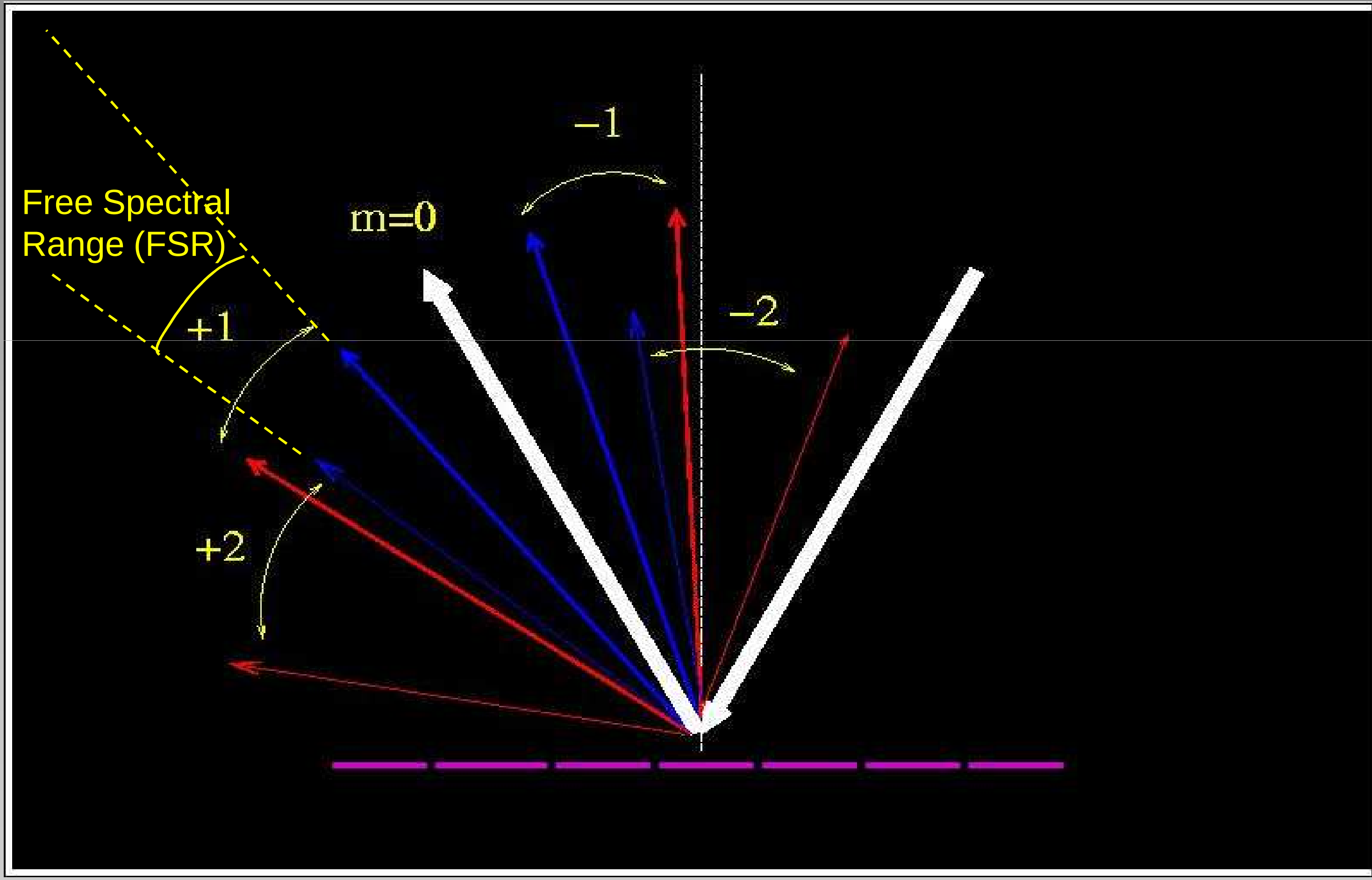
Reflection grating (n=small, *low* dispersion)

Spectroscopy

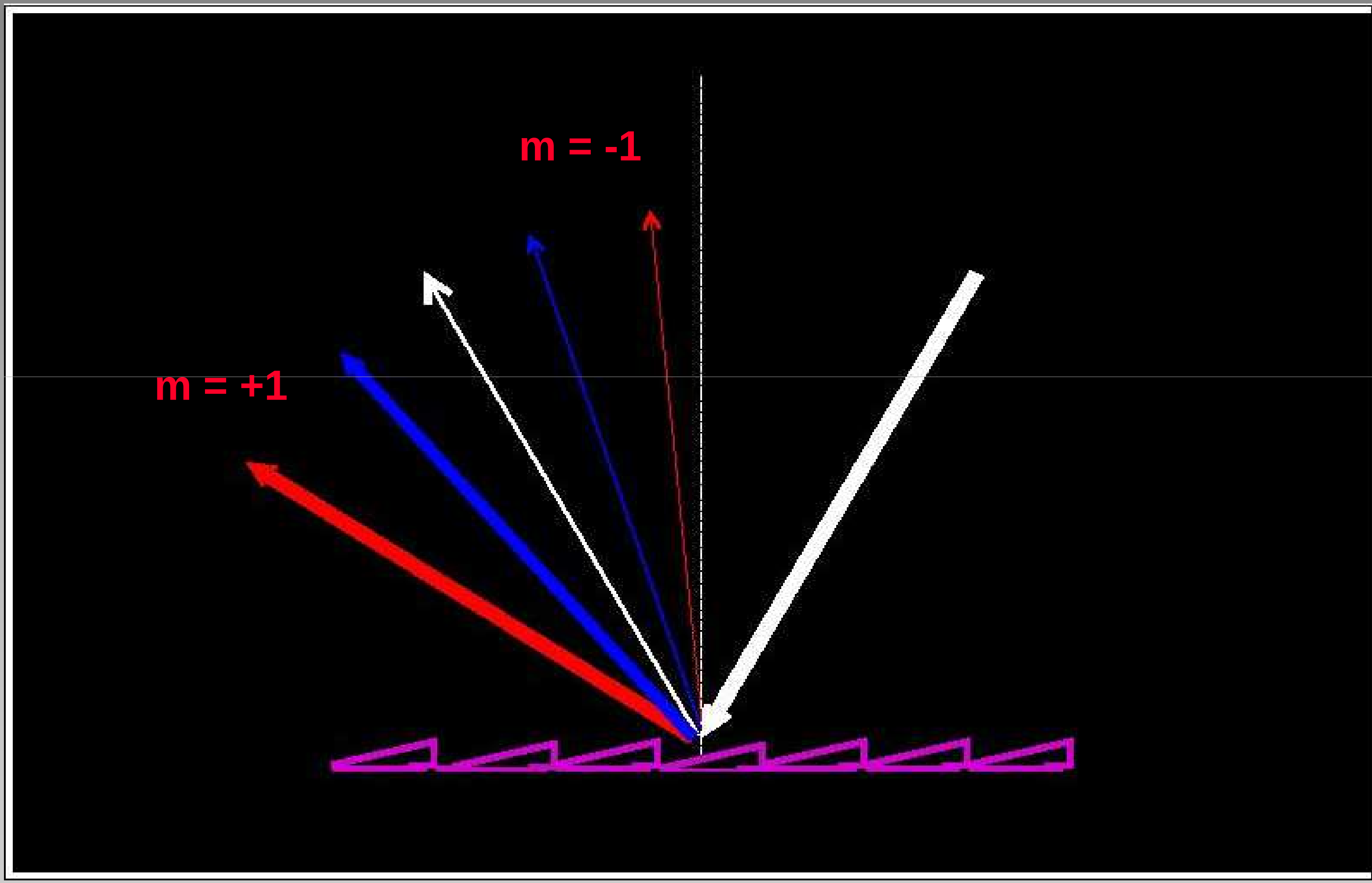


Reflecting grating (n=large, *high* dispersion)

Spectroscopy

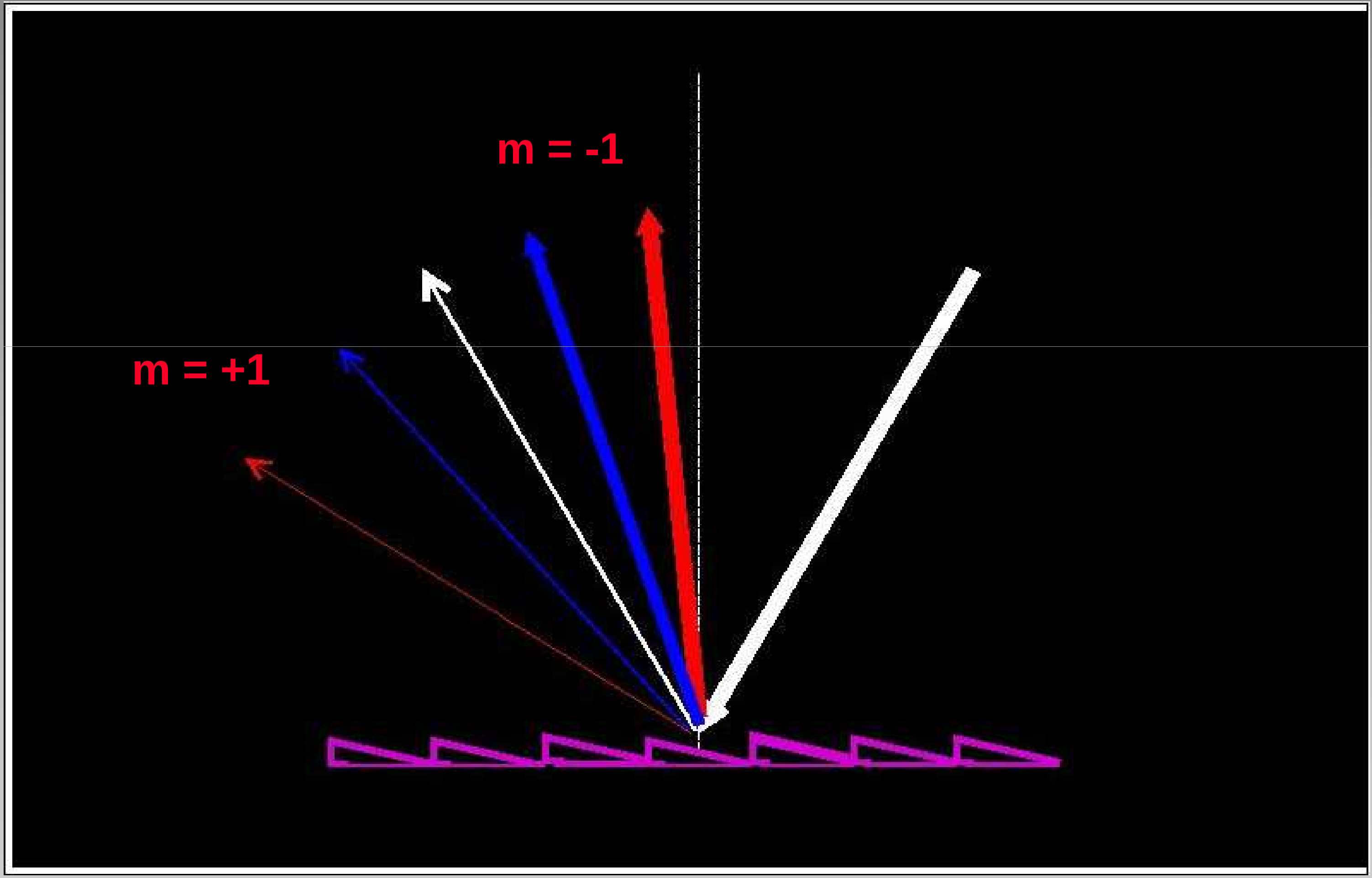


Spectroscopy



Blazed reflection grating (blazed at +1 order red)

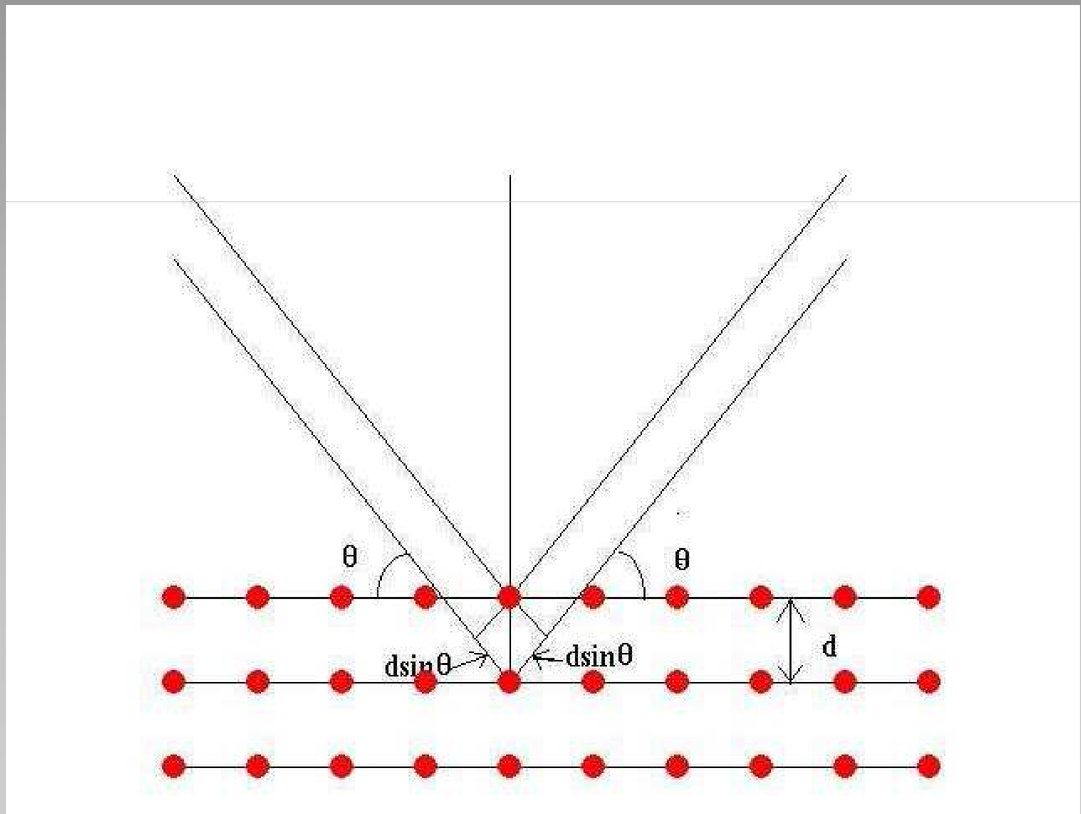
Spectroscopy



Blazed reflecting grating (blazed at -1 order red)

“New” Grating Technology: Volume Phase Holographic Gratings

- **Uses properties of Bragg diffraction in crystals**

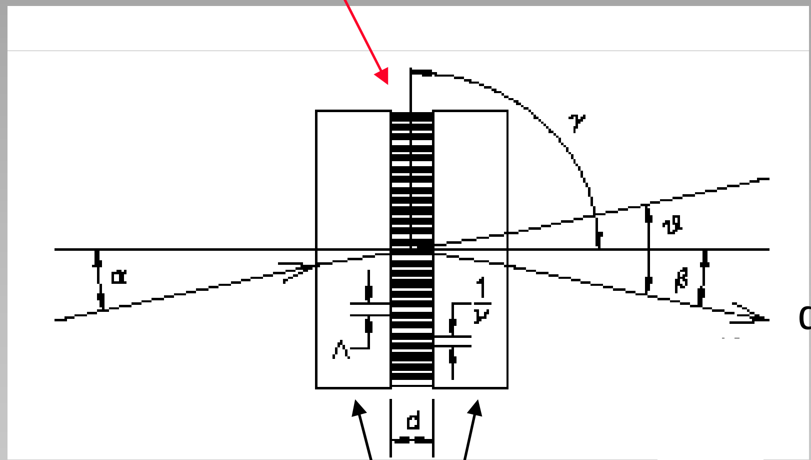


Volume Phase Holographic Gratings

- **Uses a "volume" (depth) of material**
- **Photosensitive material (*dichromated gelatin*) has laser hologram exposed in it**
- **Processing produces *modulation* of refractive index**
- **Diffraction occurs in transmission through material**

Dichromated gelatin layer (exposed to laser hologram)

Incident ray



diffracted ray

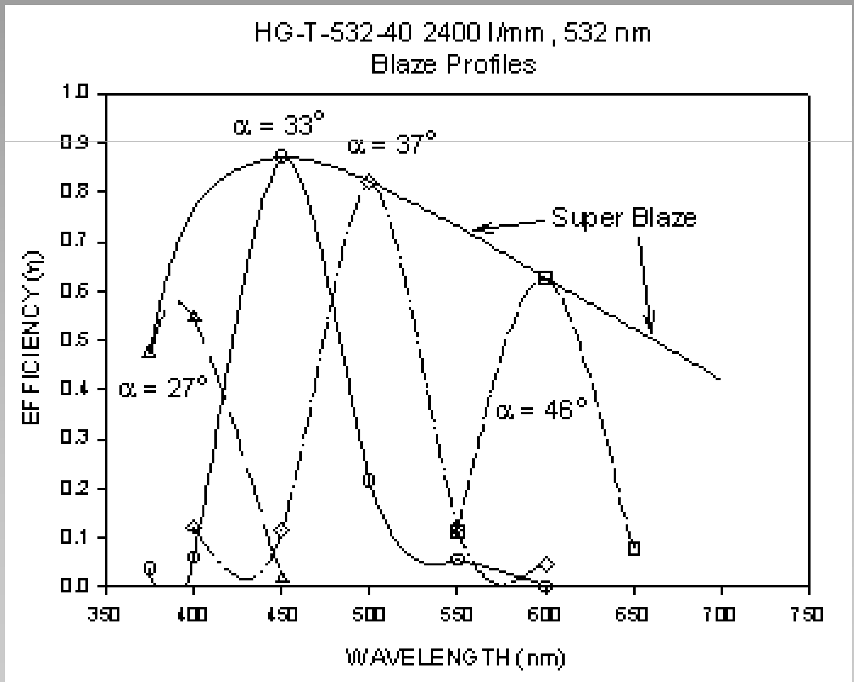
Work at the Bragg condition:
$\alpha = \beta$

Optically flat fused silica
or BK7 glass (can AR coat)

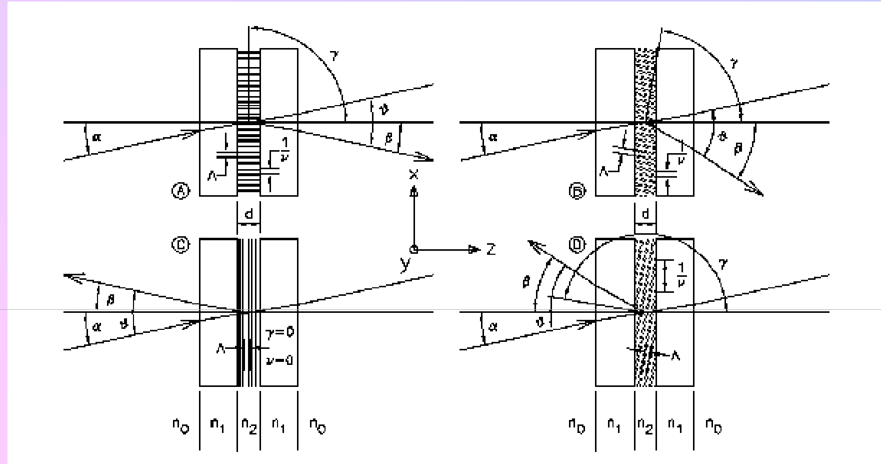
Thickness (d) is > than depth of groove in surface-relief grating.
Implies efficiency profile governed by Bragg diffraction.

Volume Phase Holographic Gratings

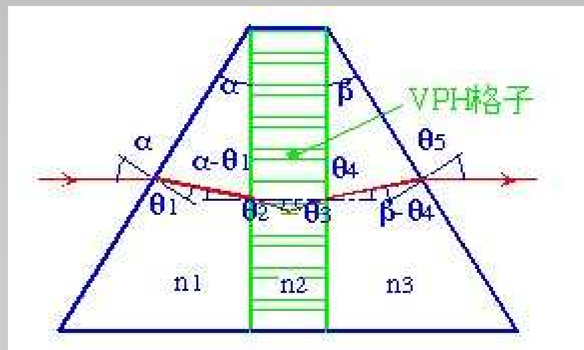
- Wavelength of operation is “tuneable”
- Efficiencies can be very high
- Now used in most modern astronomical spectrographs



VP Grating Configurations



A. Littrow transmission configuration.
B. Non-Littrow transmission configuration.
C. Non-dispersive reflection (notch filter).
D. Reflection grating configuration.



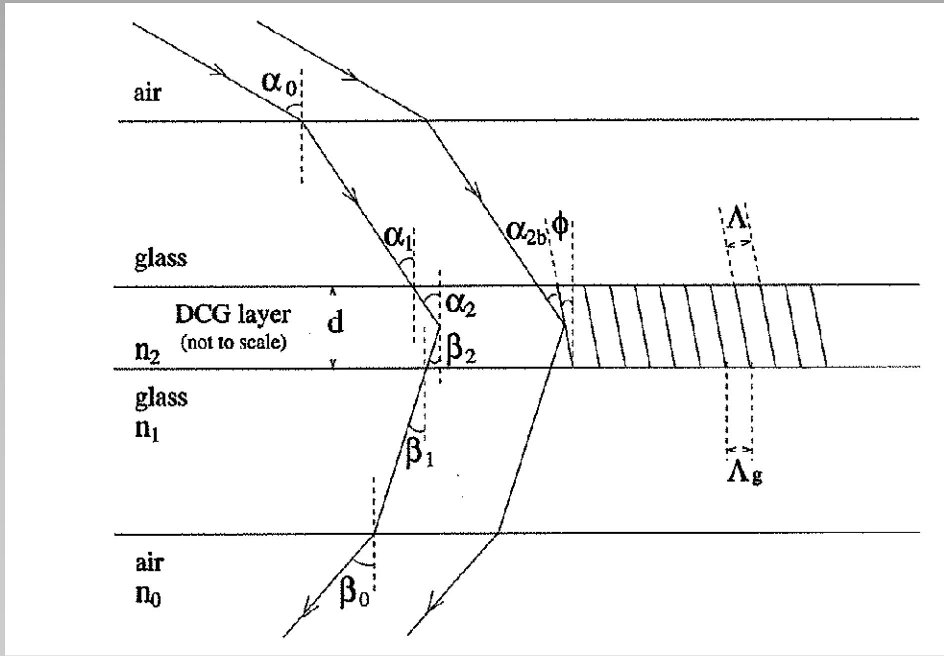
Recap on Dispersers

- **Volume Phase Holographic gratings (VPHGs)**
  - **Diffraction at the Bragg condition ($\alpha = \beta$)**
  - **Grating equation for a VPHG is:**

$$m\lambda = 2n_2\Lambda \sin \alpha_{2b}$$

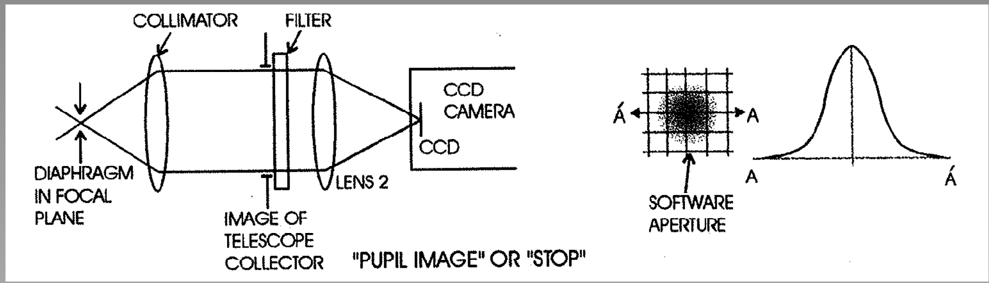
Where Λ= index plane ("groove") density, α_{2b} = Bragg angle w.r.t. index planes, n2 = index of refraction of DCG layer

  - ***Used extensively on the SALT RSS***



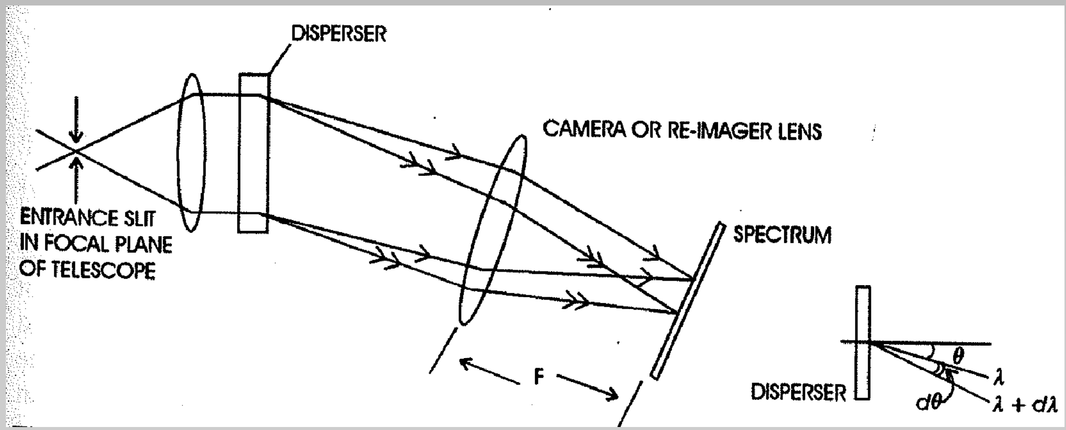
Real Instruments

- **Imaging camera (like SALTICAM, *but not quite)***

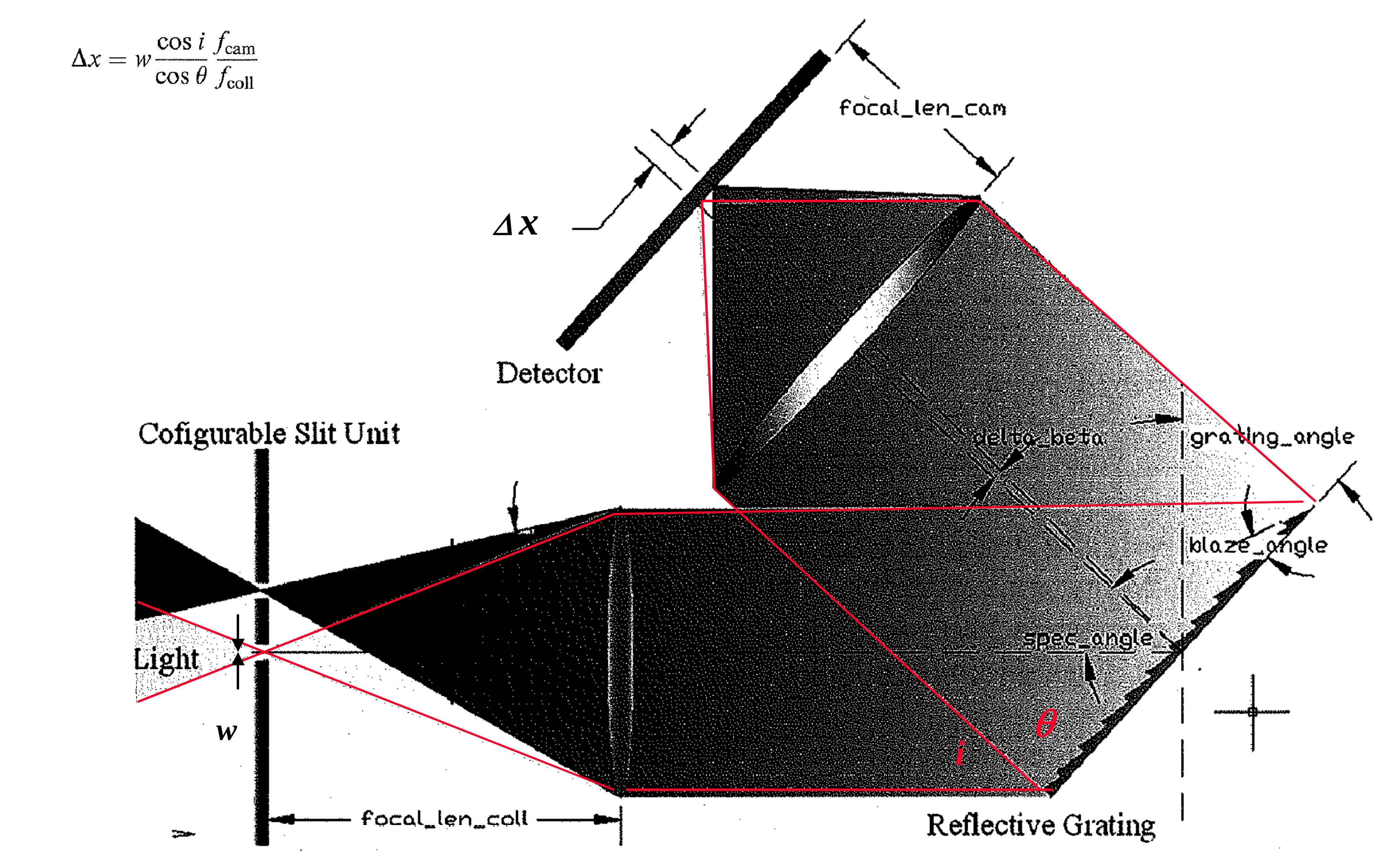


  - SALTICAM does *not* collimate (beam at f/2)
    - » Not so important for ***broad band*** filters
  - RSS imaging mode ***does*** collimate
    - » Much more important for narrow band interference filters

- **Spectrometer**



Generic Grating Spectrograph



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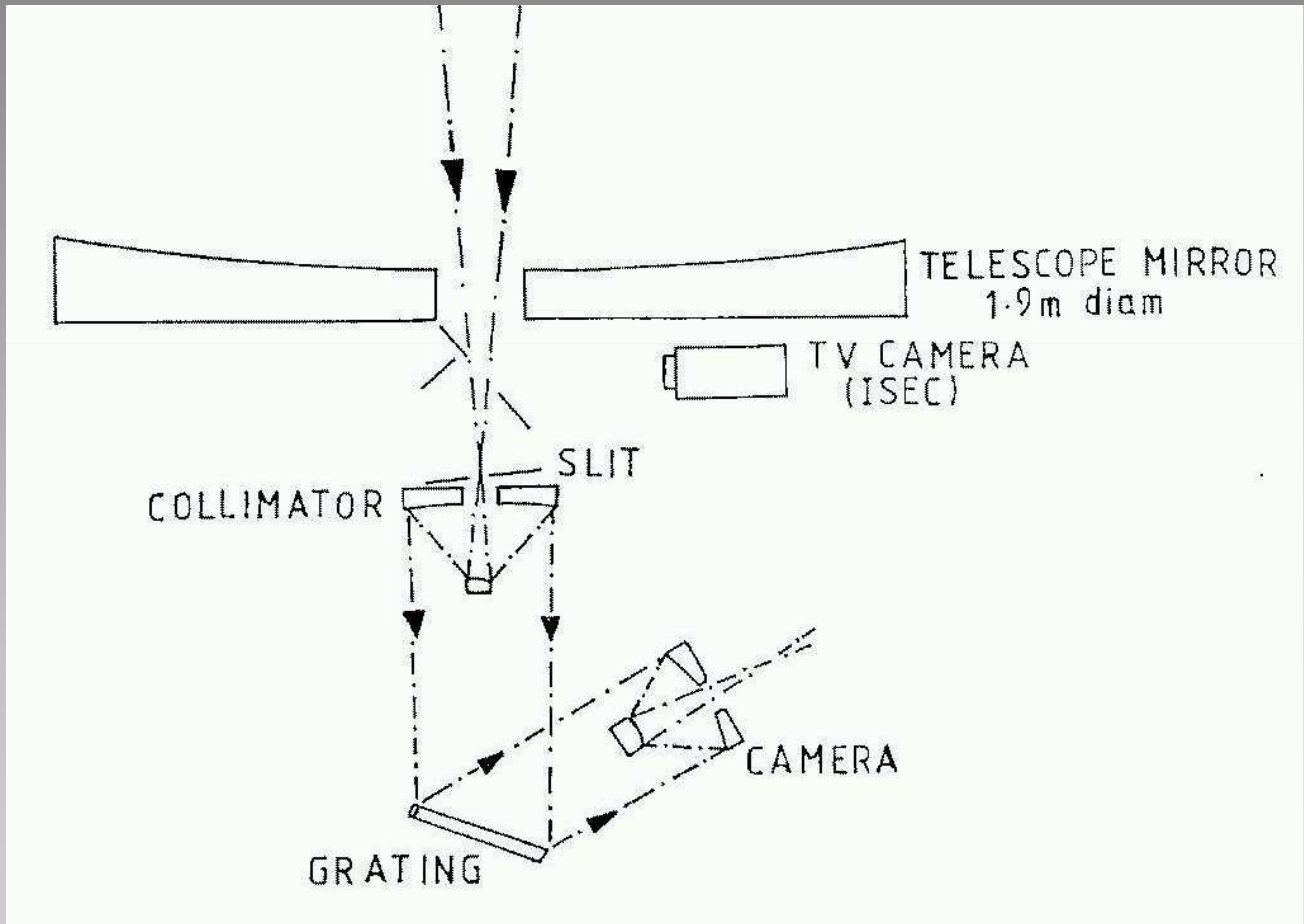
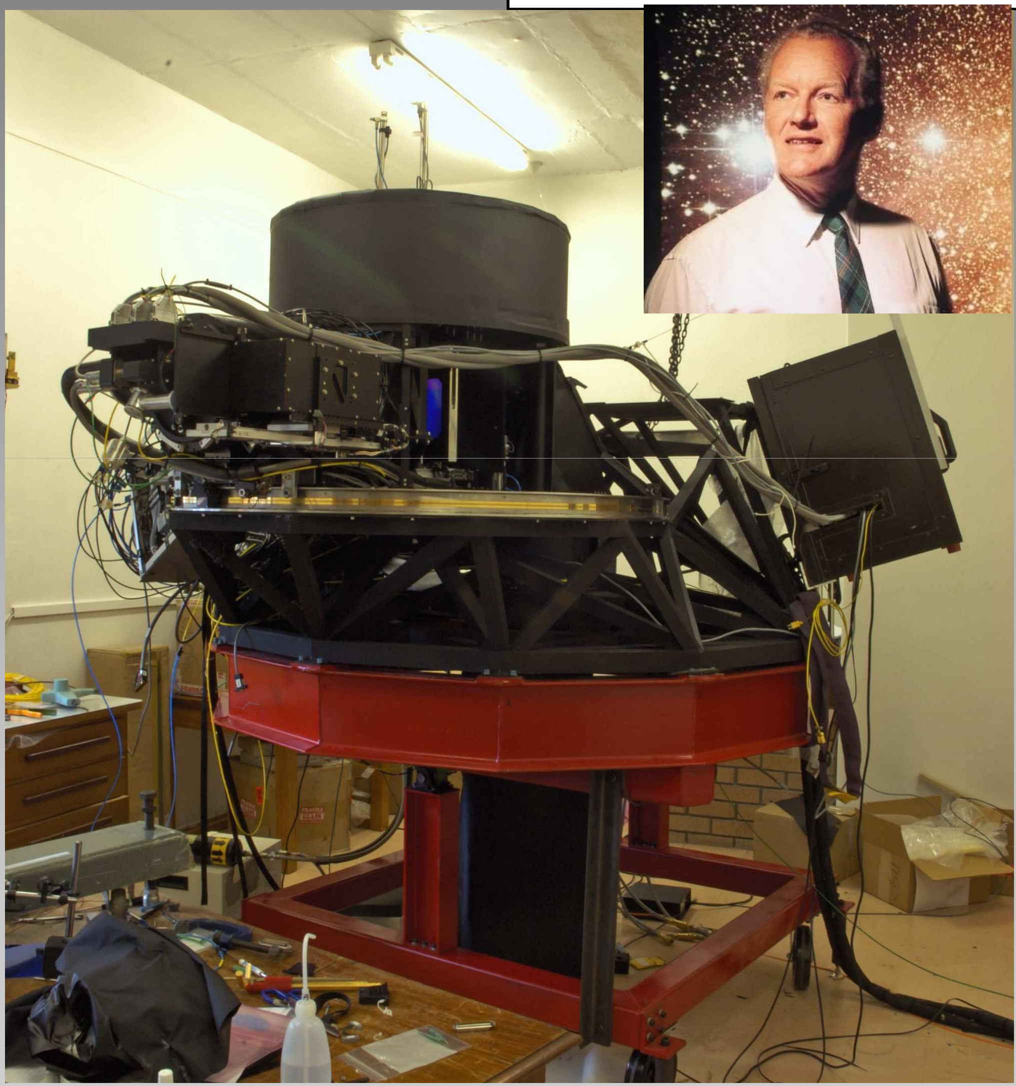
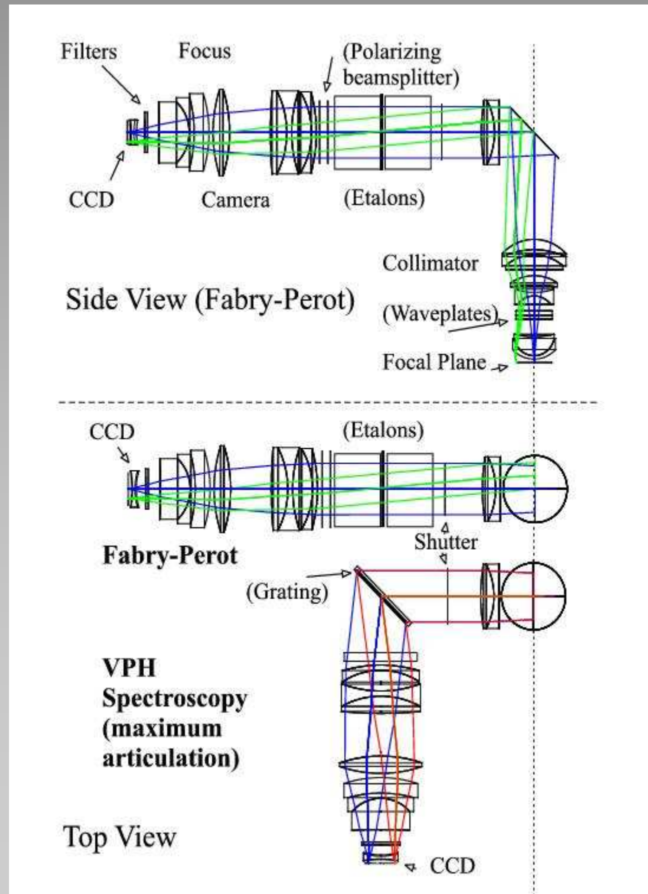
SAAO 1.9-m Cassegrain Spectrograph



RSS: Robert Stobie Spectrograph

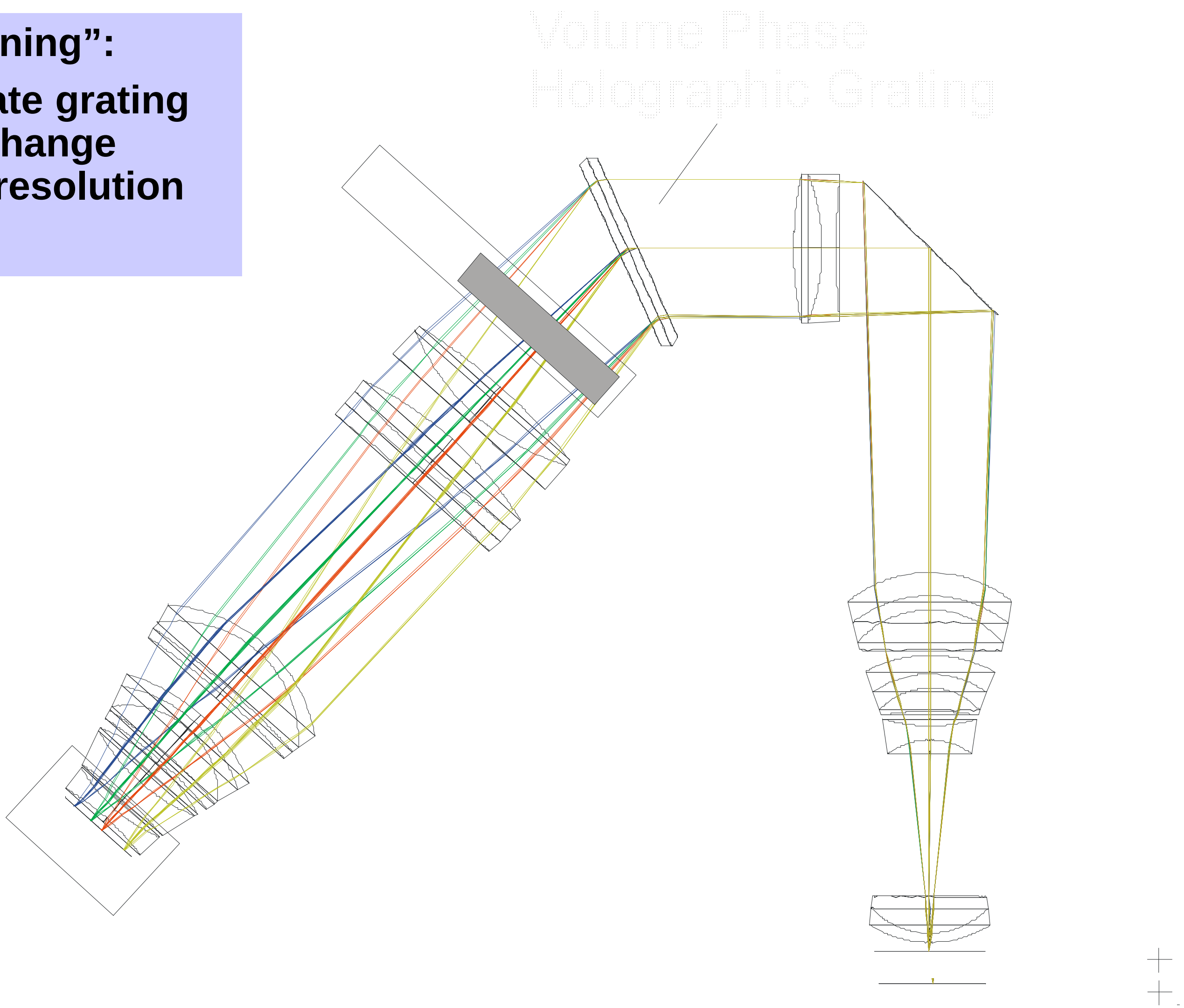


PFIS re-named in memory of Bob Stobie, previous SAAO Director and one of the instigators of SALT and first Chairman of SALT Board.

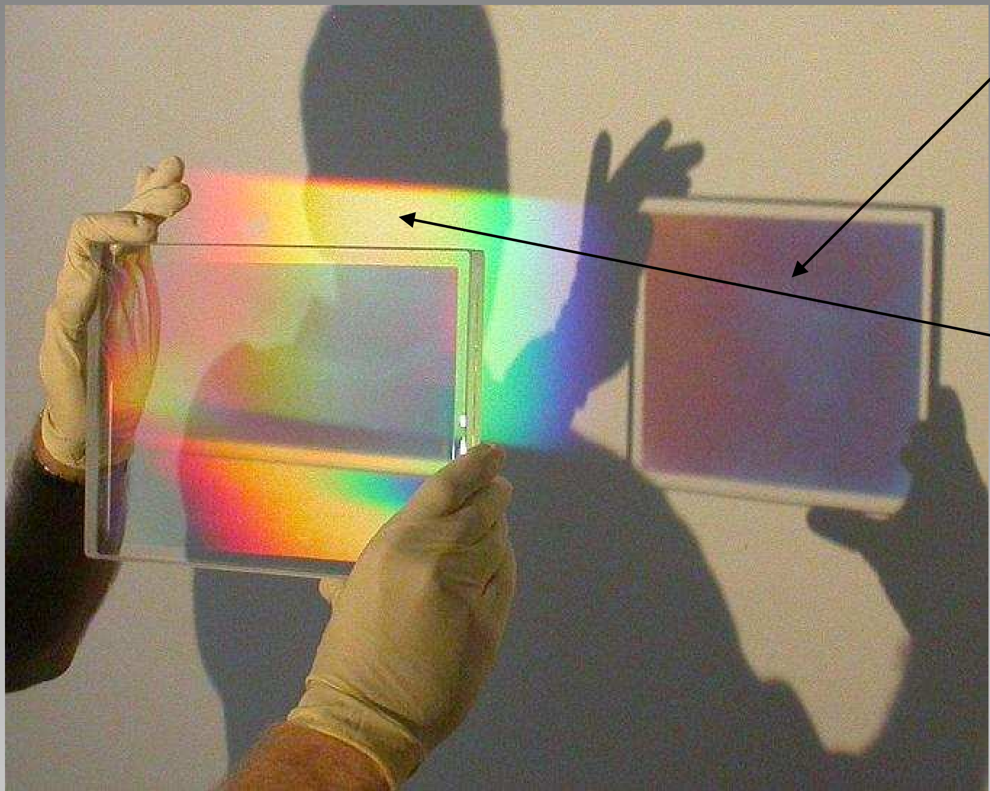


RSS VPHG "tuning":

Articulate (rotate grating & camera) to change wavelength & resolution



Example of an RSS VPHG



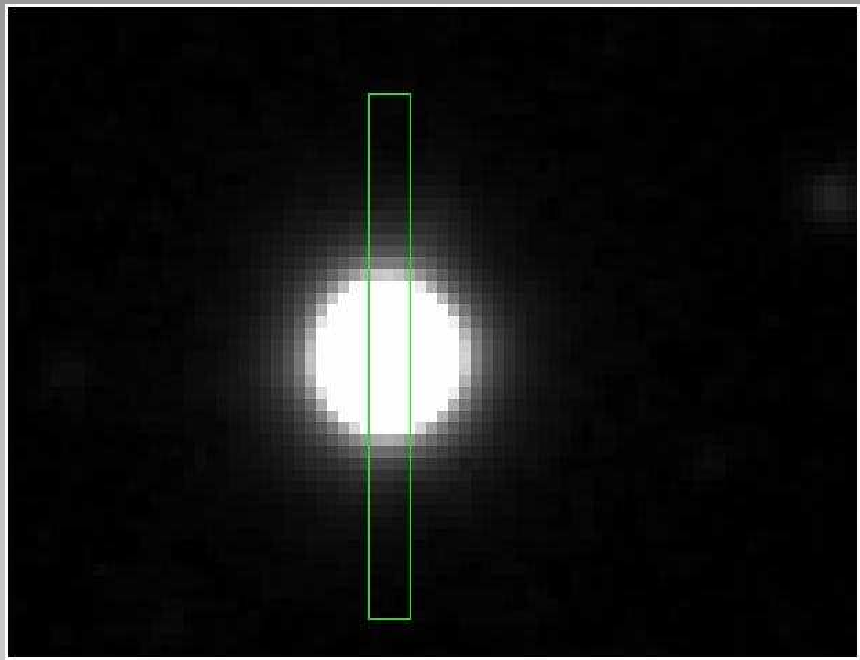
Note the dark shadow: implies little zero order throughput.

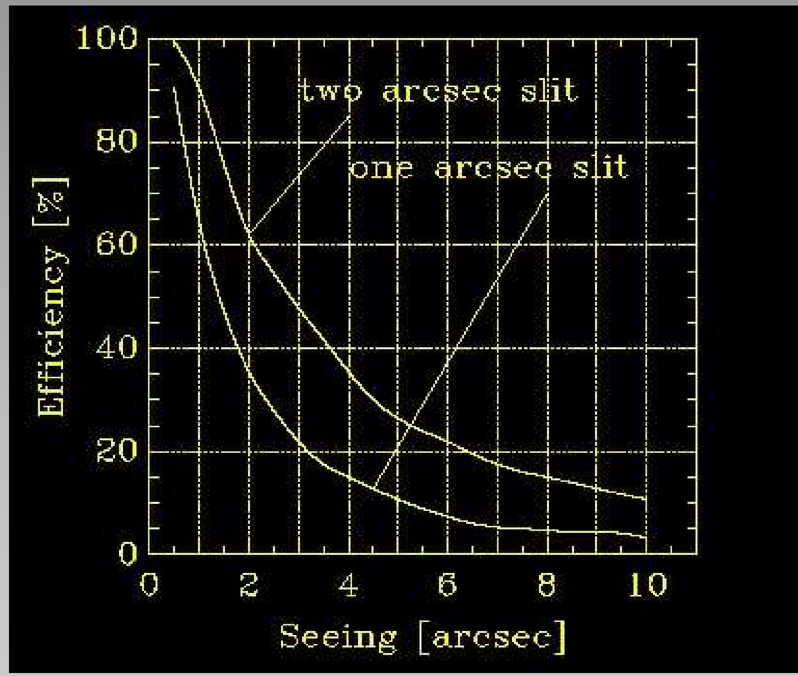
Most of the light is diffracted into the first order

1300 gr/ mm VPH

Effect of bad focus and seeing in Spectroscopy

Slit width/ Slit loss





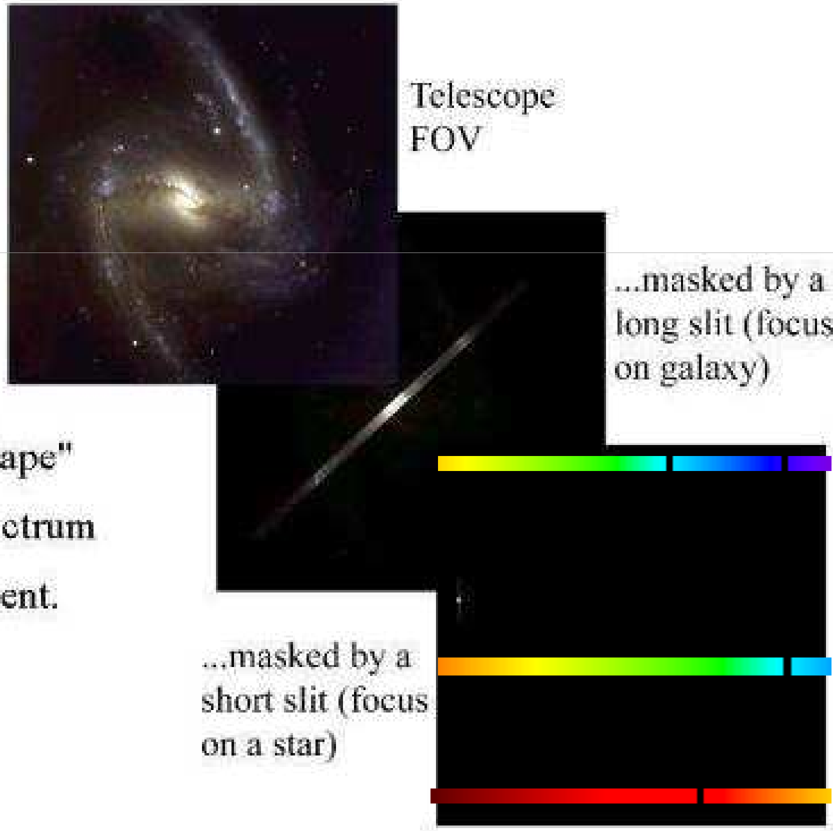
$$\Delta x = w \frac{\cos i}{\cos \theta} \frac{f_{\mathrm{cam}}}{f_{\mathrm{coll}}}$$

The Spectrograph Slit

The Entrance slit

- Selects light from a particular object in the telescope's focal plane.

- Helps to give good "shape" and resolution to the spectrum produced by the instrument.



Signal to Noise

S/N for object measured in aperture with radius r: n_{pix}=# of pixels in the aperture= πr^2

Signal ↔

$$\frac{R_* t}{\left[R_* \cdot t + R_{sky} \cdot t \cdot n_{pix} + \left(RN + \frac{gain}{2}\right)^2 \cdot n_{pix} + Dark \cdot t \cdot n_{pix}\right]^{\frac{1}{2}}}$$

Noise ↔

$\sqrt{(R_* \cdot t)^2}$

Noise from sky e- in aperture

Readnoise in aperture

Noise from the dark current in aperture

All the noise terms added in quadrature

Note: always calculate in e-

Signal to Noise in mags

Side Issue: S/N ⇔ δmag

$$m \pm \delta(m) = c_o - 2.5\log(S \pm N)$$
$$= c_o - 2.5\log\left[S\left(1 \pm \tfrac{N}{S}\right)\right]$$
$$= \underbrace{c_o - 2.5\log(S)}_{\mathrm{m}} \underbrace{- 2.5\log(1 \pm \tfrac{N}{S})}_{\delta\mathrm{m}}$$

$$\delta(m) \approx 2.5\log(1 + \tfrac{1}{S/N})$$
$$= \frac{2.5}{2.3}\left[\tfrac{N}{S} - \tfrac{1}{2}(\tfrac{N}{S})^2 + \tfrac{1}{3}(\tfrac{N}{S})^3 - \ldots\right]$$
$$\approx 1.087(\tfrac{N}{S})$$

Note:in log +/- not symmetric

Fractional error

This is the basis of people referring to +/- 0.02mag error as "2%"

S/N	δmag
2	0.44
10	0.10
100	0.01

Signal to Noise

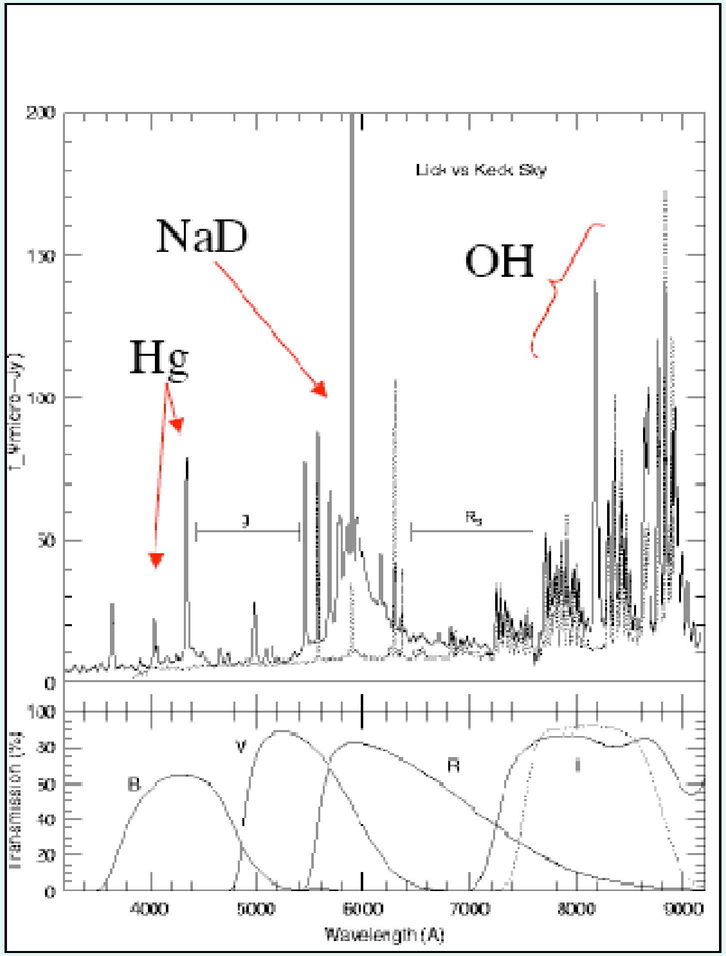
S/N Calculations

- **So, what do you do with this?**

  – Demonstrate feasibility
  – Justify observing time requests
  – Get your observations right
  – Estimate limiting magnitudes
  – Discover problems with instruments, telescopes or observations

- **So, how do you calculate it?**
  – Could use the S/N formula
  need to know which regime you're operating in
  need to know the various parameter (pixel scale, gain, RN, Dark count, etc.)
  – Usually there are simple tools available to calculate all of this for you!

Sky Background



R_{sky}

Signal from the sky background is present in every pixel of the aperture. Because each instrument generally has a different pixel scale, the sky brightness is usually tabulated for a site in units of mag/arcsecond^2.

(mag/□)

Lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

Two most common cases

S/N - some limiting cases. Let's assume CCD with Dark=0, well sampled read noise.

$$\frac{R_* t}{\left[R_* \cdot t + R_{\text{sky}} \cdot t \cdot n_{\text{pix}} + (RN)^2 \cdot n_{pix}\right]^{\frac{1}{2}}}$$

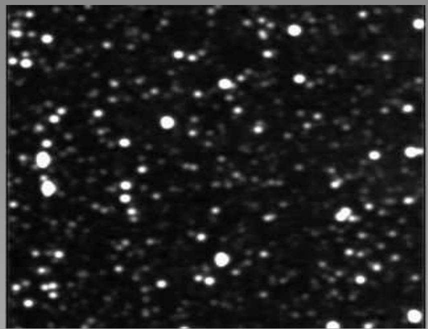
Bright Sources: $(R_* t)^{1/2}$ dominates noise term

$$S/N \approx \frac{R_* t}{\sqrt{R_* t}} = \sqrt{R_* t} \propto t^{\frac{1}{2}}$$

Sky Limited $(\sqrt{R_{sky} t} > 3 \times RN)$: $S/N \propto \frac{R_* t}{\sqrt{n_{pix} R_{sky} t}} \propto \sqrt{t}$

Note: seeing comes in with n_{pix} term

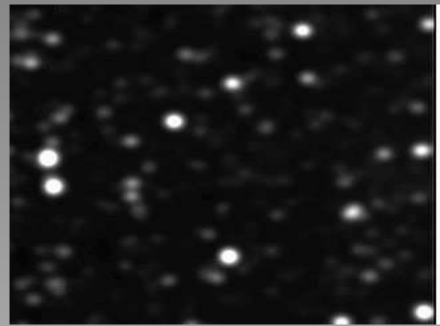
Effect of bad focus and seeing in Spectroscopy



Good seeing

Signal-to-Noise for typical SALT case

$$\frac{S}{N} = \frac{O}{\sqrt{(O+B)}}$$



Bad seeing:
n times bigger seeing psf

Bright object: **not so affected**

$$\frac{S}{N} \approx \frac{O}{\sqrt{O}} \quad \sim \quad \frac{S}{N} \approx \frac{O}{\sqrt{O}}$$

Faint object [Background (sky) dominating]: **badly affected**

$$\frac{S}{N} \approx \frac{O}{\sqrt{B}} \quad > \quad \frac{S}{N} \approx \frac{O}{\sqrt{Bn^2}} = \frac{O}{\sqrt{B}}\frac{1}{n}$$

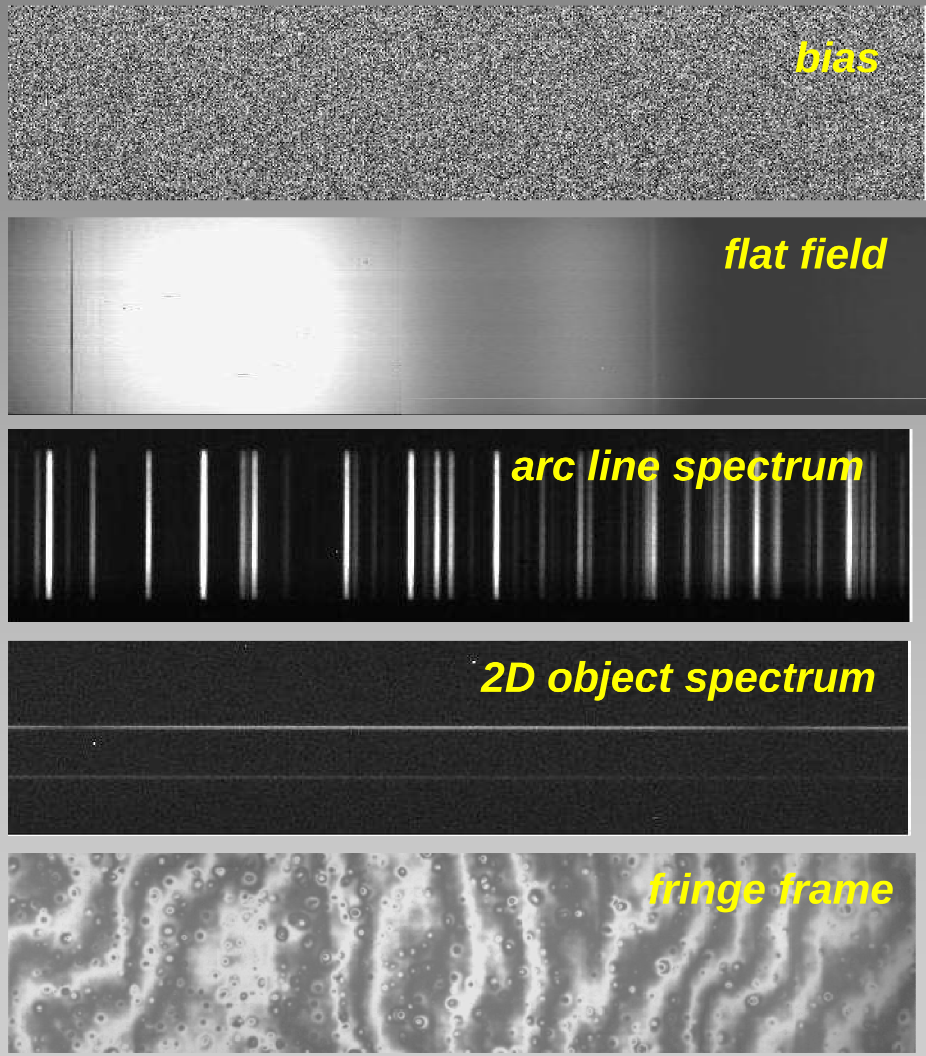
Reducing Spectroscopic Data

<u>Calibration frames:</u>

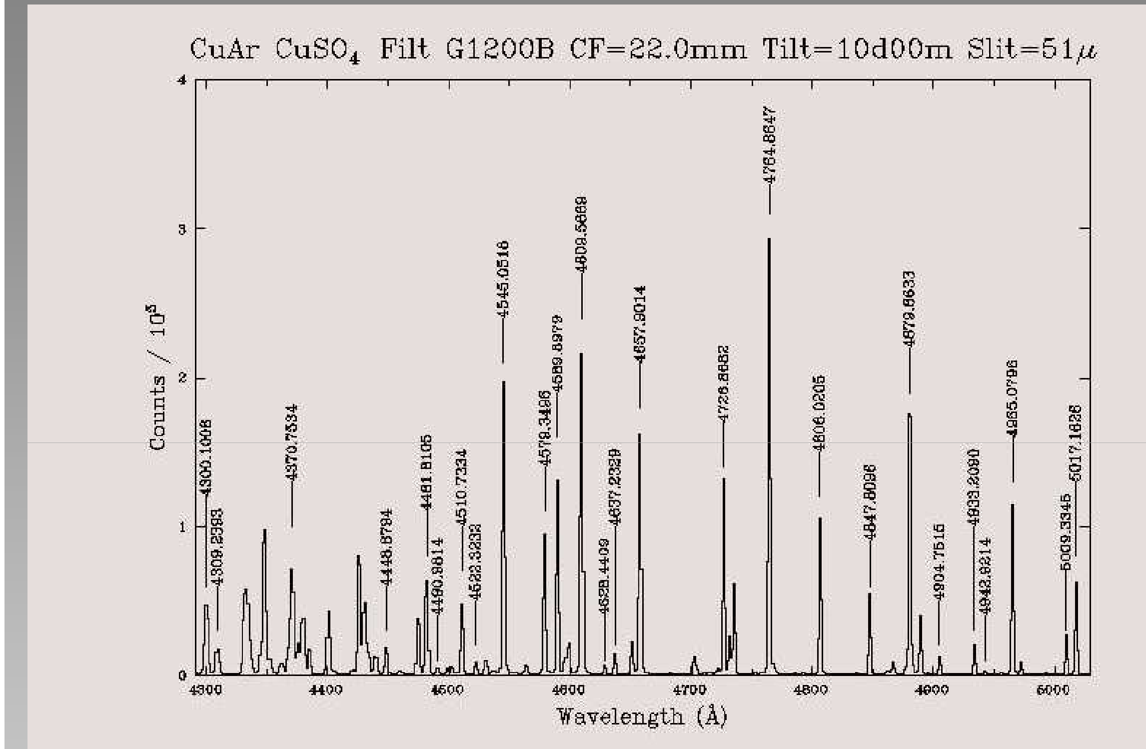
* **Bias frame (electronic DC level)**
  - **sometimes derived from "overscan" or "prescan"**
* **Flat field (detector sensitivity)**
* **Arc Lamp (wavelength calibration)**
* **Flux Standard**
  - **flux from** *electrons* cm^{-2} sec^{-1} $Å^{-1}$ **to** *ergs*/cm^{-2} sec^{-1} $Å^{-1}$
* **Fringe frame correction**

<u>Basic reduction procedures:</u>

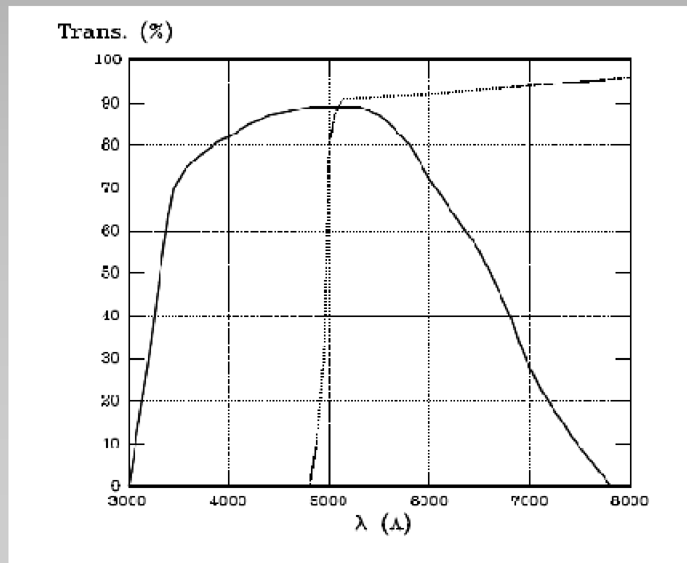
1. Bias correction
2. Flat fielding
3. Cosmic ray removal
4. Wavelength determination
5. Background subtraction
6. Spectrum extraction
7. Flux calibration (remove atm. effects)



Wavelength Calibrations



- Determine ***wavelength*** as a function of ***pixel number*** on the detector
- Typically use 3rd order polynomial fit to known wavelengths
- Need to have ***order blocking*** filters to exclude 2nd order overlap in the 1st order, 3rd in 2nd, etc.



Spectroscopy