1. Optical Spectroscope

- Prism spectroscopy
- Diffraction/Reflection grating
- Echelle Gratings

Vocabulary

- Spectral resolution, Resolving Power $R = \lambda/\Delta\lambda$
  - λ is the wavelength and $\Delta\lambda$ is the smallest wavelength interval that can be resolved. In general,
  - "low" resolution $10<R<1{,}000$
  - "moderate" resolution $1{,}000<R<10{,}000$
  - "high" resolution $R>10{,}000$

2. Refraction and Prisms

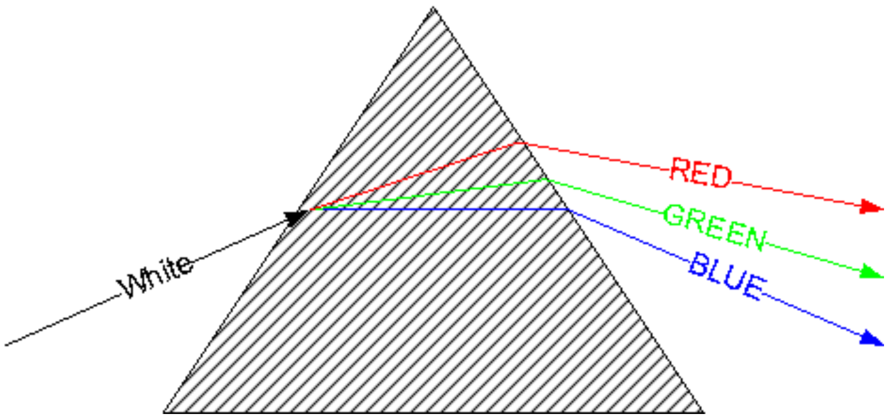
- The speed of light in a dense medium (air, glass…) is (usually) slower than in a vacuum.

- Refraction index (ratio of speed of light in a vacuum to the speed in the medium)
  - air: $n = 1.0003$
  - water: $n= 1.33$
  - salt: $n= 1.53$

- The speed of light in a material depends on wavelength – "dispersion"

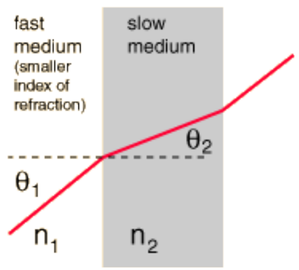
2. Refraction and Prisms

- Prisms disperse light by refraction.
- When a beam of white light passes from one medium into another at an angle, the direction of the beam changes due to refraction.
- Different colors of light are bent at different angles.
- Generally, red light is bent less, blue light is bent more.



Snell's Law

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



2-1. Dispersion by a Prism

- For the most optical glass, n is proportional to the inverse square of λ (so-called, Cauchy's equation), that is,

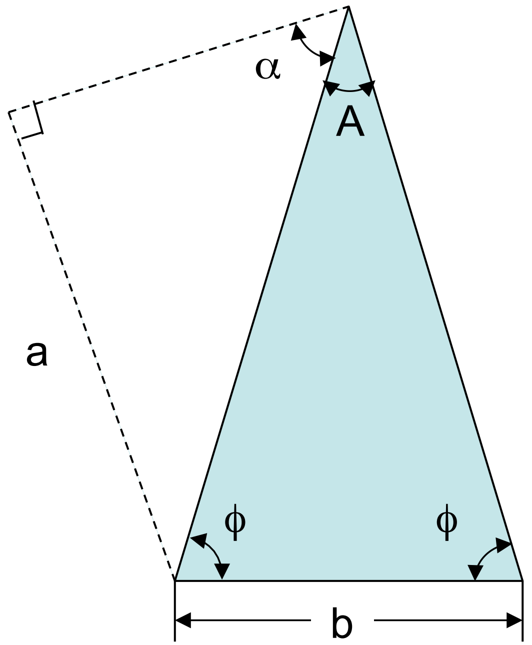
$$n(\lambda)=Z+C\lambda^{-2}$$

- Differentiating the equation,

$$dn/d\lambda = -2C\lambda^{-3}$$

$$\boxed{d\theta/d\lambda = -(2Cb/a)\ \lambda^{-3}}$$

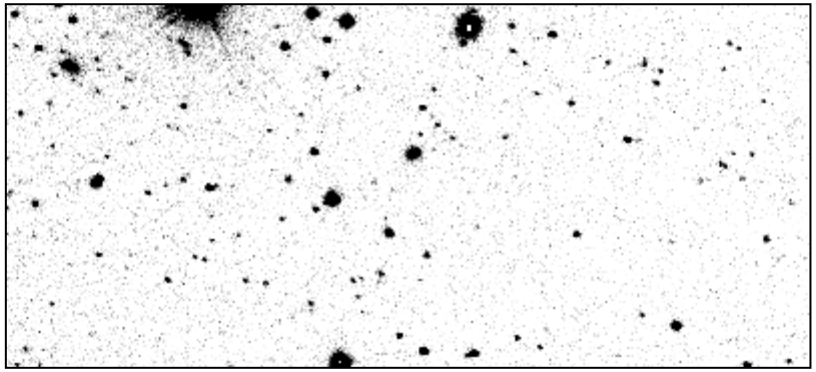
- Angular deviation is wavelength dependence
- It usually becomes smaller as increasing λ

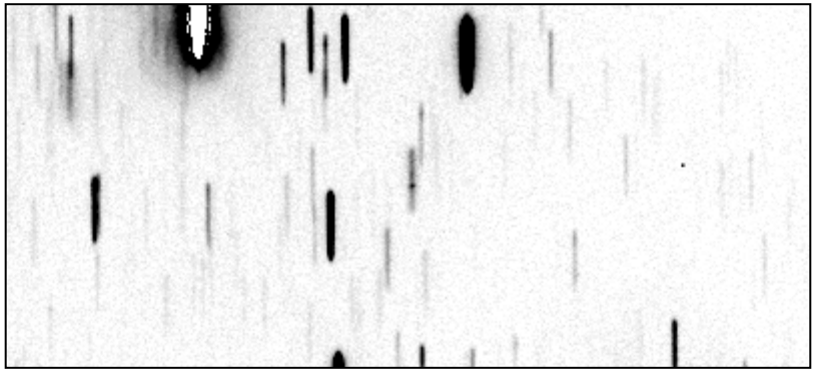


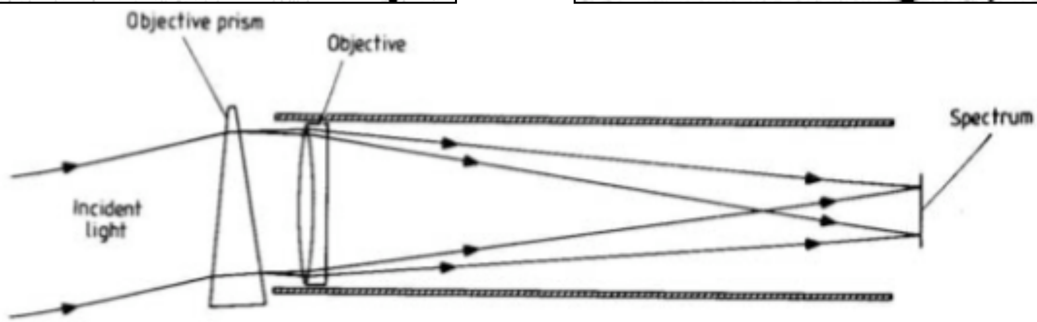
(because $d\theta/d\lambda = (b/a)\ dn/d\lambda$)

2-2. Prism Spectroscopy: Example

- Objective prism spectroscopy: Prism installed at the top of the telescope
- Simplest. Light is already parallel, so no extra lenses.
- Each point source produces a spectrum
- No reference spot of the wavelength for continuous emission
- Usually low resolution, good for wide-field surveys and meteors



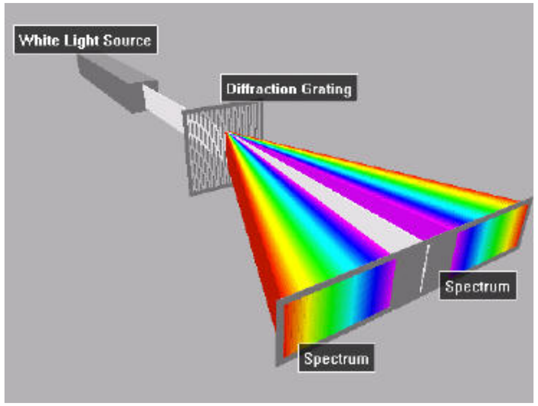




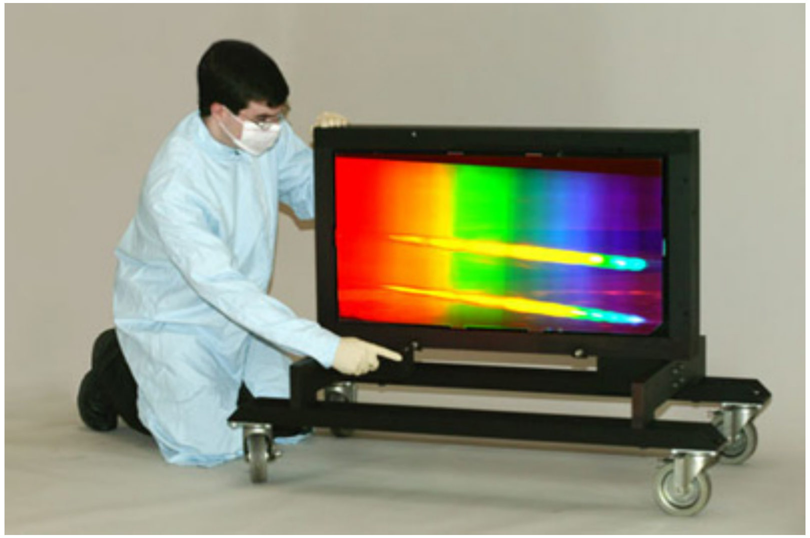
2-3. Weak Points of Prism Spectroscopy

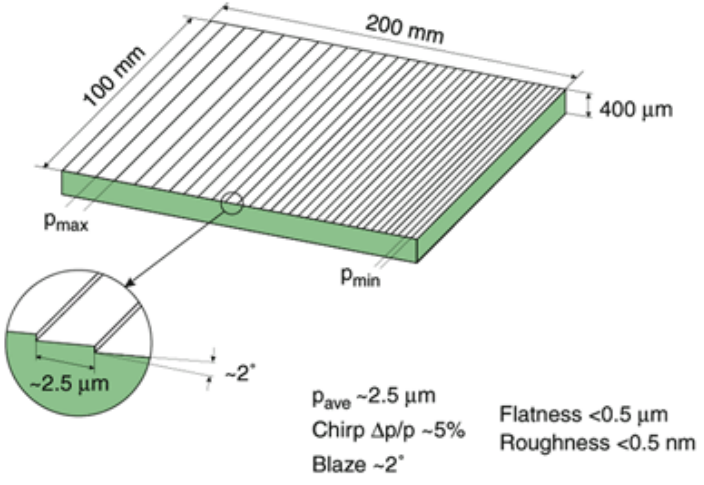
- The prism needs to be large to have a reasonable spectral resolution
- Expensive, heavy, and would absorb the electromagnetics passing through it
- The lengths of spectra should be complicated function of wavelength
- Comparable spectral resolution could be achieved with a quite cheap ‘grating’

2. Reflection/Diffraction Gratings



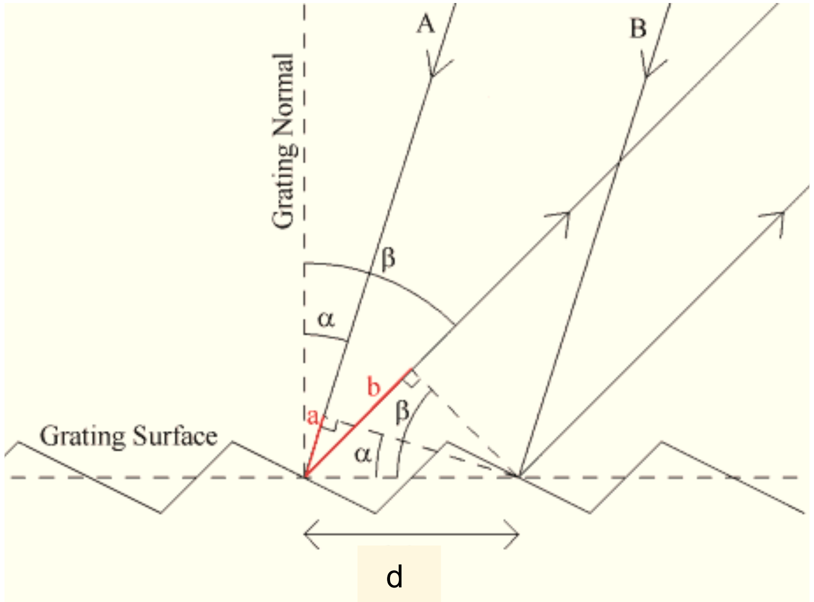
- Reflection / Diffraction gratings
- Multi-slit diffraction
- reflection gratings and transmission gratings





2-1. Reflection Gratings

- Light reflecting from grooves A and B will interfere constructively if the difference in path length is an integer number of wavelengths.



- The path difference is $d\sin\alpha + d\sin\beta$ (where d is the distance between facets on the grating), so

$$\boxed{d\sin\alpha + d\sin\beta = n\lambda}$$

→ the grating equation

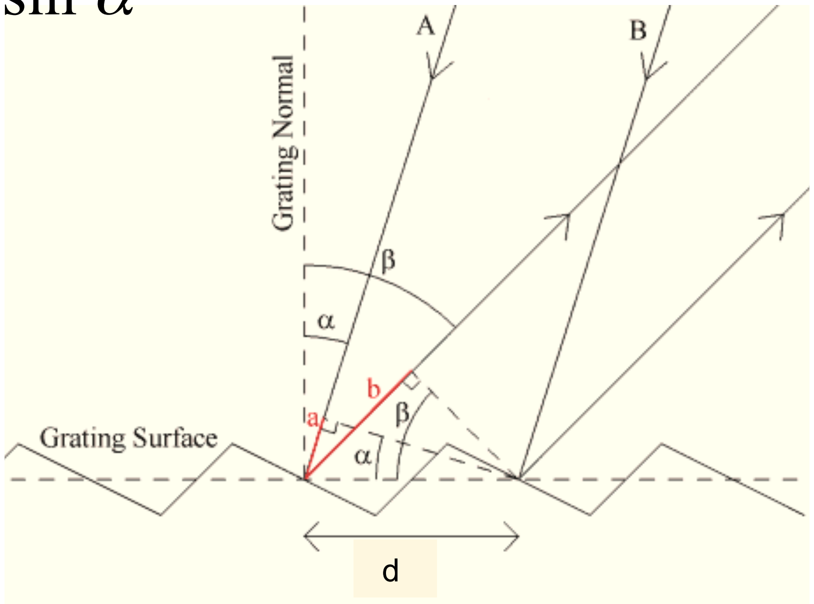
- "n" is the "spectral order" and quantifies how many wavelengths of path difference are introduced between successive facets or grooves on the grating)

2-2. Grating Equation

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

- The groove spacing d is a feature of the grating
- The angle of incidence, α, is the same for all wavelengths
- The angle of diffraction, β, must then be a function of wavelength

$$\sin\beta = n\lambda/d - \sin\alpha$$



Quiz [1]

$$\sin \beta = n\lambda/d - \sin \alpha$$

- We are working with a grating with 1000 grooves per millimeter.
- The incident angle α is 15º.
- At what angle will light of 400 nm be diffracted in 1st order (n=1)?
- 500 nm? 600 nm?
- Careful: express wavelength and groove spacing in similar units

Answer: 8.1° (400nm), 14.0° (500nm), 19.9° (600nm)

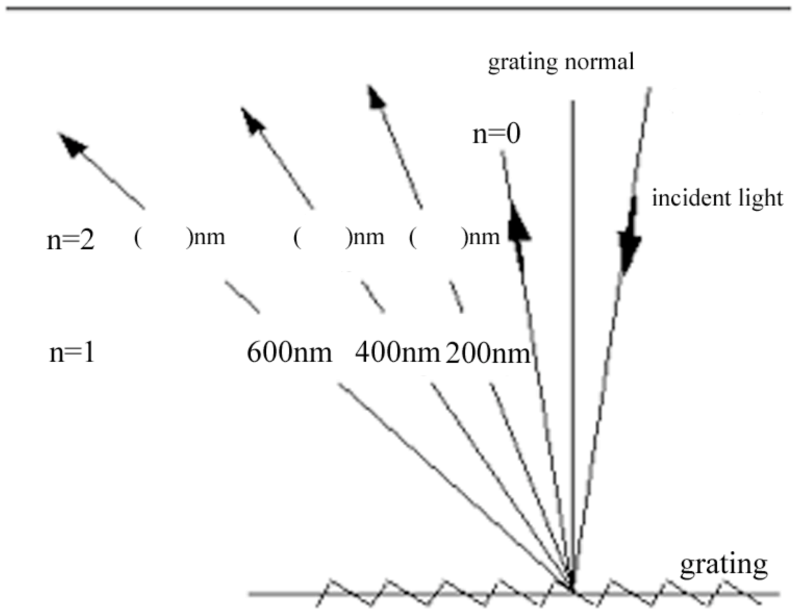
2-3. Multiple Grating Orders and Order Sorting Filter

$$\sin \beta = n\lambda/d - \sin \alpha$$

- Multiple spectra are produced by a diffraction grating, corresponding to different orders (n=1,2,3…)

- Quiz [2]
  - For a grating of 1000 grooves/mm and 15º incident angle, what wavelength of light will be diffracted to an angle of 14º in second order?

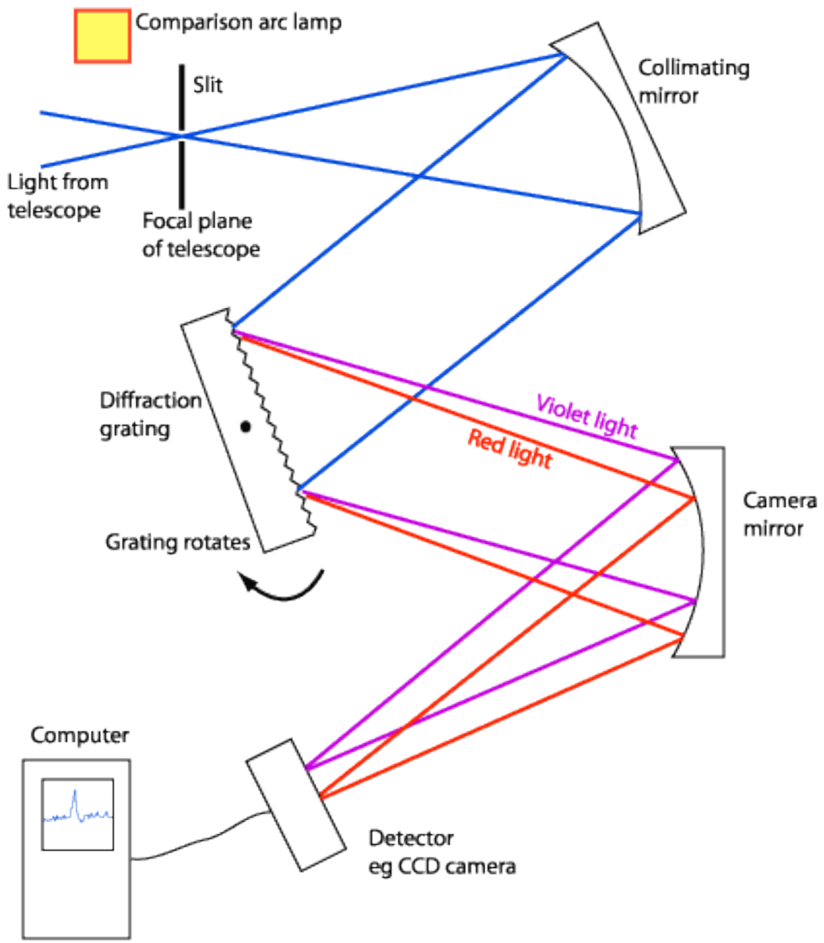
- Quiz [3]
  - Fill the blanks in the right figure.



Answer2 300, 200, 100 (from left to right)
Answer1 250nm

3. Typical Design for Spectrographs

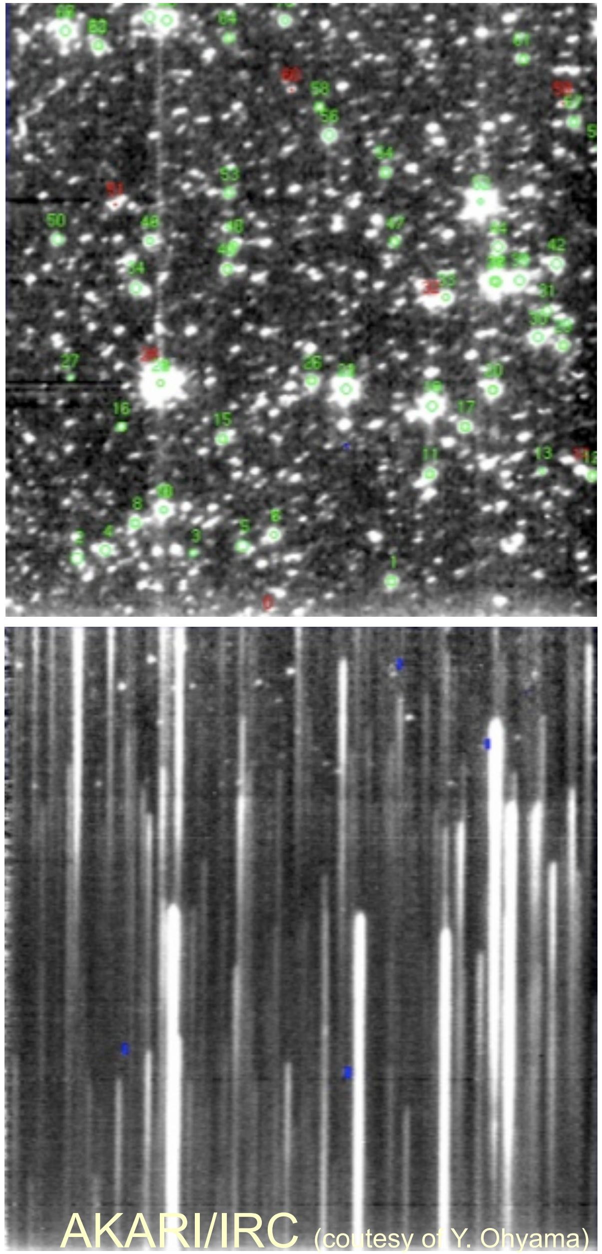
- **Entrance Aperture**: A slit, usually smaller than that of the seeing disk
- **Collimator**: converts a diverging beam to a parallel beam
- **Dispersing Element**: sends light of different colors into different directions
- **Camera**: converts a parallel beam into a converging beam
- **Detector**: CCD, IR array, etc.



A Schematic Diagram of a Slit Spectrograph

3-1. Why use a slit?

- to increase resolution
  – by narrowing the slit
  – also decreases throughput
- to block unwanted light
  – from the sky
  – other nearby sources
- to set a reference point

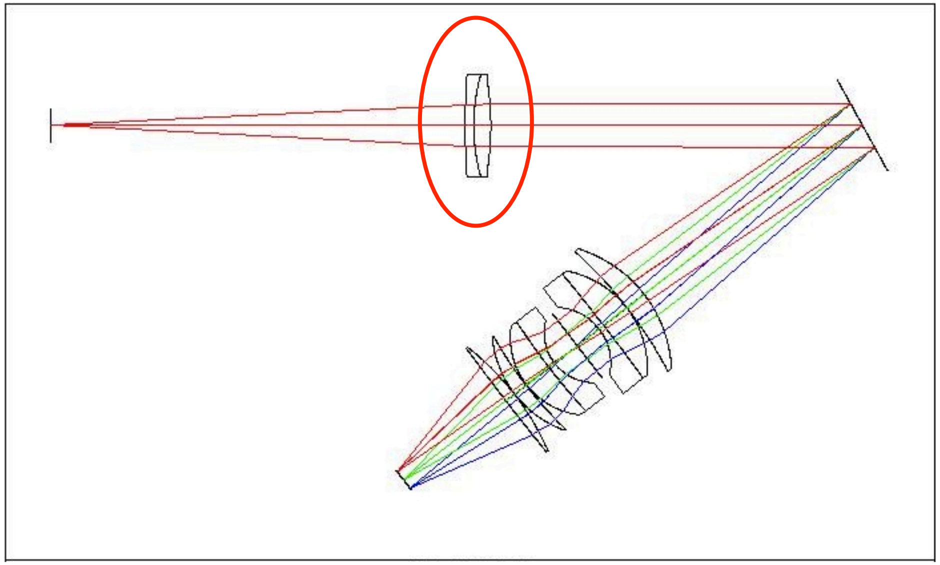


3-2. Collimator

- The collimator converts the diverging beam of white light from the slit to a parallel beam.

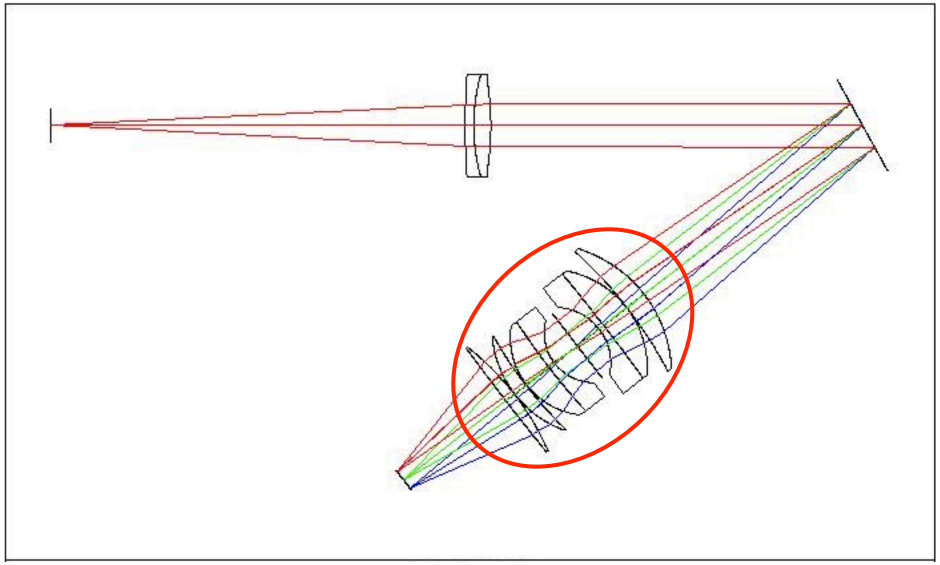
- The focal ratio of the collimator must be matched to the effective focal ratio of the telescope.

- The diameter of the collimator determines the diameter of the light beam in the spectrograph. The size of the collimator affects the size of the “slit image” on the detector.



3-3. Camera Types

- reflecting camera
  - broad wavelength coverage
  - on- of off-axis

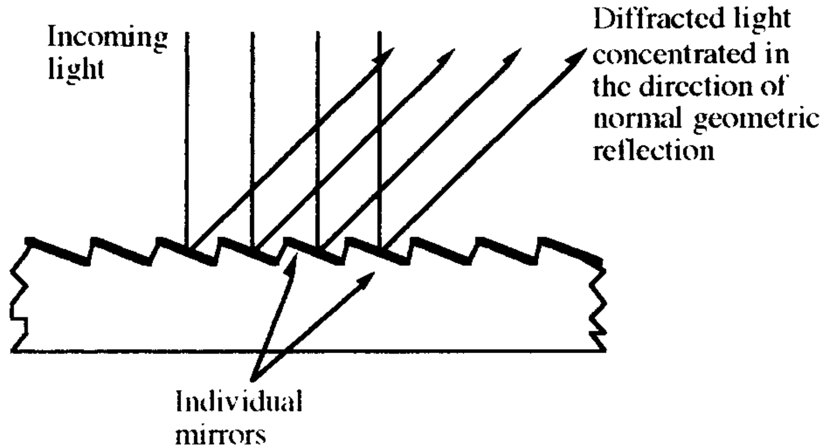


- transmission camera
  - lenses
  - generally on-axis, no central obstruction
  - broad wavelength coverage against aberration requires multiple elements

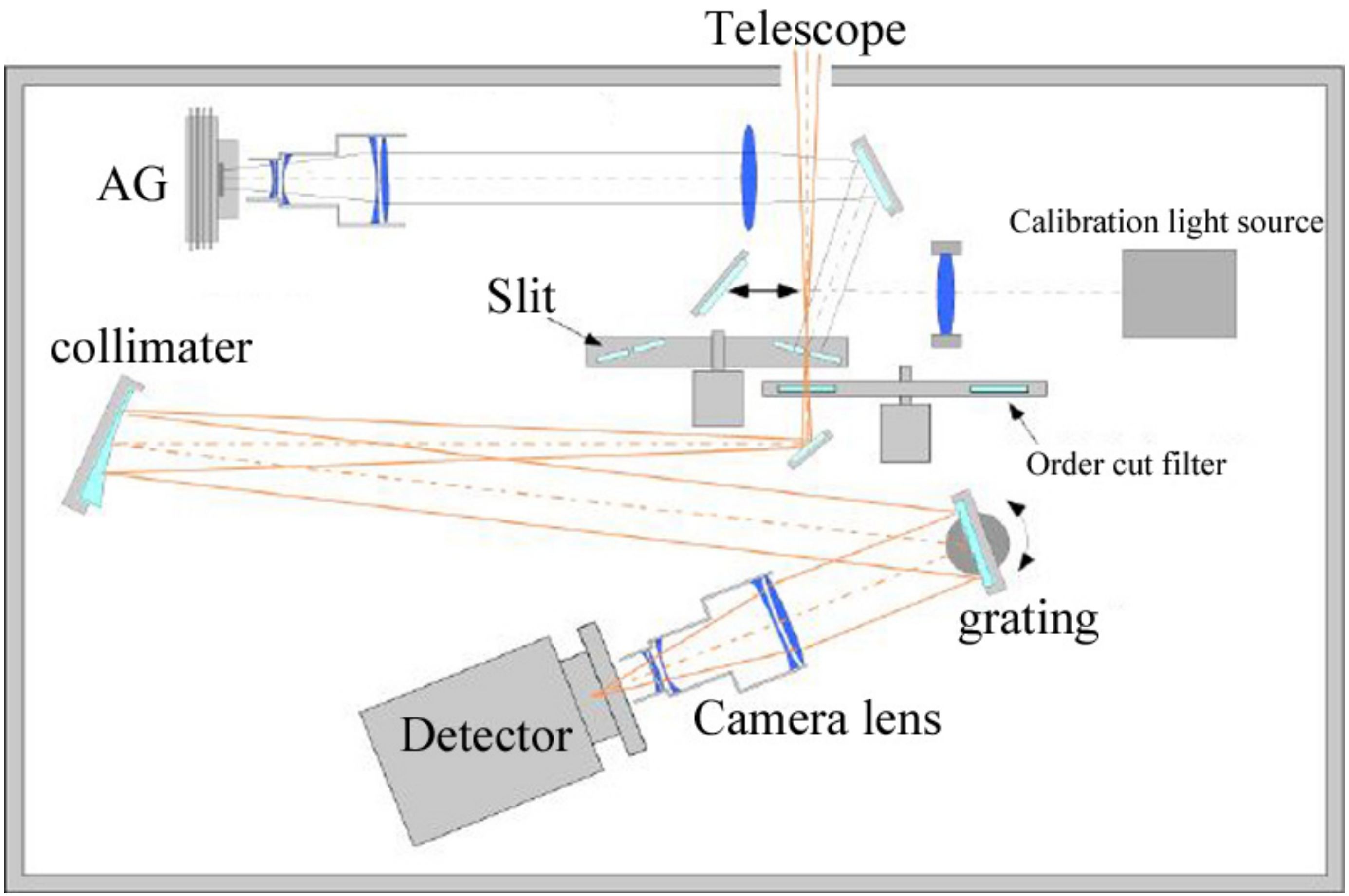
4. Reflection Grating Efficiency

- **Problem**: A grating diffracts light into many orders; each order contains only a fraction of the light

- **Fix**: Gratings can be designed to concentrate most of the incident intensity into a particular order, by a process called "blazing". This is a process where the grooves of a grating are cut so that the reflecting surfaces are at a certain angle, the blaze angle. About 90% of the incident light is diffracted preferentially into the first order.



Example of Spectrograph

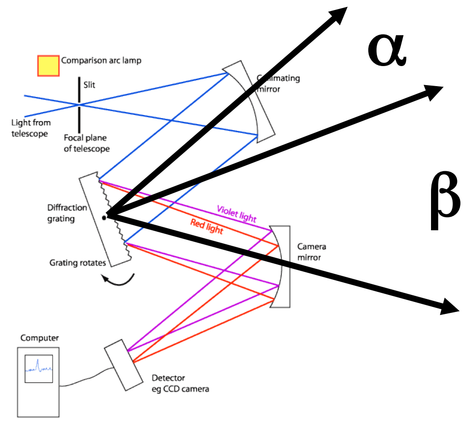


Nayuta 2-m Telescope Spectrograph
Courtesy of S. Ozaki (NAJO)

5. How to Improve the Resolution?

- based on the grating equation

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



A Schematic Diagram of a Slit Spectrograph

- "α" is the angle from the slit to the grating normal and "β" is the angle from the grating normal to the camera. α is usually fixed.

- The "angular dispersion" of a spectrograph is given by $\delta\beta/\delta\lambda$:

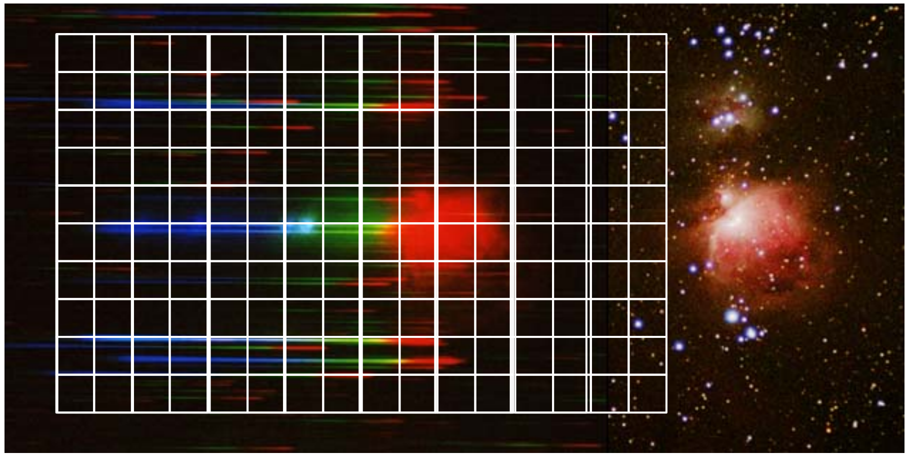
$$\frac{\partial \beta}{\partial \lambda} = \frac{\partial \beta}{\partial \sin\beta}\frac{\partial \sin\beta}{\partial \lambda} = \frac{1}{\partial \sin\beta / \partial\beta}\frac{\partial \sin\beta}{\partial \lambda} = \frac{1}{\cos\beta}\frac{n}{d}$$

resolution

$$\boxed{\frac{\partial \beta}{\partial \lambda}} = \frac{1}{\cos \beta}\frac{n}{d}$$

- The resolution varies as
  - the order number (higher order ↔ more resolution)
  - the grating spacing (narrower grooves ↔ more resolution)
  - the camera-collimator angle (as β increases, cos β gets smaller and resolution increases)

- The effective resolution of a spectrograph is a function of
  - Not only <u>the grating resolution</u>
  - But also <u>the size of the slit image</u> and <u>the pixel size</u>



5. Throughput Matters

- The higher the throughput, the better
- Limitations:
  - slit width (get a bigger collimator or better seeing)
  - efficiency of
    - mirror coatings
    - grating
    - lens transmission
    - detector

6-1. Limitations for High Dispersion

- **Problem**: detector size, shape
  - generally square or 1x2 format
  - a conventional grating spectrograph produces a very LONG high dispersion spectrum that does not fit on a CCD

- **Solution**: the echelle grating
  - works in high orders (n=100)
  - a second dispersing element spreads the light in a perpendicular direction

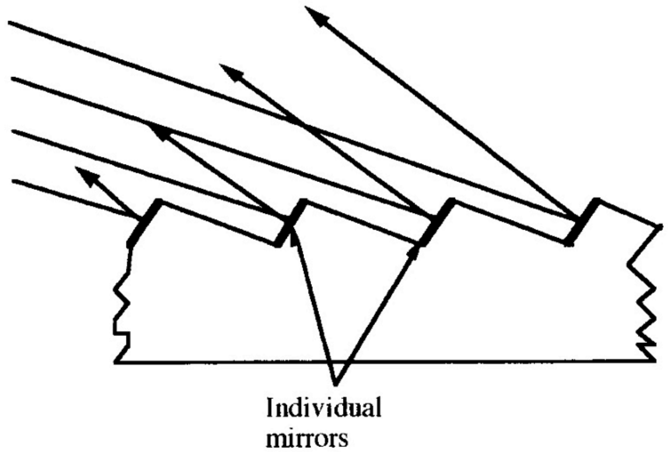
6-2. Echelle Gratings

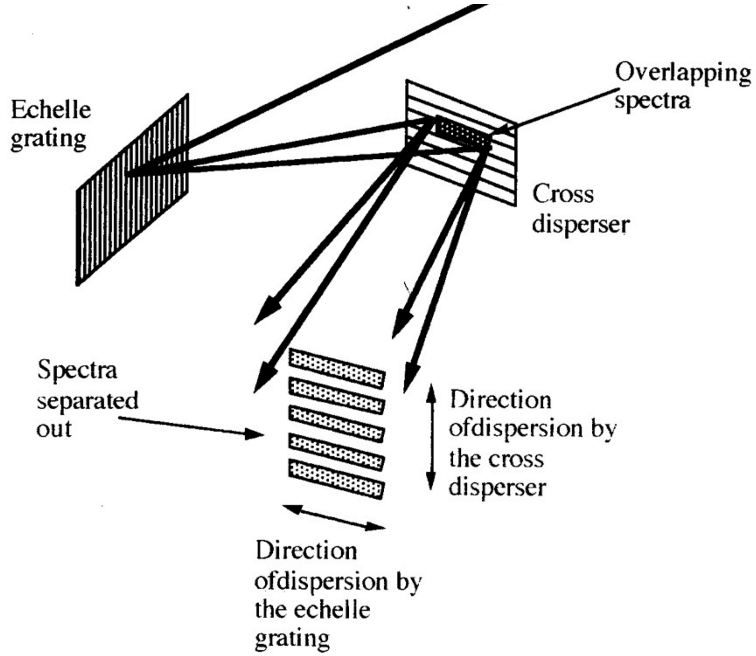
- To increase spectral resolution, increase the order at which a grating is used

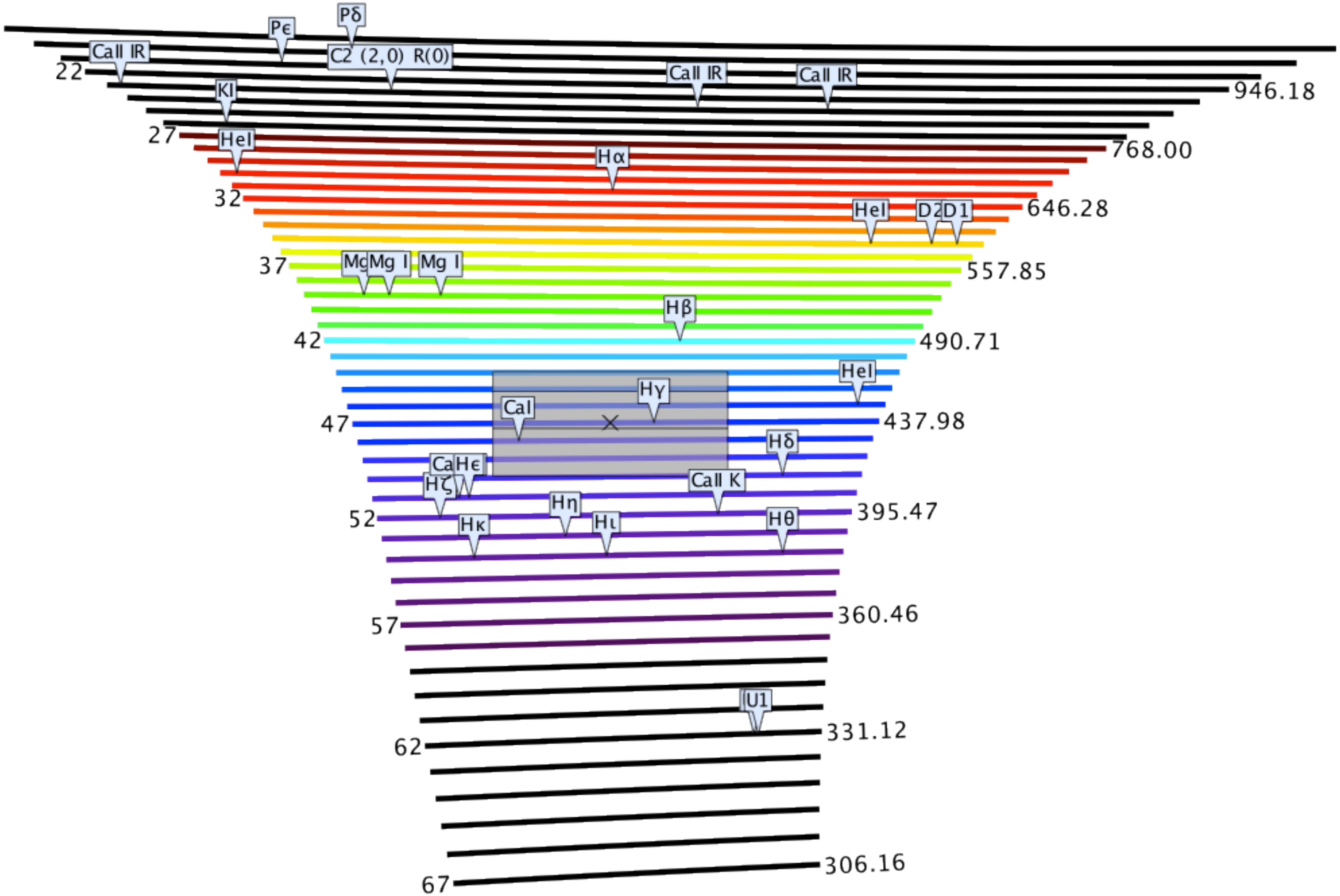
- For high orders, we must increase α and β in the grating equation (to ~50-75°)

- The spectral range for each order is small so the orders overlap

- Separate the orders with a second disperser (cross disperser) acting in a perpendicular direction.



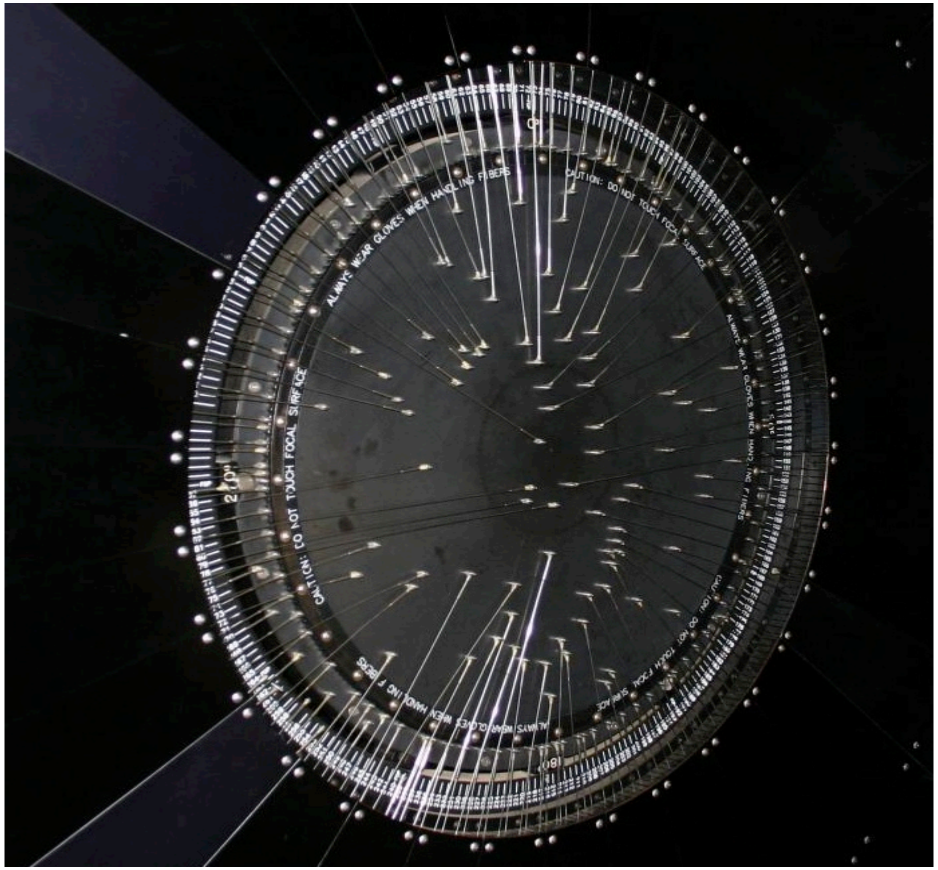


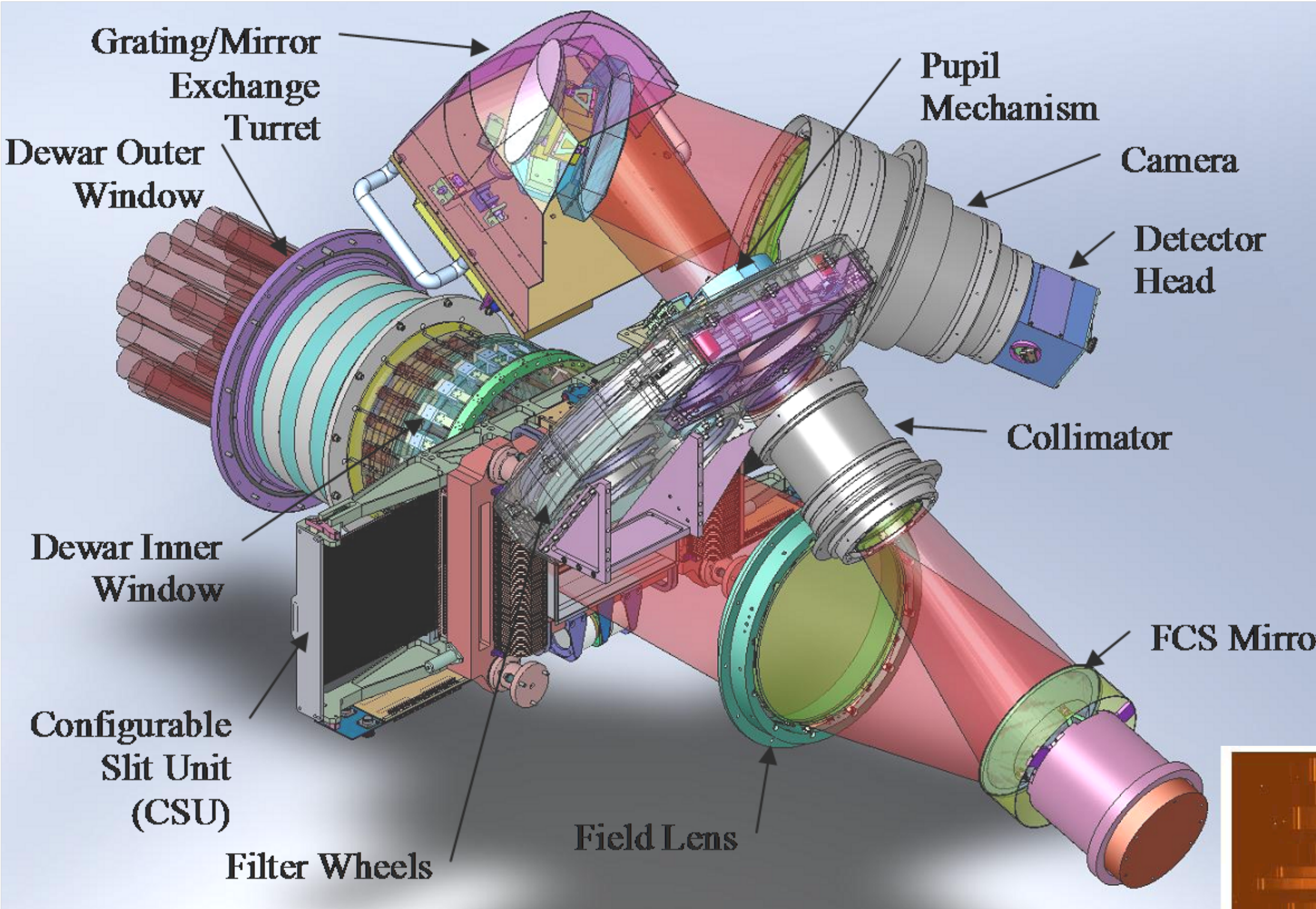


Pδ
Pϵ
CaII IR
C2 (2,0) R(0)
22
CaII IR
CaII IR
946.18
KI
27
HeI
Hα
768.00
32
HeI
D2
D1
646.28
37
Mg
Mg I
Mg I
557.85
Hβ
42
490.71
HeI
Hγ
CaI
47
437.98
Hδ
Ca
Hϵ
Hζ
CaII K
Hη
52
395.47
Hκ
Hι
Hθ
57
360.46
U1
62
331.12
67
306.16

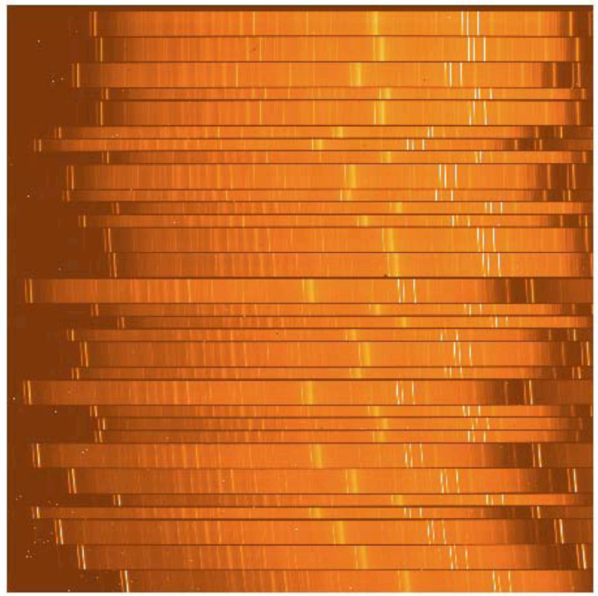
7. Multi-object Spectroscopy (MOS)

- Observing one object at a time is <u>inefficient</u>
- When many stars are available in a field (e.g. a star cluster) use multi-object spectroscopy
- Put an optical fiber at locations of objects to take spectra.
- Feed the optical fibers into a spectrograph.





MOSFIRE for Keck-I Telescope



Multi-slit using cryogenic robotic slit mask system that is reconfigurable electronically

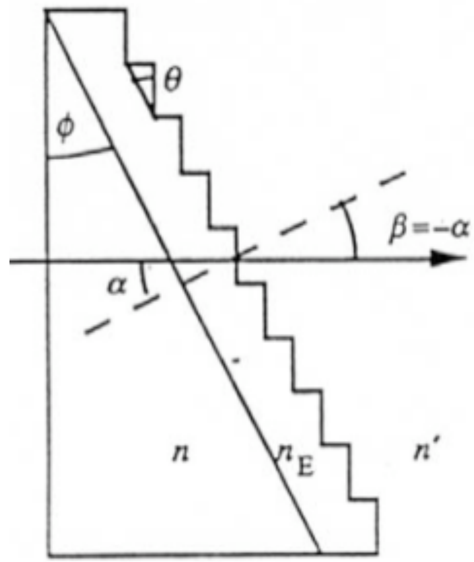
The other techniques for spectroscopy

Grism

- A grism is a combination of a prism and grating arranged so that light at a chosen central wavelength passes straight through.
- The advantage of a grism is that it can be placed in a filter wheel and treated like another filter. The basic relationships required to design a grism are

$$m\lambda T = (n-1)\sin\phi$$

where λ is the central wavelength; T 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.

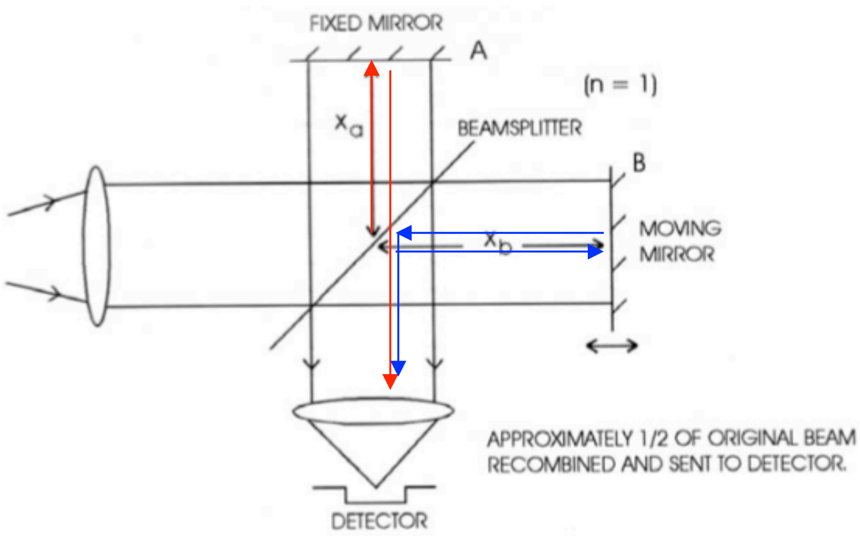


The Fourier Transform Spectrometer (FTS)

- The FTS is a scanning interferometer with collimated light as a input.

- A typical scheme is shown below. For a collimated monochromatic beam, the intensity at the detector is determined by the phase difference.

- The primary disadvantage for astronomical work is the fact that the measurements require a time sequence to determine the spectrum.



Fabry-Perot Interferometer

- The Fabry-Perot interferometer is an imaging spectrometer which is formed by placing a device called an "etalon" in the collimated beam.

- The etalon consists of two plane-parallel plates with thin, highly reflective coatings on their inner faces. The plates are in near contact but separated by a distance d.

- Assuming that the refractive index of the medium in the gap is n (usually n=1) and θ is the angle of incidence of a ray on the etalon (usually very small), then multiple reflections and interference within the gap occurs and the wavelengths transmitted with maximum intensity obey the relation: $m\lambda=2nd\cos\theta$.

Haleakala Spectrograph (1995)