Overview:
Astronomical Spectroscopy

or

How to Start Thinking Creatively about Measuring the Universe

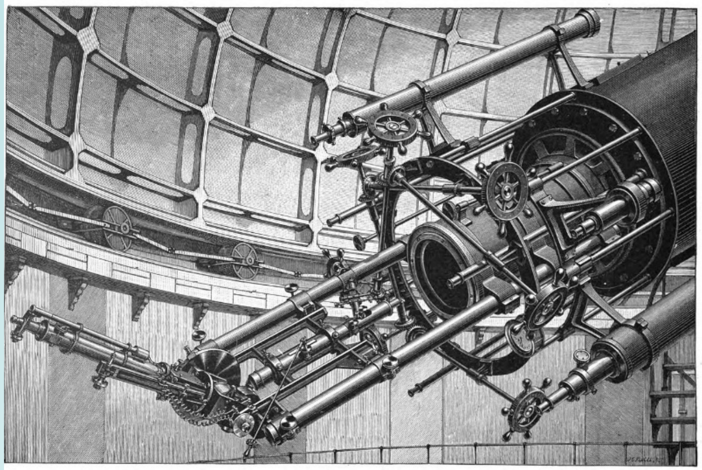
- Basic Spectrograph Optics
- Objective Prism Spectrometers - AESoP
- Slit Spectrometers
- Spectrometers for all purposes

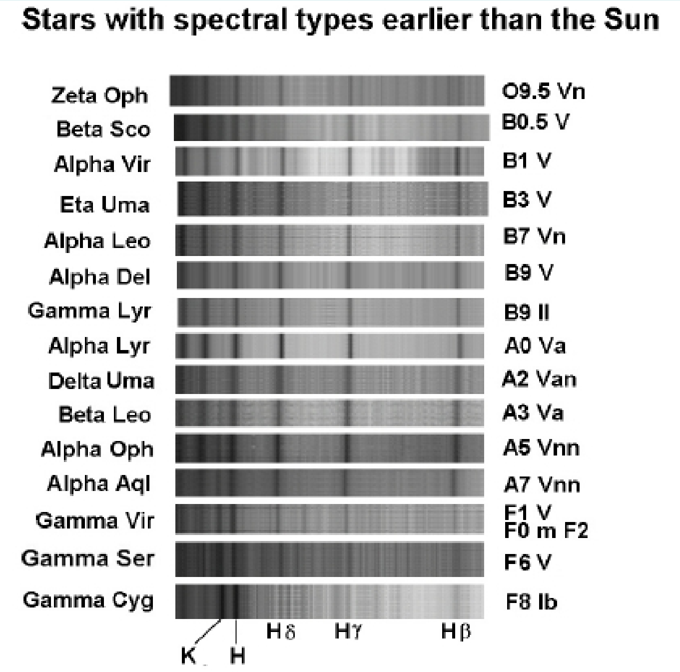
In the Beginning: Fraunhofer Lines in the Solar Spectrum (~1817)

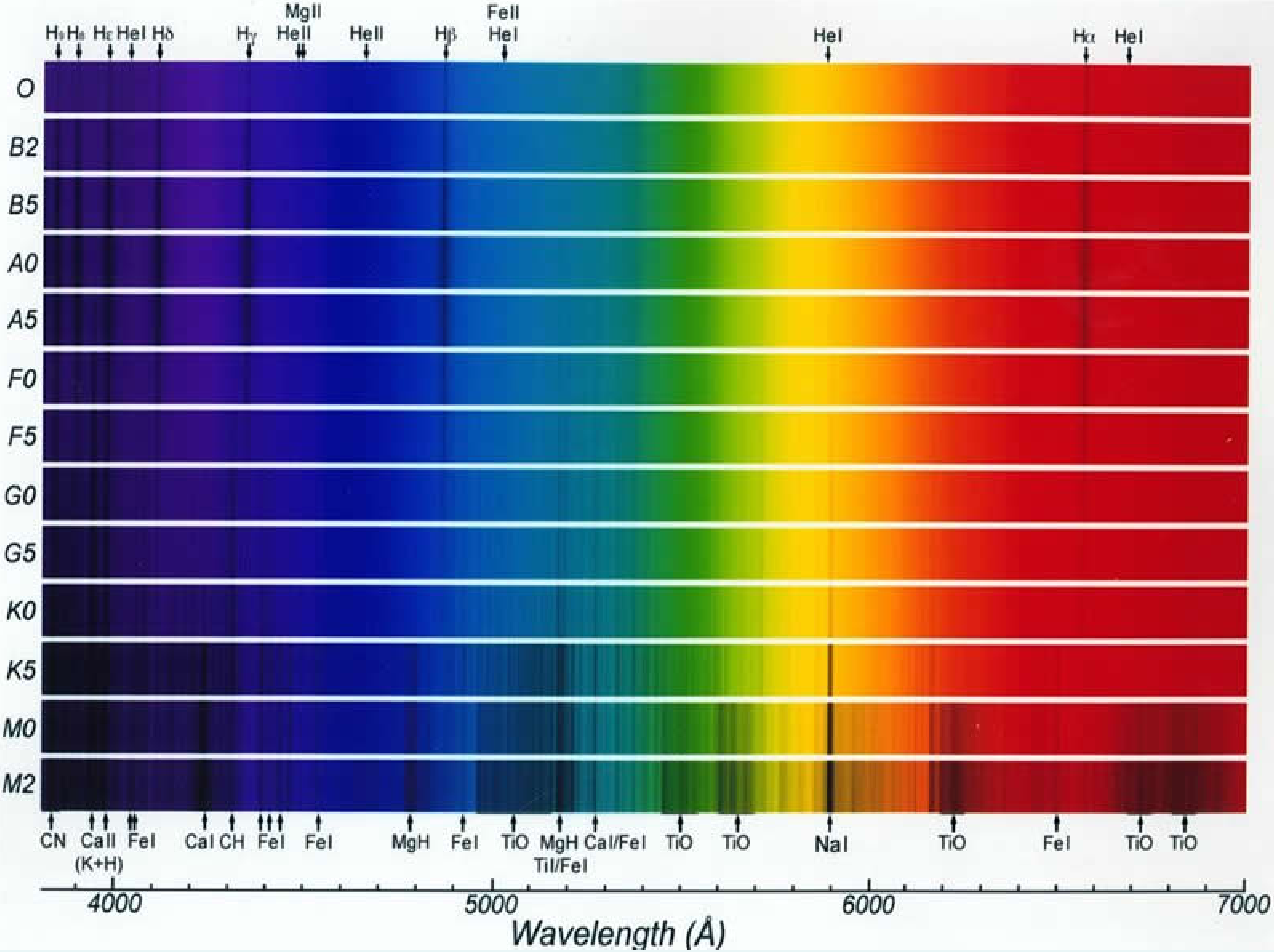
Designation	Wavelength	Origin
A	759.4 nm	telluric (terrestrial) oxygen
B	686.7	telluric oxygen
C	656.3	hydrogen (H alpha)
D	589.0	neutral sodium (Na I)
E	527.0	neutral iron (Fe I)
F	486.1	hydrogen (H beta)
G	430.3	metal blend
H	396.8	ionized Calcium (Ca II)
K	393.4	ionized Calcium (Ca II)

Stellar Spectral Classification

- Spectroscopy (visual and photographic) started in the late 19th century.
- Classifiers originally arranged them alphabetically, A-O
- A. J. Cannon figured out the right order from 200,000 objective prism spectra
- O B A F G K M
- And astronomers realized it was a well defined sequence in line strength.






Hη
Hζ
Hε
HeI
Hδ
Hγ
MgII
HeII
HeII
Hβ
FeII
HeI
HeI
Hα
HeI
O
B2
B5
A0
A5
F0
F5
G0
G5
K0
K5
M0
M2
CN
CaII
(K+H)
FeI
CaI
CH
FeI
FeI
MgH
FeI
TiO
MgH
TiI/FeI
CaI/FeI
TiO
TiO
NaI
TiO
FeI
TiO
TiO
4000
5000
6000
7000
Wavelength (Å)

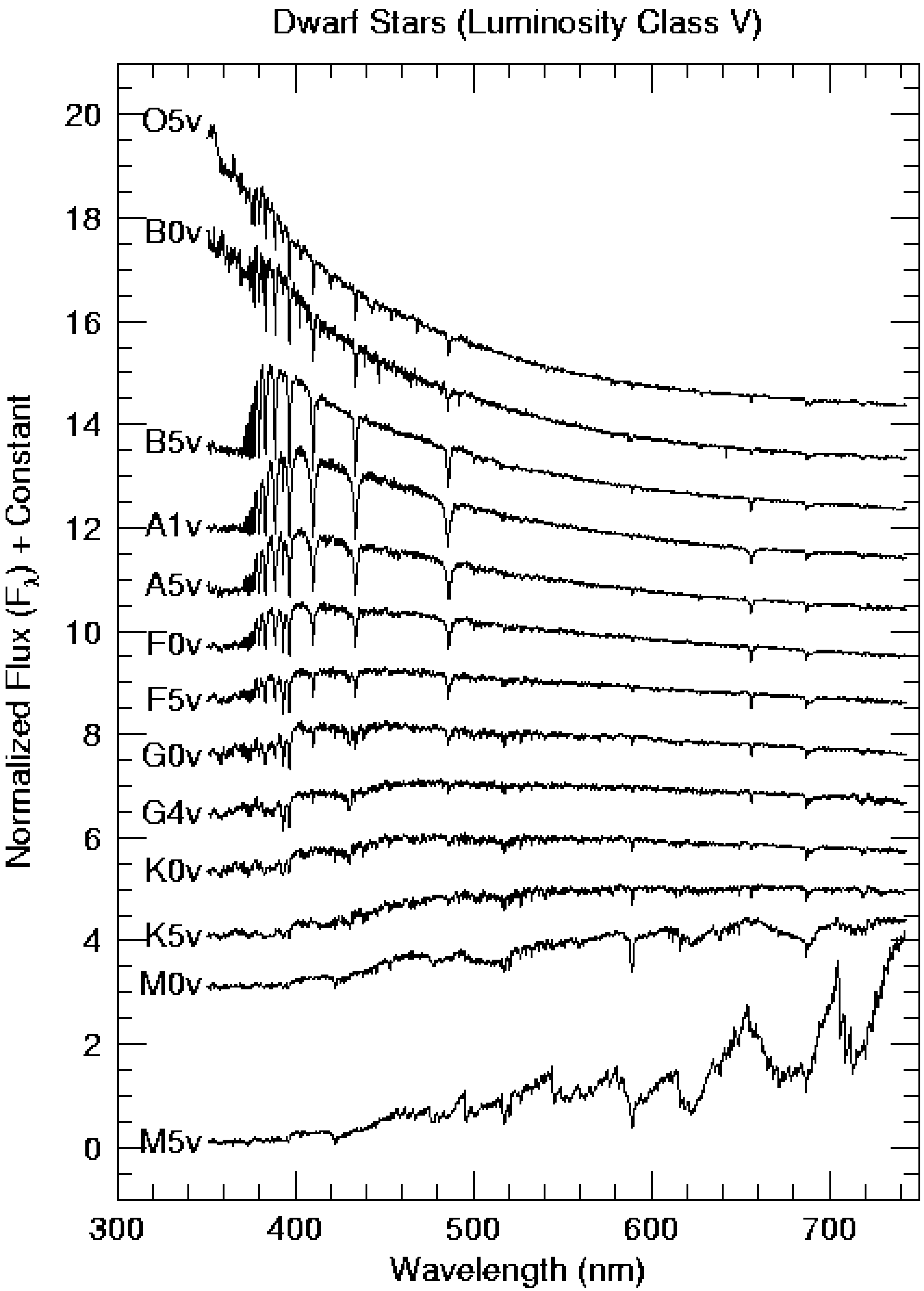
Digital spectral atlas

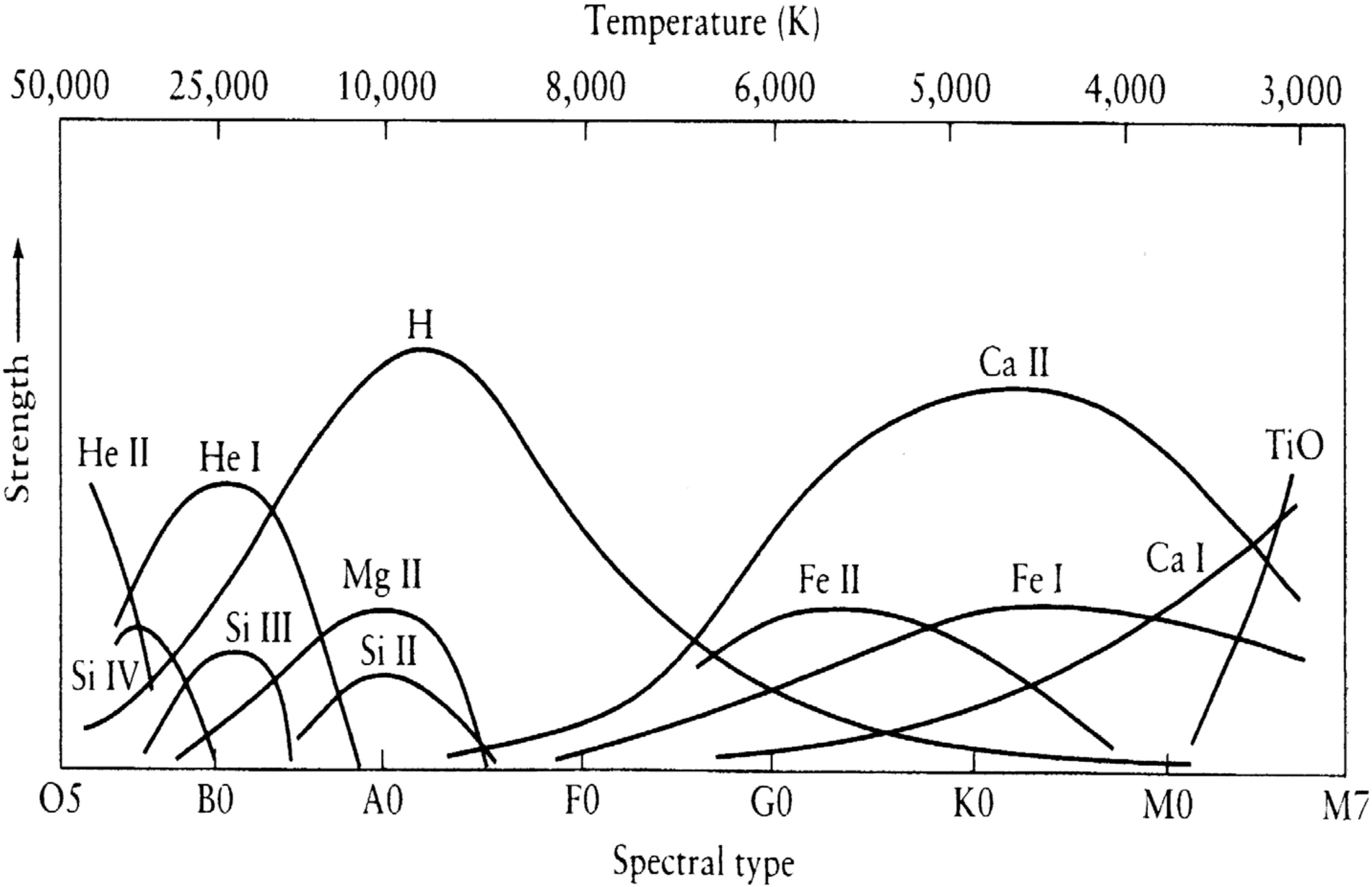
(the modern version of the photographic atlas!)

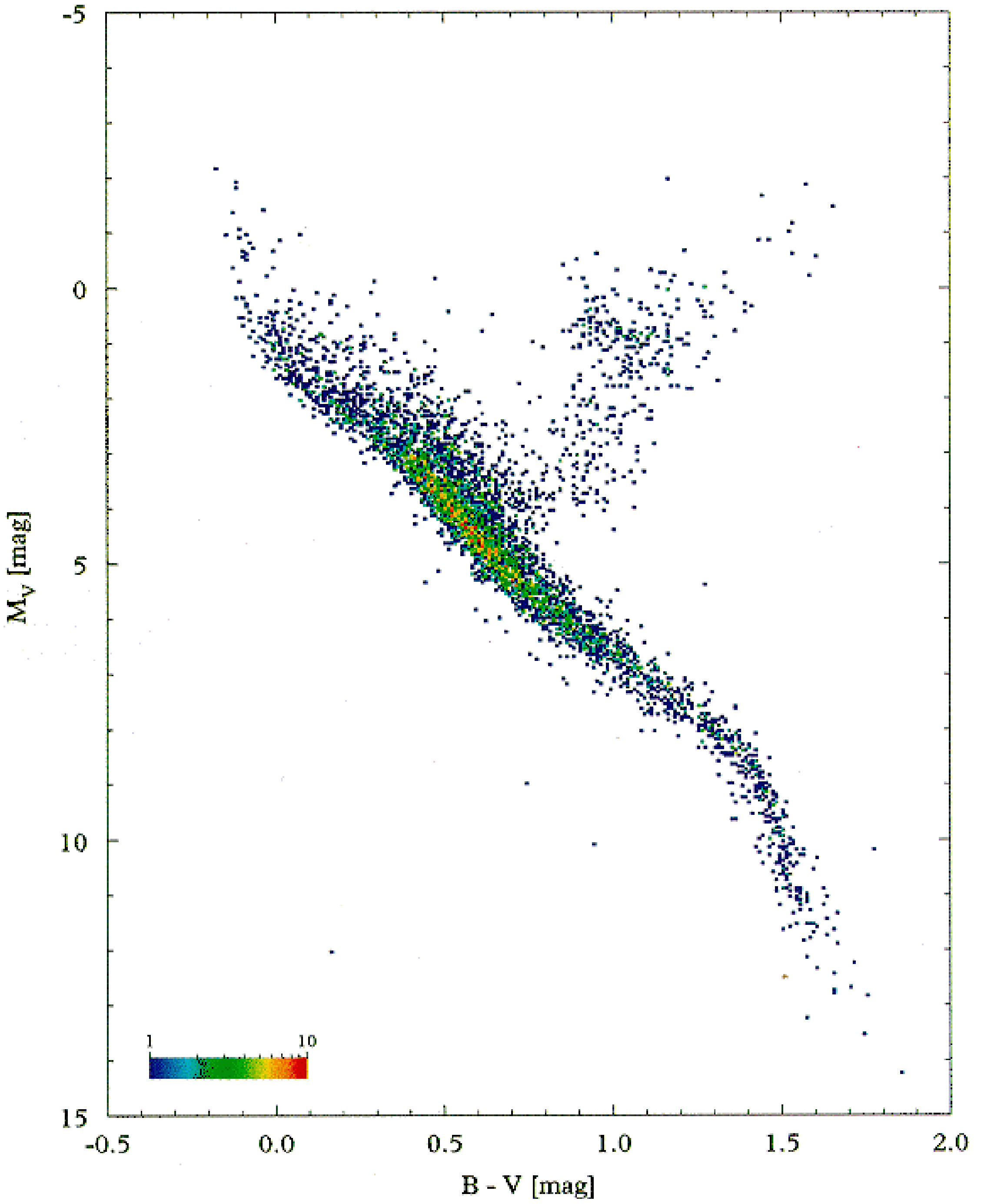
http://www.stsci.edu/hst/observatory/crds/pickles_atlas.html

http://www.stsci.edu/hst/observatory/crds/k93models.html

http://spectra.freeshell.org/spectroweb.html (Java-based)



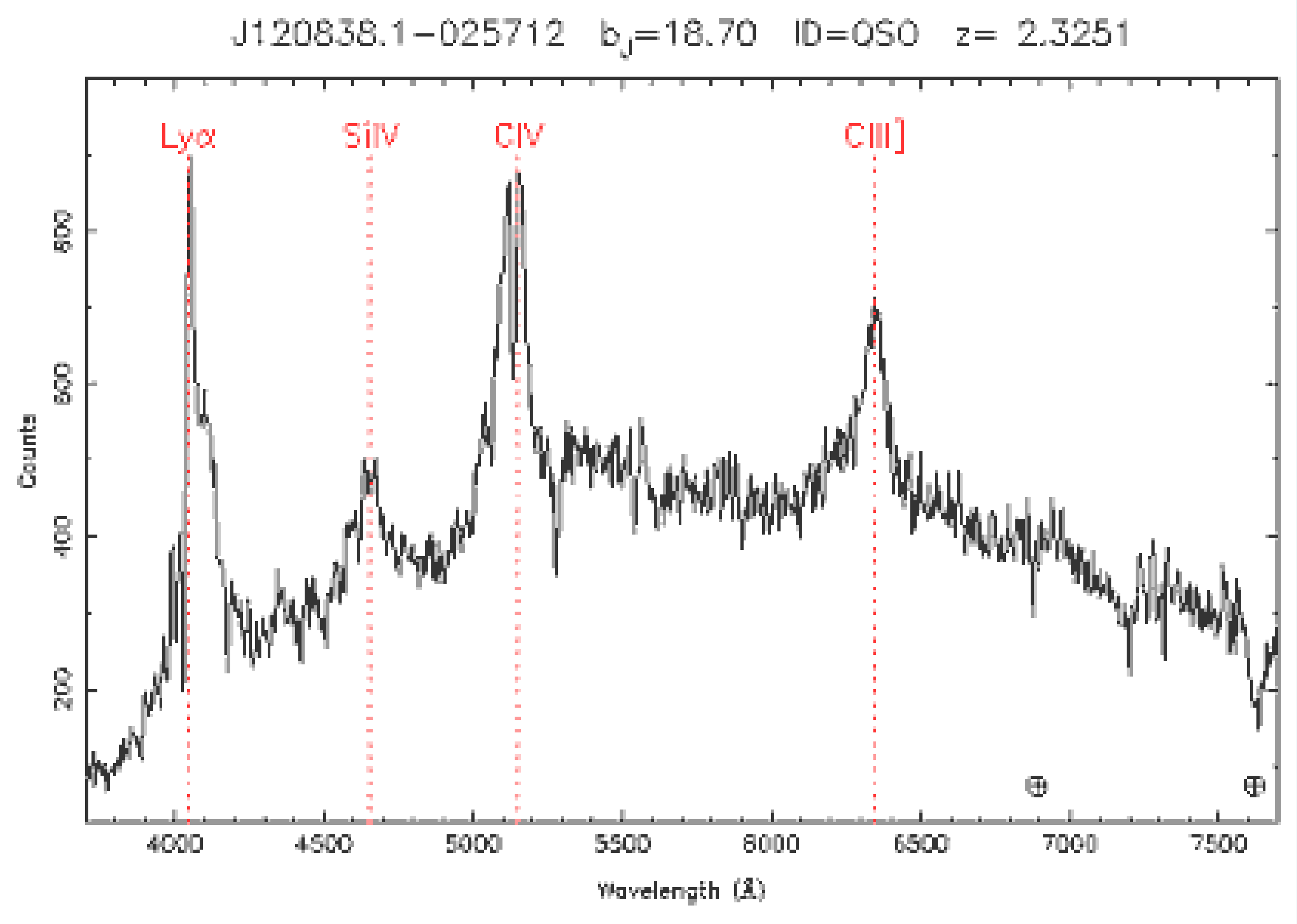

Temperature (K)
50,000
25,000
10,000
8,000
6,000
5,000
4,000
3,000
Strength
H
Ca II
He II
He I
TiO
Ca I
Mg II
Fe II
Fe I
Si III
Si II
Si IV
O5
B0
A0
F0
G0
K0
M0
M7
Spectral type



Hipparcos HR Diagram

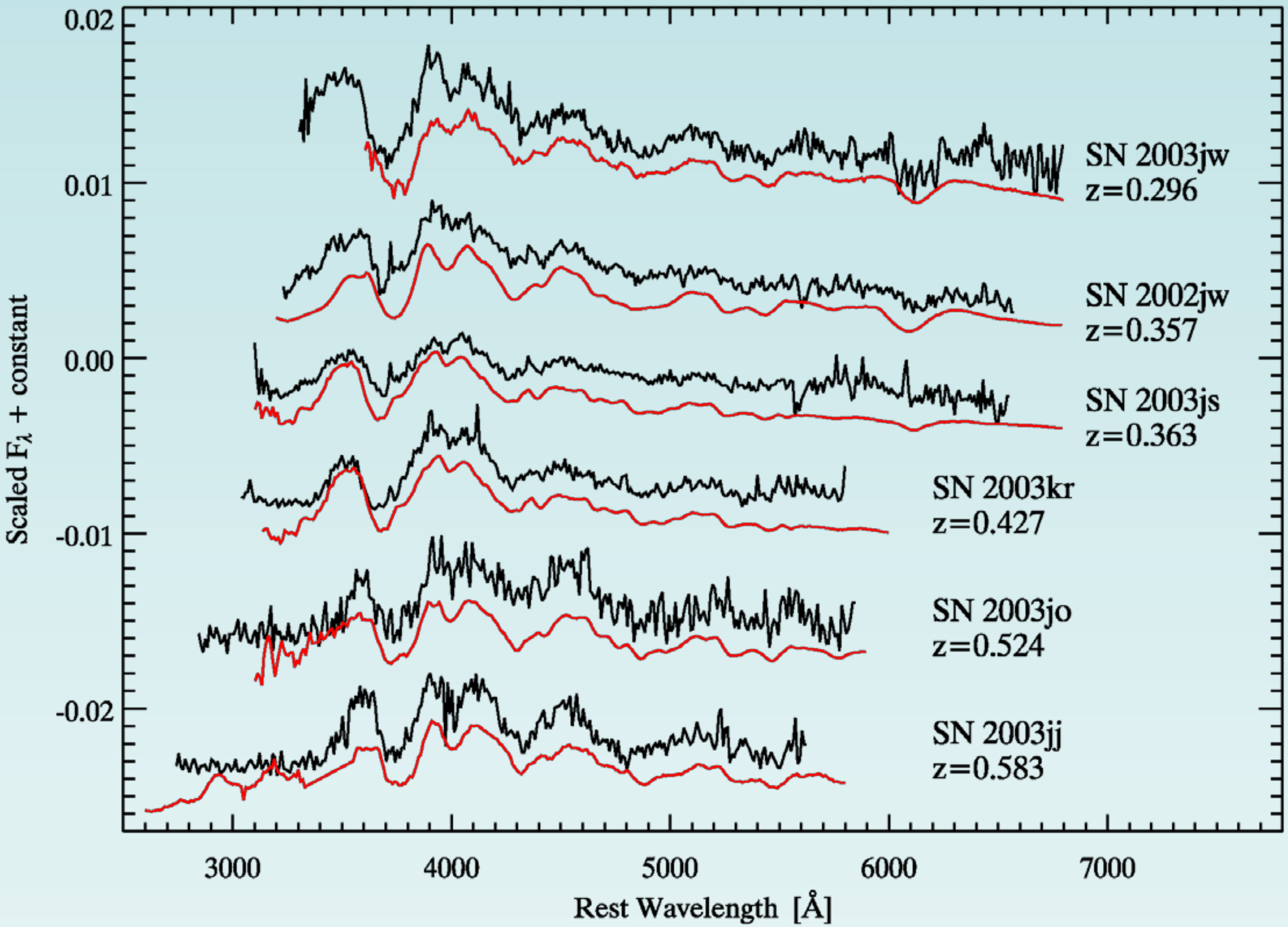
4907 nearby stars with distances to < 5%.

QSO J1208-0257



Ultraviolet lines redshifted into the visible

High redshift supernova spectra



Doppler-broadened lines and cosmological redshift

Refraction

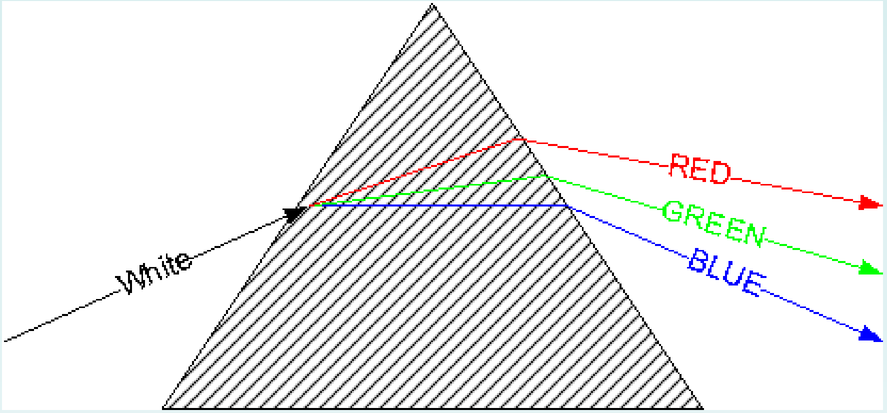
- The speed of light in a dense medium (air, glass…) is (usually) slower than in a vacuum.

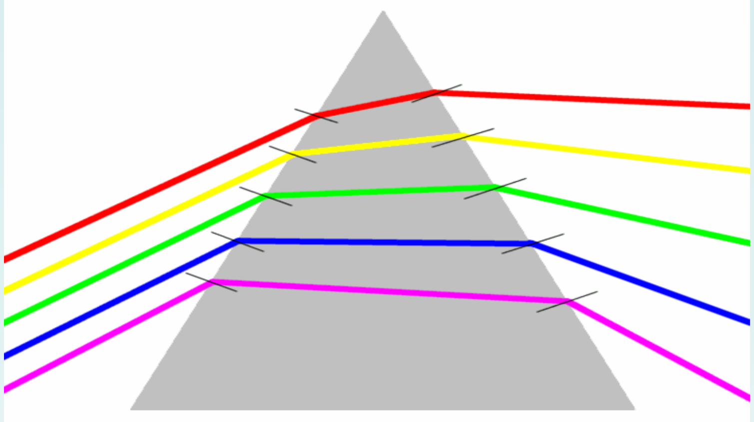
- Refraction index (ratio of speed of light in a vacuum to the speed in the medium)
  - air: n = 1.0003
  - water: n= 1.33
  - salt: n= 1.53

- The speed of light in a material depends on wavelength – “dispersion” (another use of that word)

Prisms

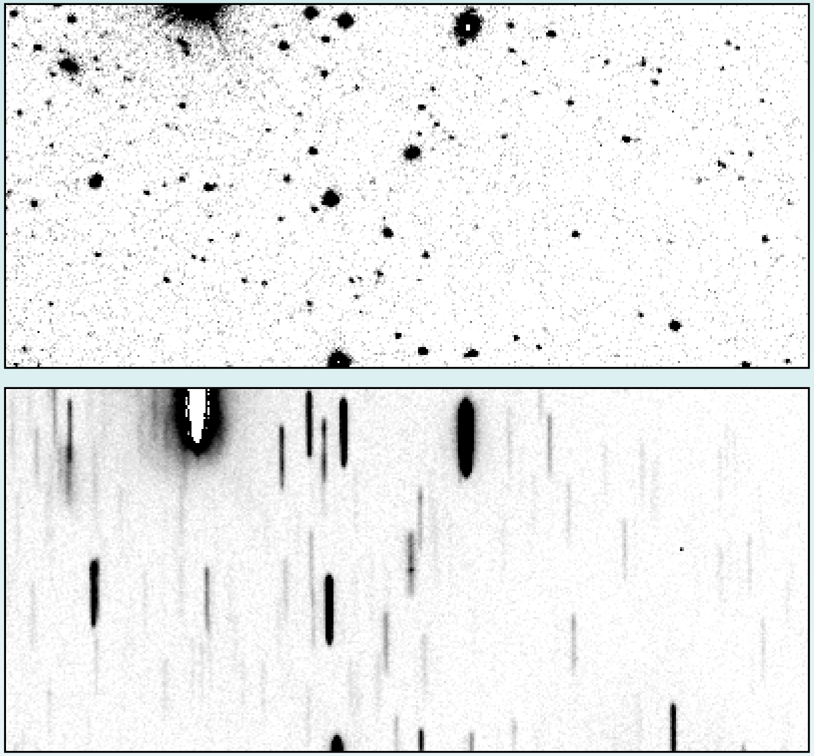
- Prisms disperse light by refraction.
- When a beam of white light passes from one medium into another at an angle, the direction of the beam changes due to refraction.
- Different colors of light are bent at different angles.
- Generally, red light is bent less, blue light is bent more.

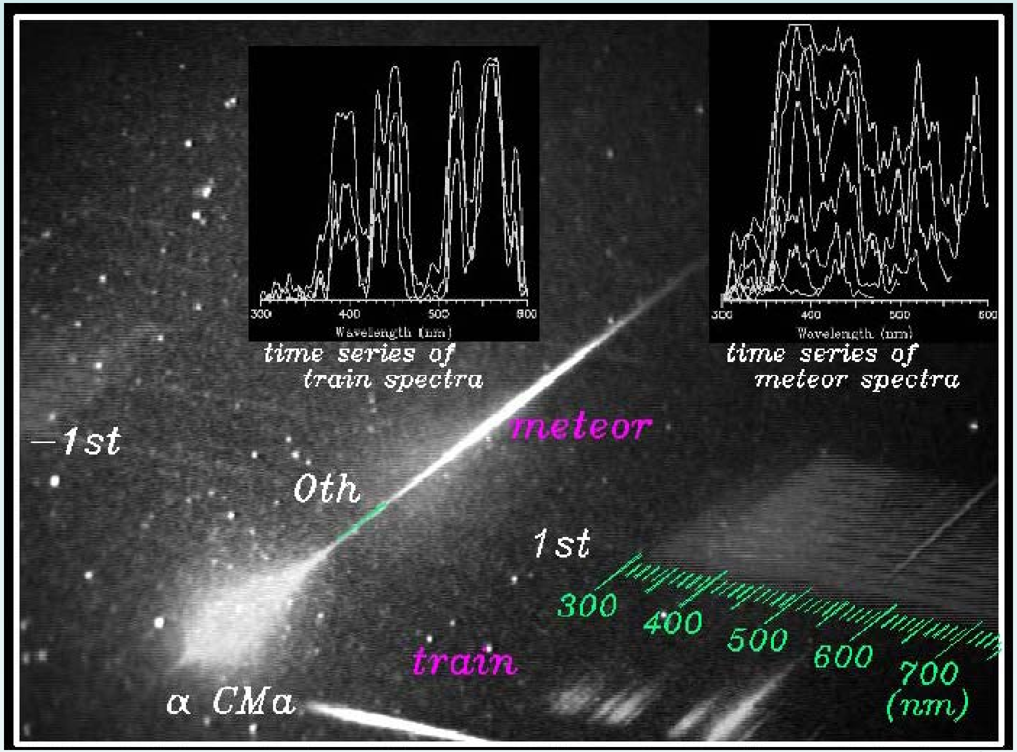




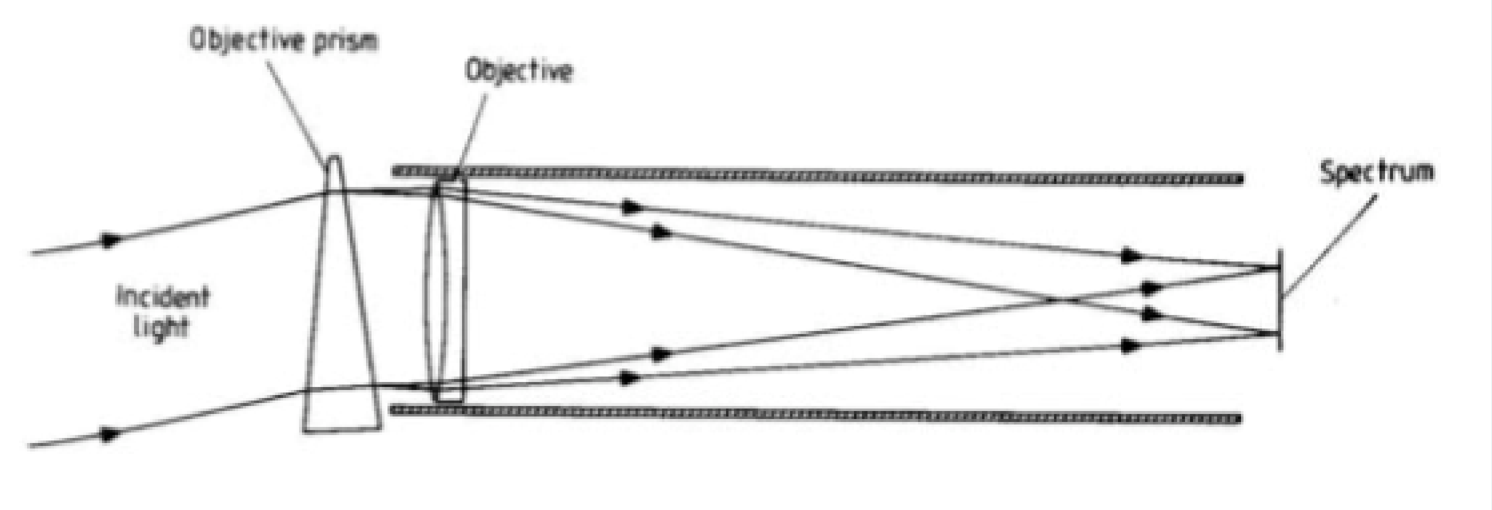
Objective Prism Spectroscopy

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

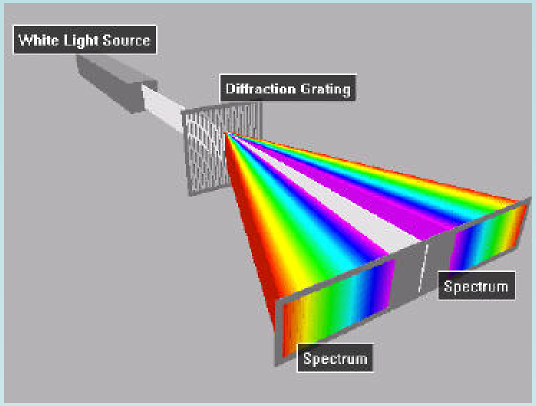




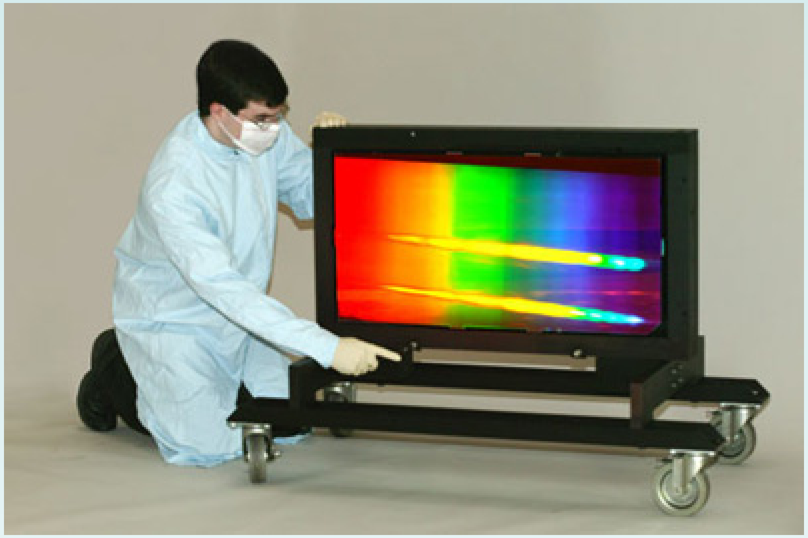
Courtesy of S. Abe

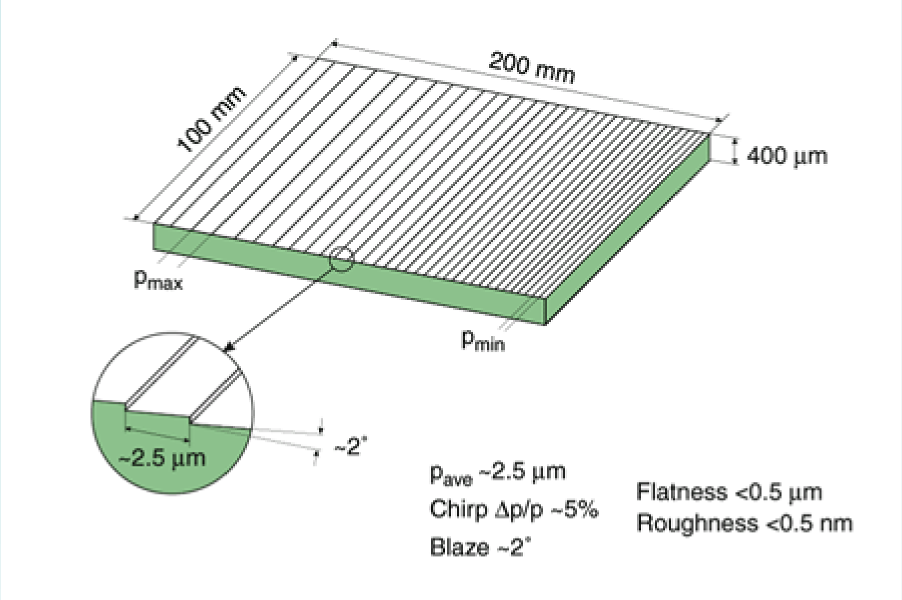

Objective prism
Objective
Spectrum
Incident
light

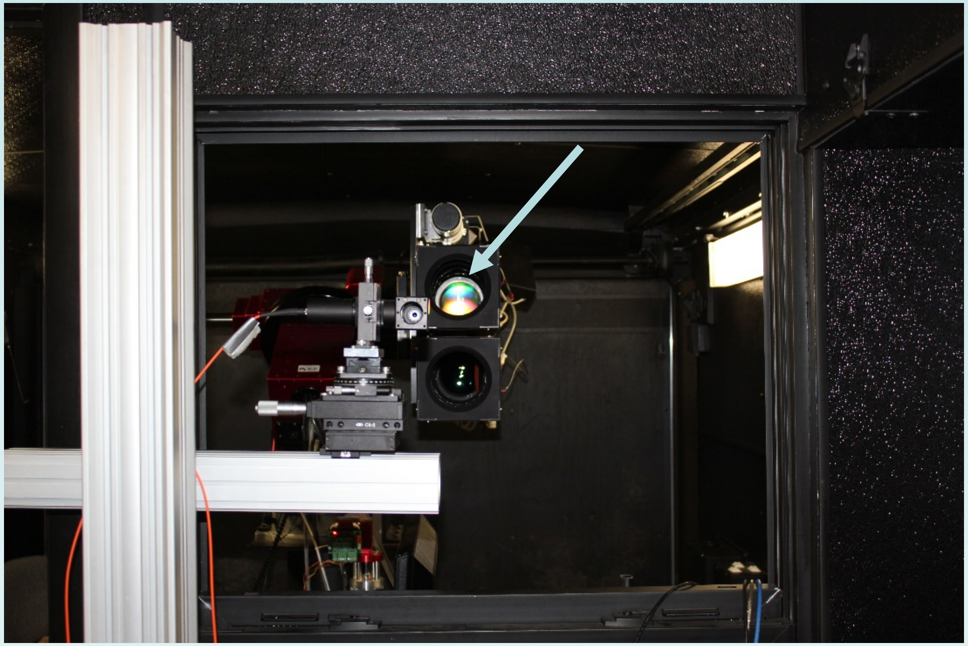
Diffraction Gratings



- Multi-slit diffraction
- reflection gratings and transmission gratings
- most astronomical gratings are reflection gratings

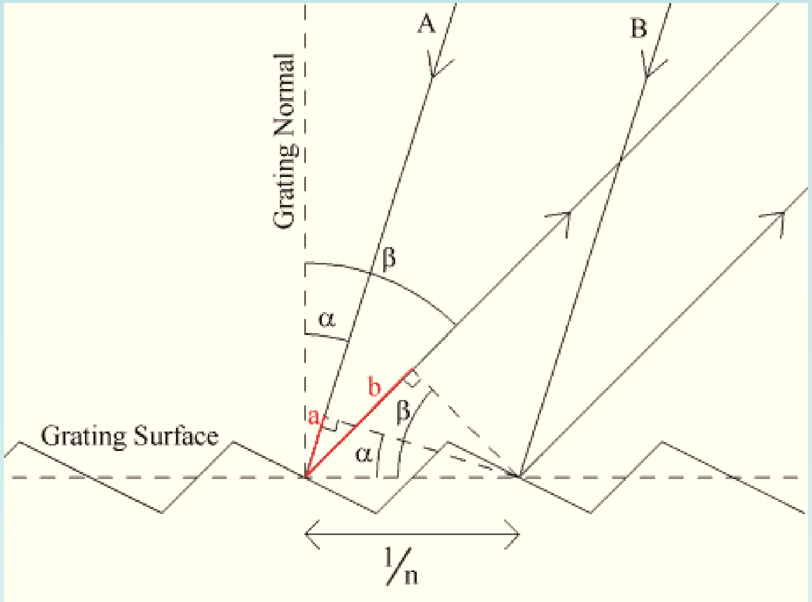






- Note the diffraction grating at the entrance aperture to AESoP. This grating produces a spectrum of every star in the FOV of the refracting telescope. The extended baffle helps limit the FOV to on-axis objects, such as a radiometrically calibrated bright star.

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

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

→ the grating equation

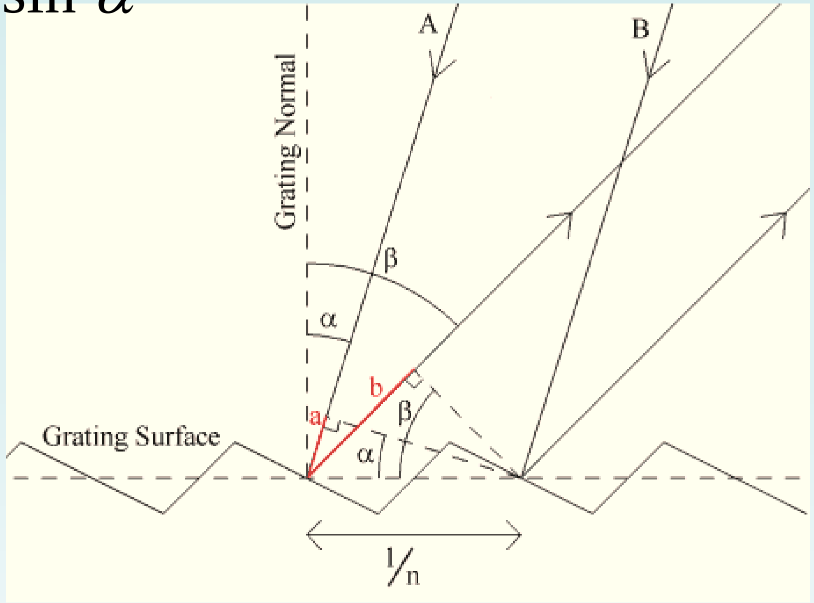
- n is the "spectral order" and quantifies how many wavelengths of path difference are introduced between successive facets or grooves on the grating)

The 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]

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

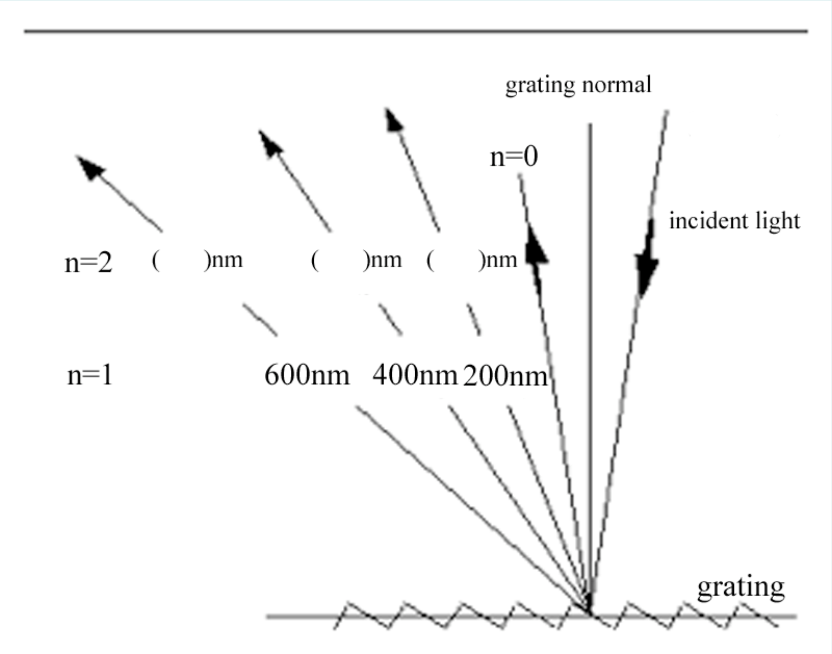
- We are working with a grating with 1000 grooves per millimeter.
- The incident angle α is 15°.
- At what angle will light of 400 nm be diffracted in 1st order (n=1)?
- 500 nm? 600 nm?
- Careful: express wavelength and groove spacing in the same units

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

Multiple Grating Orders

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

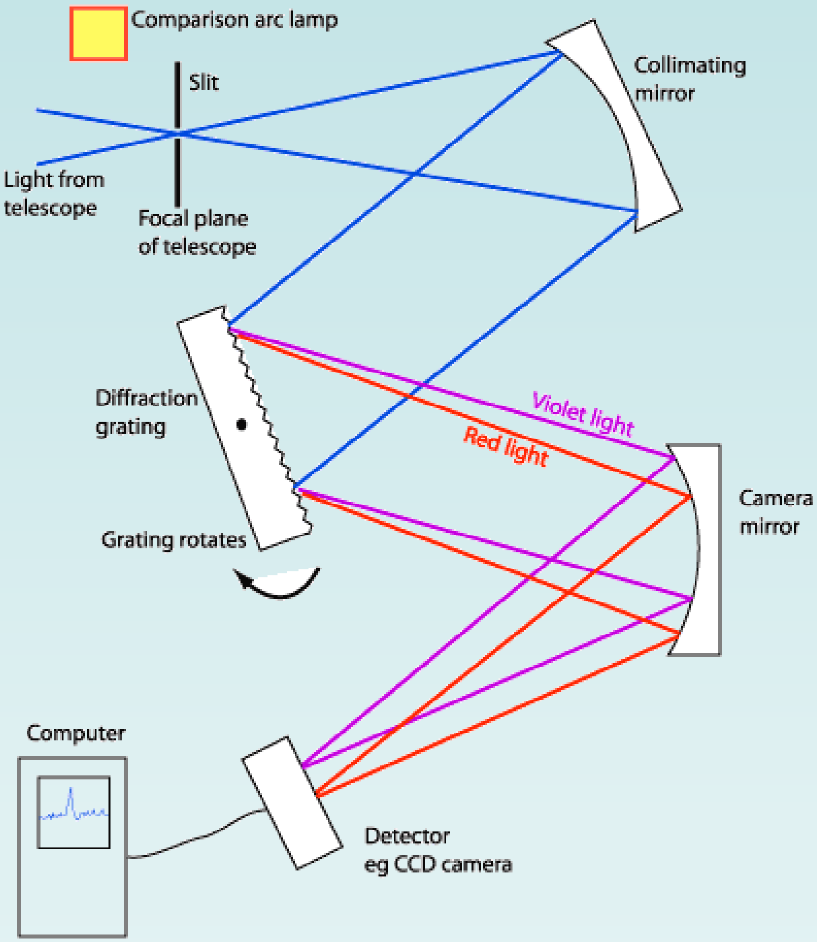
- Multiple spectra are produced by a diffraction grating, corresponding to different orders (n=1,2,3…)
- Quiz [2]
  - For a grating of 1000 grooves/mm and 15° incident angle, what wavelength of light will be diffracted to an angle of 14° in second order?
- Quiz [3]
  - Fill the blanks in the right figure.



Answer1 370nm
Answer2 300, 200, 100 (from left to right)

Slit Spectrographs

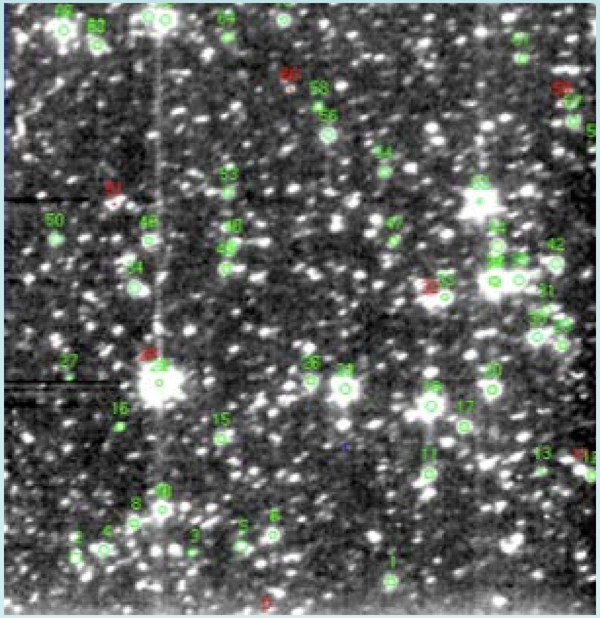
- **Entrance Aperture**: A slit, usually smaller than that of the seeing disk
- **Collimator**: converts a diverging beam to a parallel beam
- **Dispersing Element**: sends light of different colors into different directions
- **Camera**: converts a parallel beam into a converging beam
- **Detector**: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

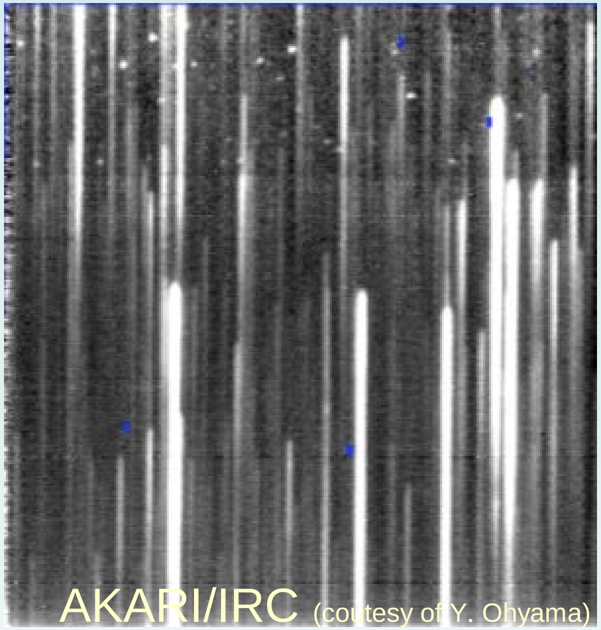


A Schematic Diagram of a Slit Spectrograph

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



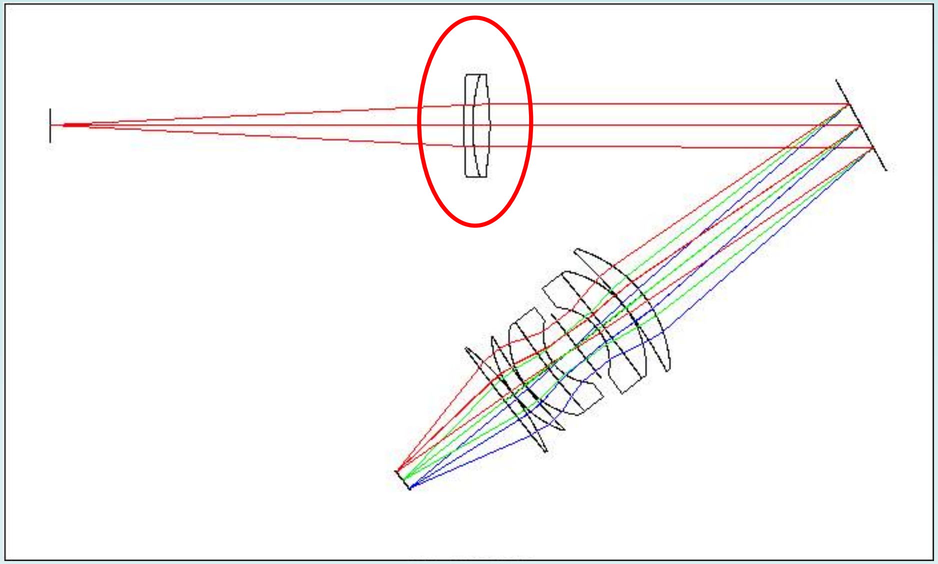


Objective spectrum of the above star field.

AKARI/IRC (coutesy of Y. Ohyama)

Collimator

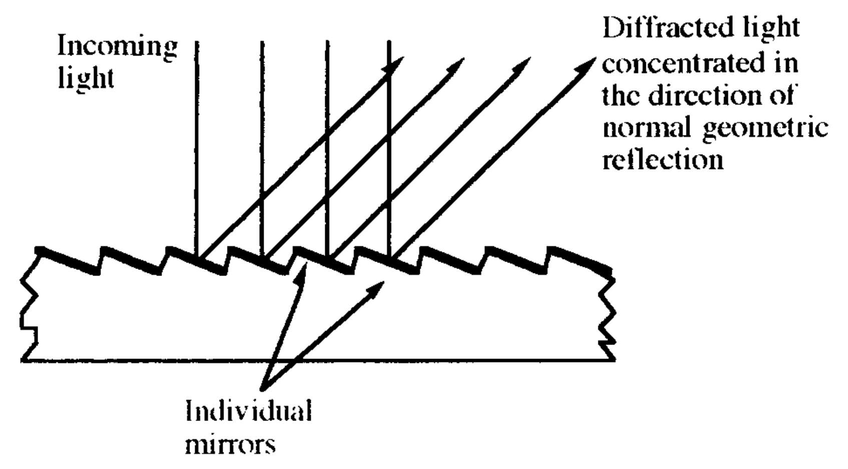
- The collimator converts the diverging beam of white light from the slit to a parallel beam.
- The focal ratio of the collimator must be matched to the effective focal ratio of the telescope.
- The diameter of the collimator determines the diameter of the light beam in the spectrograph. The size of the collimator affects the size of the "slit image" on the detector.



Reflection Grating Efficiency

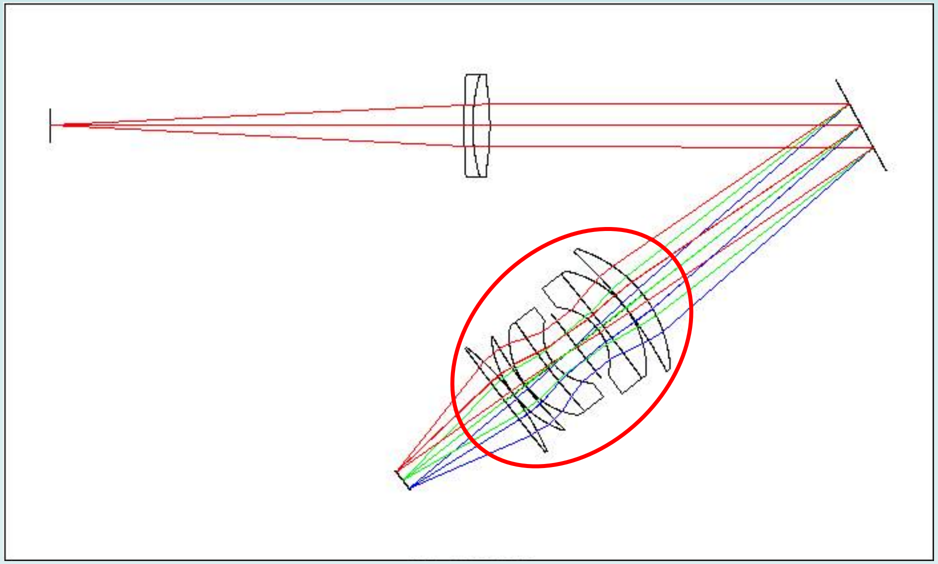
- **Problem**: A grating diffracts light into many orders; one order contains only a fraction of the light

- **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. Up to 90% of the incident light can be diffracted preferentially into the first order.

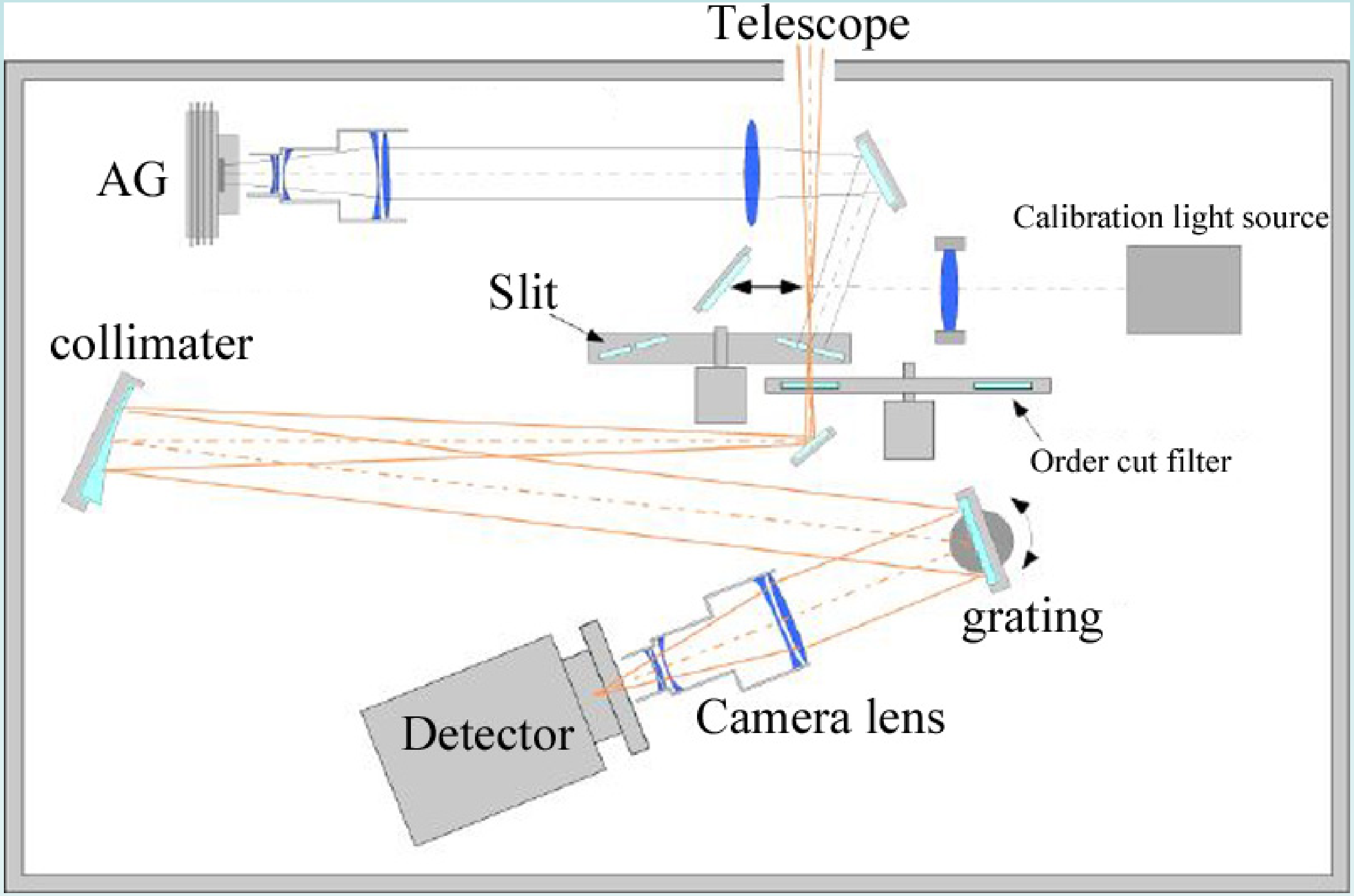


Camera Types

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



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



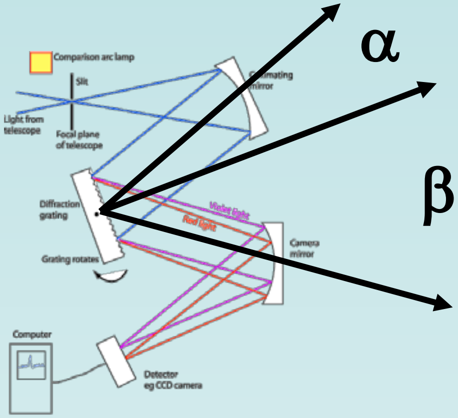
Nayuta 2-m Spectrograph

Courtesy of S. Ozaki (NAJO)

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. d is the gratng groove spacing.

- The “angular dispersion” of a spectrograph is given by δβ/δλ:

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

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

- 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
  - the grating resolution
  - the size of the slit image
  - the pixel size

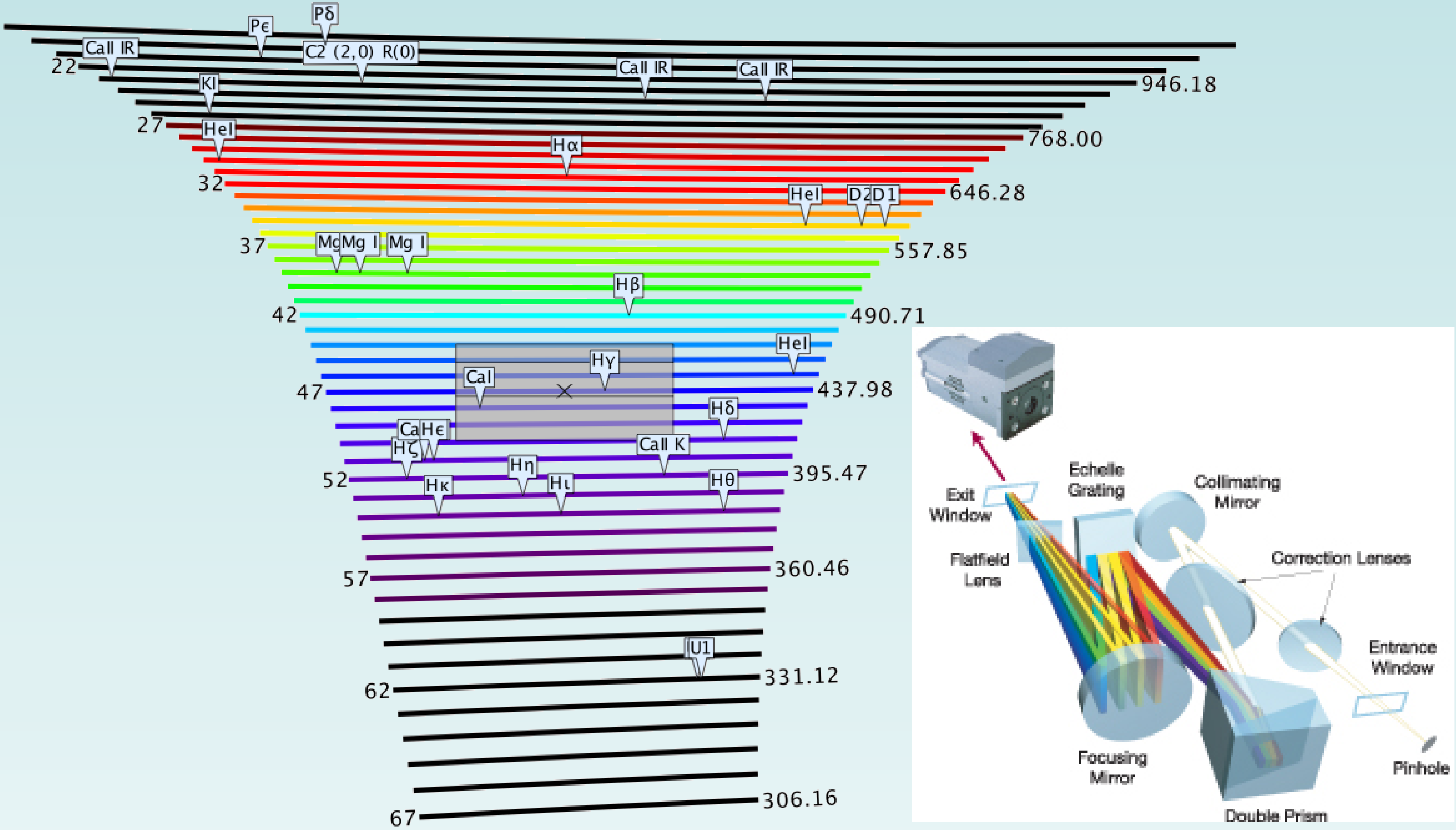
Throughput Matters

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

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


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
52
395.47
Hη
Hκ
Hι
Hθ
57
360.46
U1
62
331.12
67
306.16
Exit Window
Echelle Grating
Collimating Mirror
Flatfield Lens
Correction Lenses
Entrance Window
Focusing Mirror
Pinhole
Double Prism

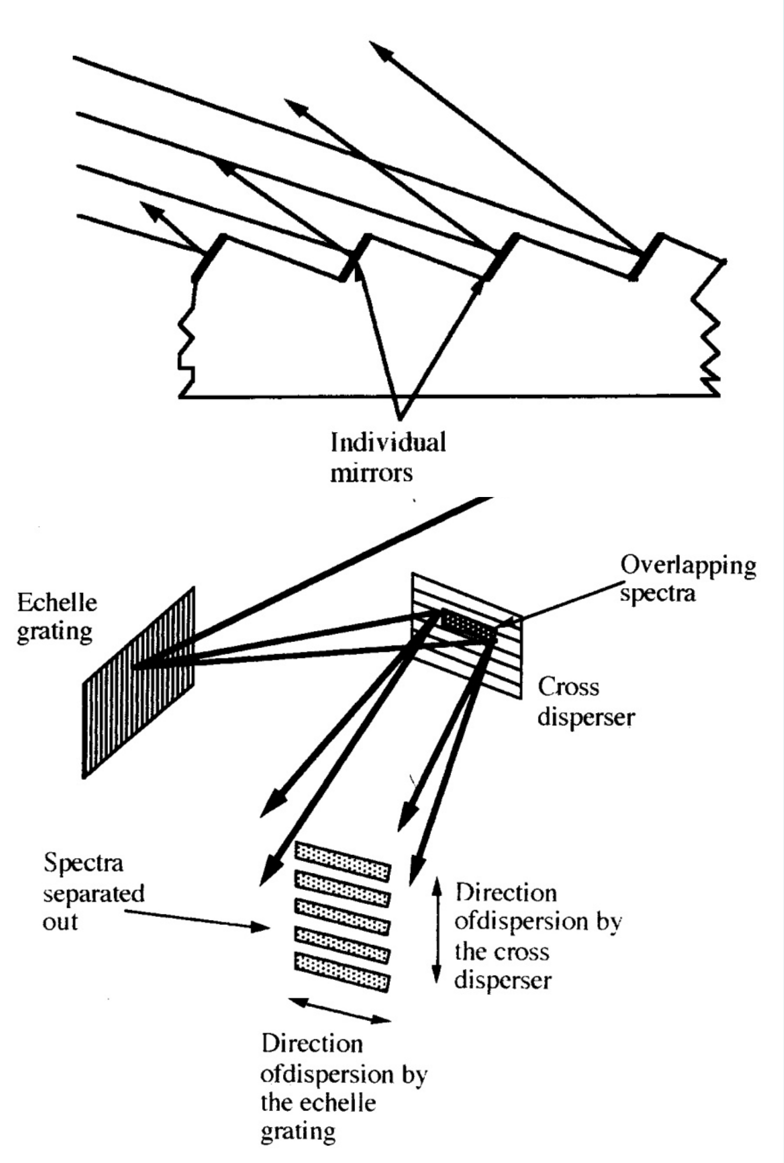
Echelle Gratings

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

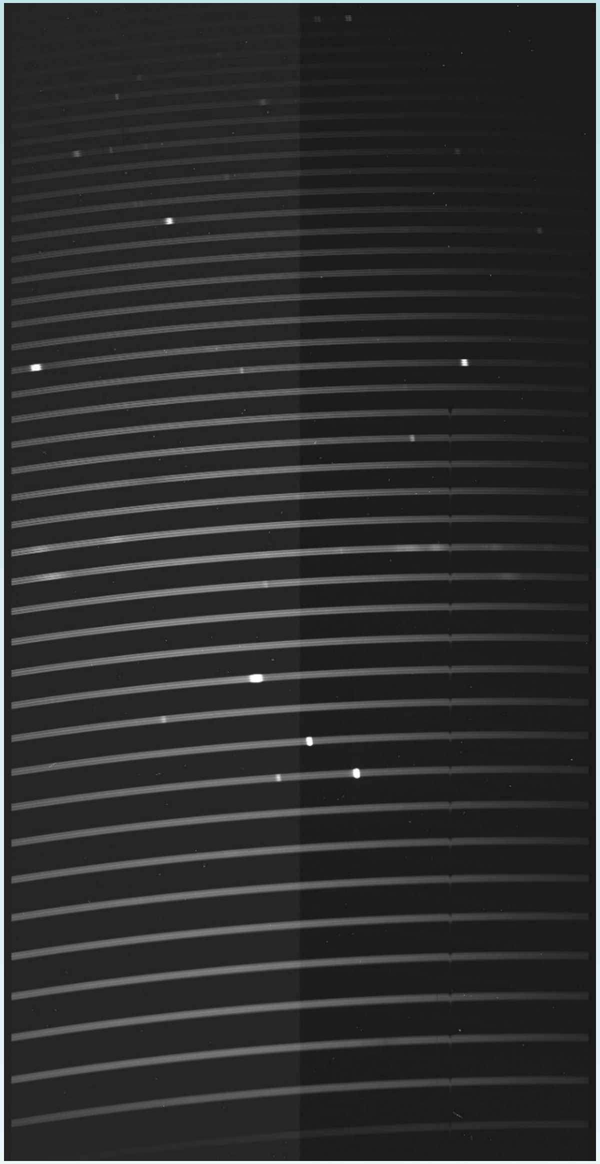
- For high orders, must increase α and β in the grating equation (to ~50-75^o)

- 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.



A Real Echelle Spectrum - PN

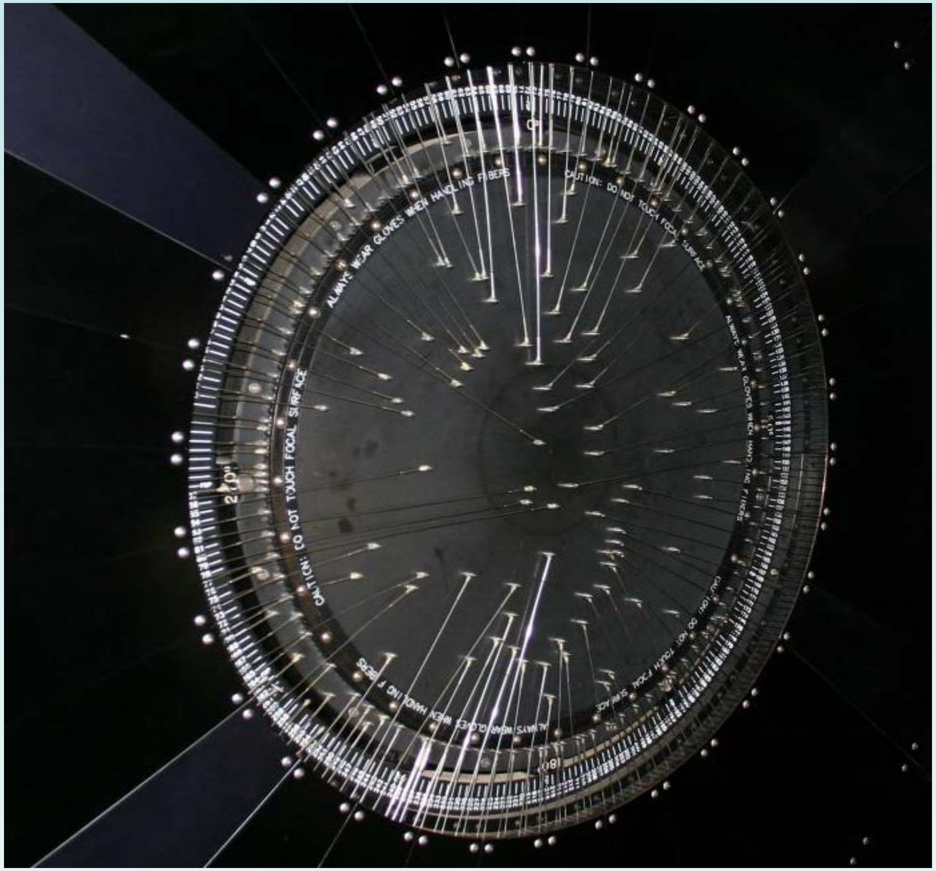


- IC 418 observed with the South African Large Telescope (SALT) High Resolution Spectrometer

- The three bright emission lines just below center are Hβ, Hγ, and Hδ from lower right to upper left.

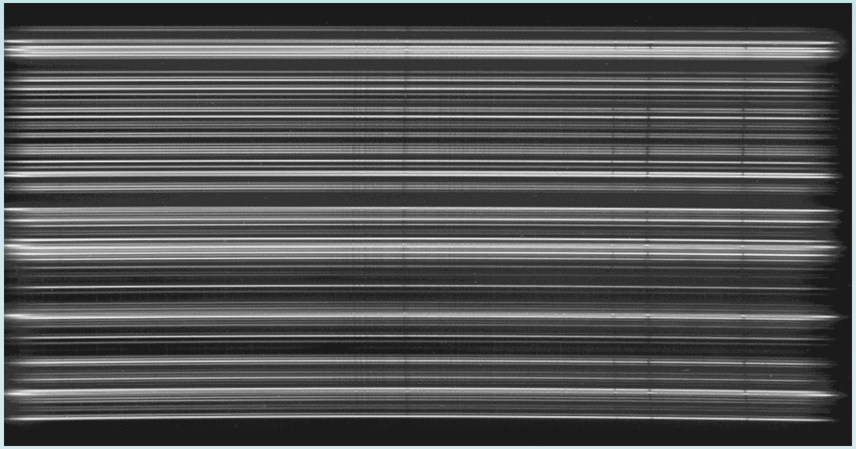
Multi-object Spectroscopy

- Observing one star at a time is inefficient
- When many targets (stars, galaxies, QSOs, …) are available in a field (e.g. a star cluster) use multi-object spectroscopy
- Robotically put an optical fiber at locations of objects to take spectra - HYDRA.
- Feed the optical fibers into a spectrograph.
- Stacked spectra on the detector.
- Requires accurate astrometry or the fiber "misses" the target.



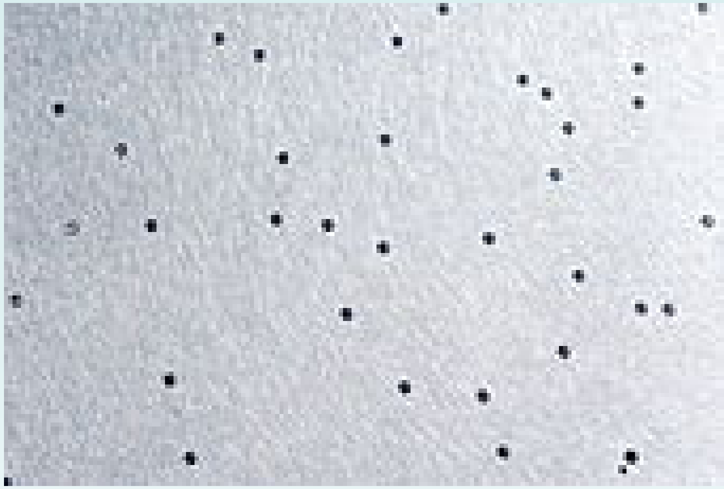
HYDRA multi-fiber slit spectra

- About 100 stellar spectra are recorded with the fiber ends acting as a slit. Note that the spectra “line up” in wavelength.

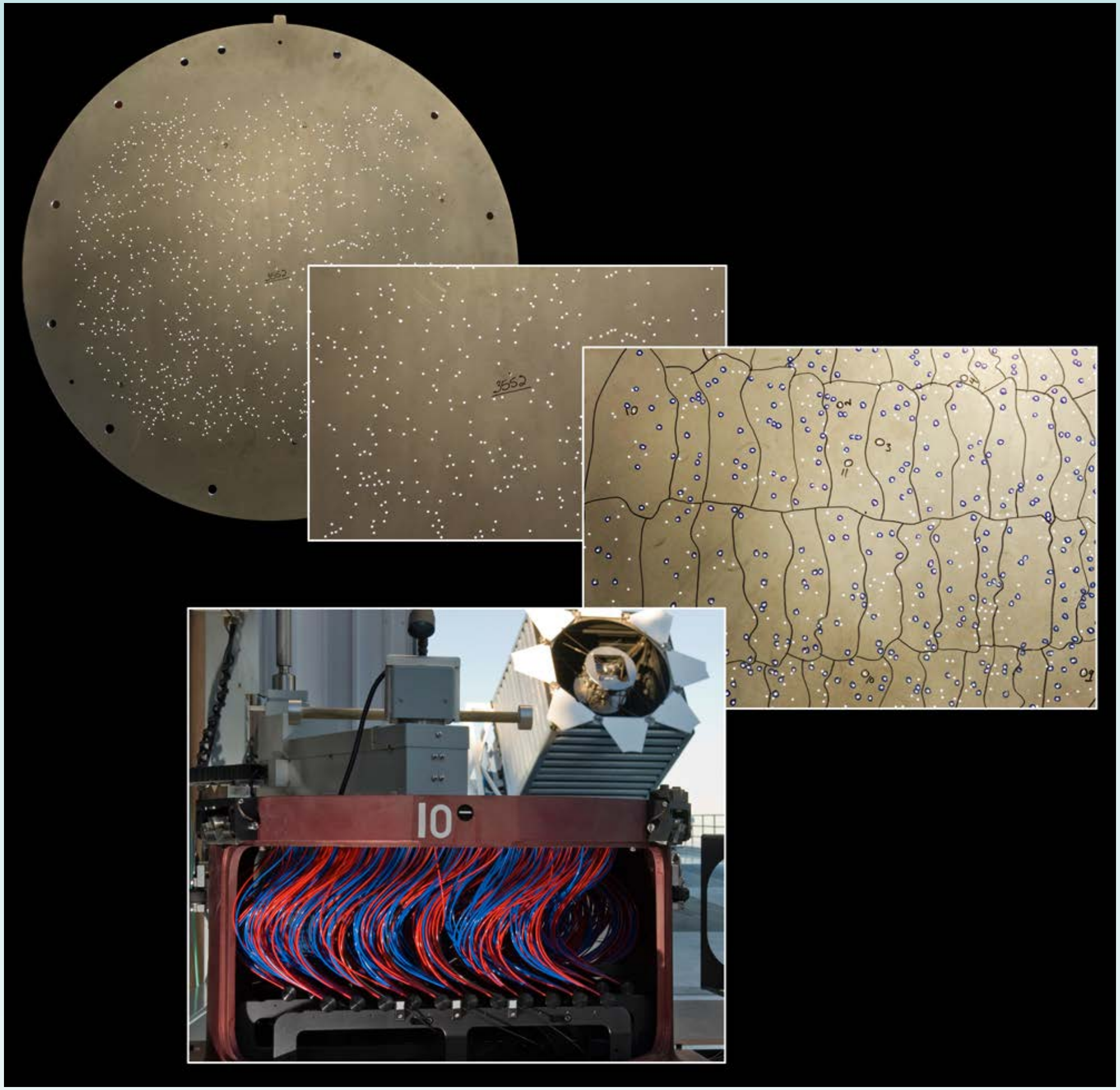


SDSS Multi-Object Spectrometry

- SDSS multi-object spectrometer
  - Galaxies
  - QSOs
  - Selected stars
- Fibers are inserted in drilled plates by hand

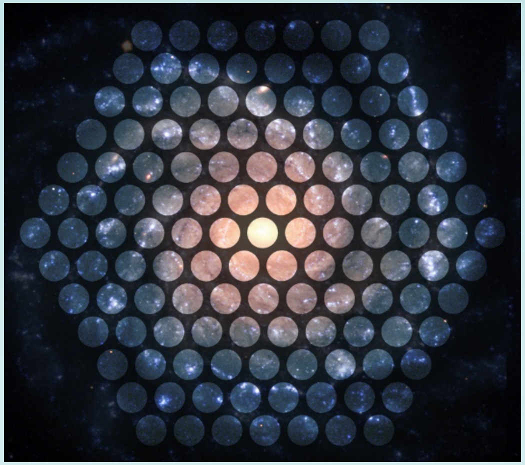


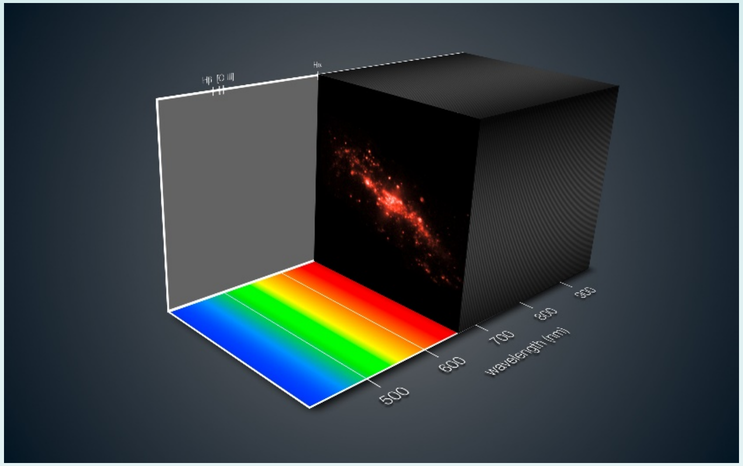
SDSS at Work (BOSS Project)



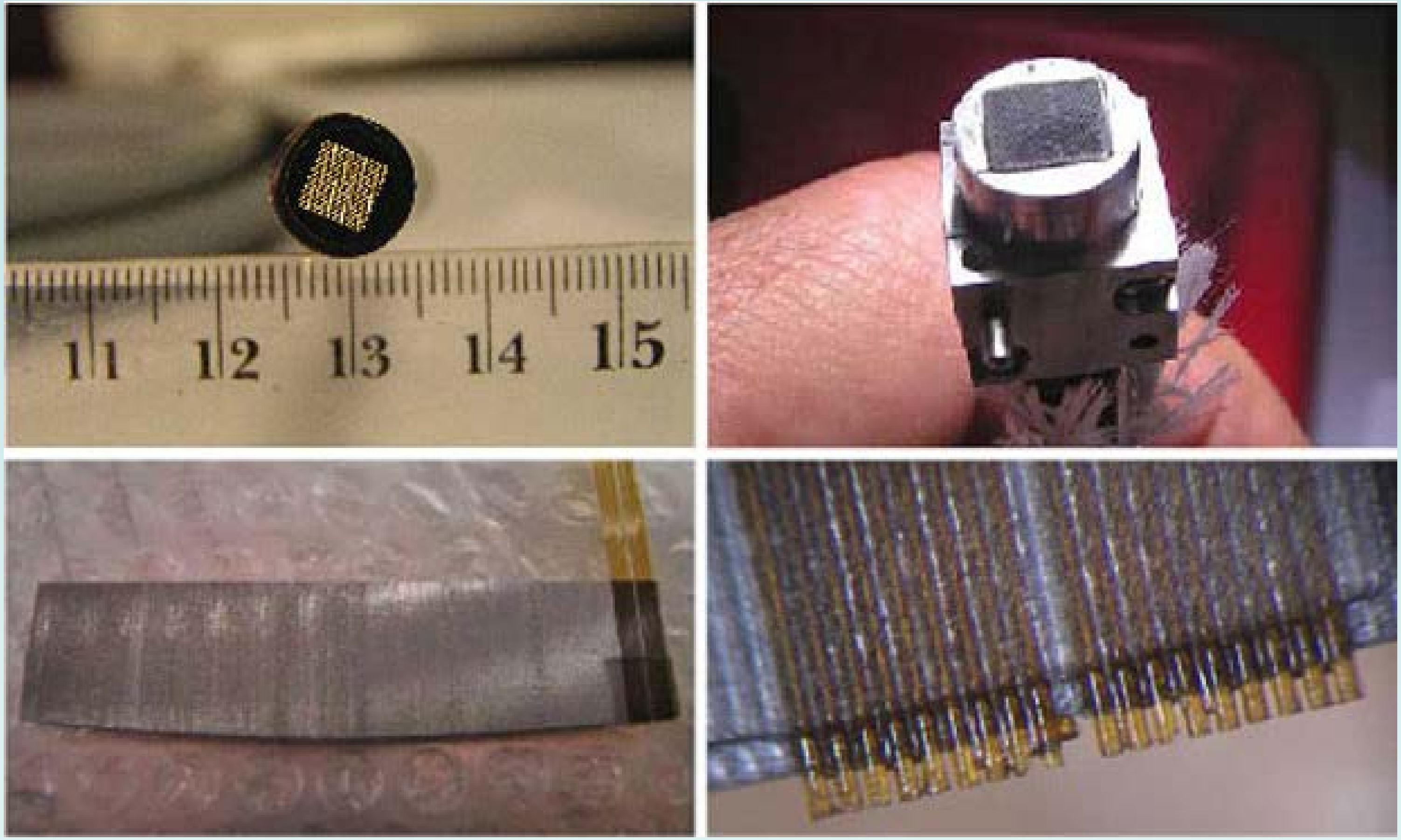
Integral Field Unit (IFU) Spectroscopy

- An image is placed on a fiber bundle (lenslet array, individual fibers in an aperture array)
- A data cube (x, y, λ) is produced

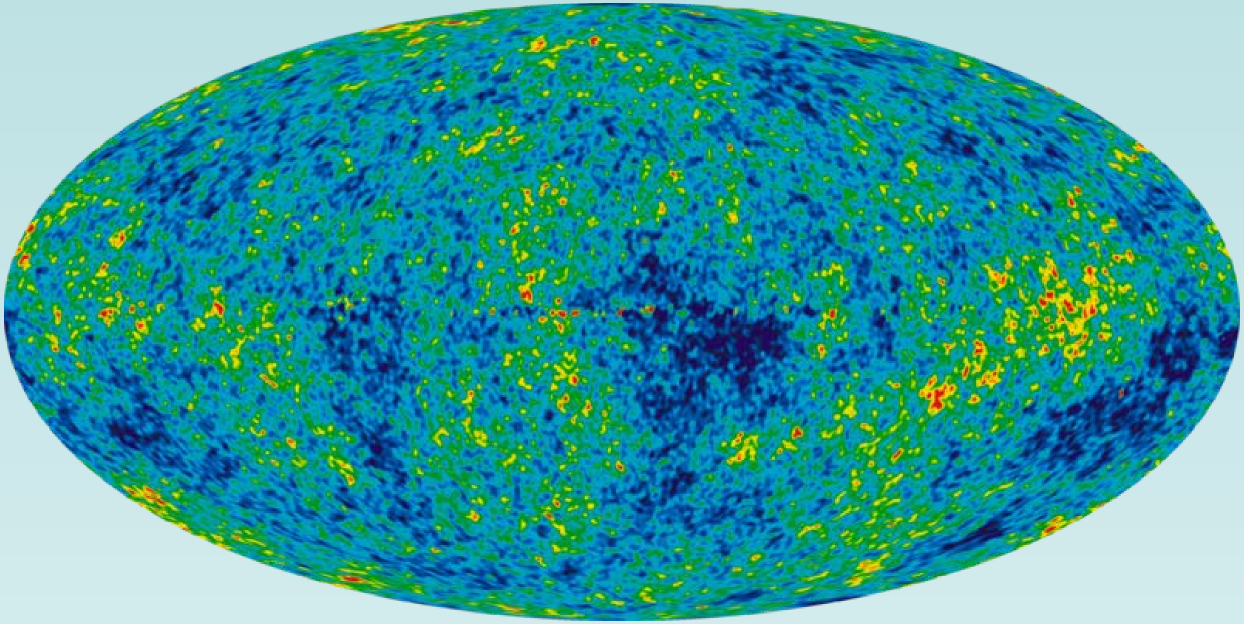


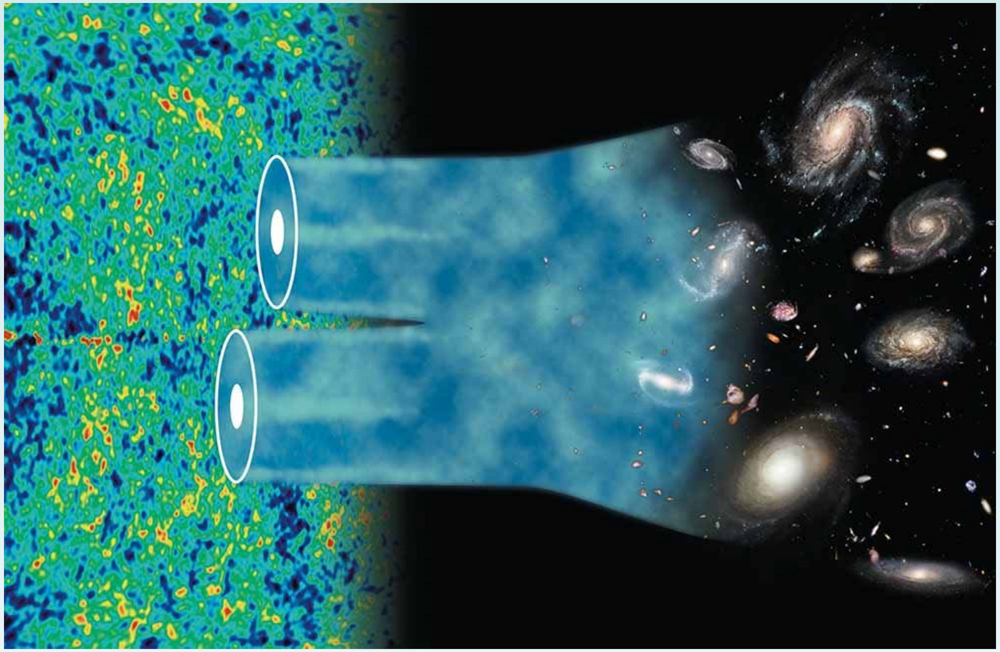


HETDEX – VIRUS Spectrometers



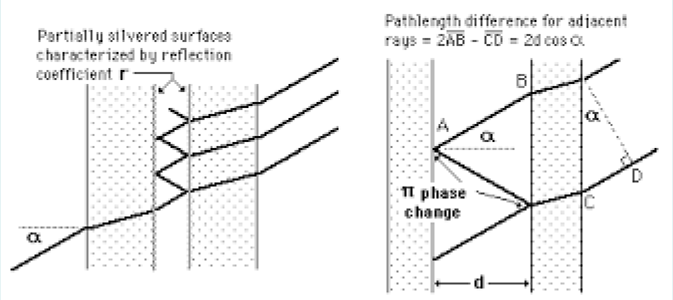
- Each IFU has 230 fibers. There are 150 spectrometers! Each data cube will contain 34,000 spectra.

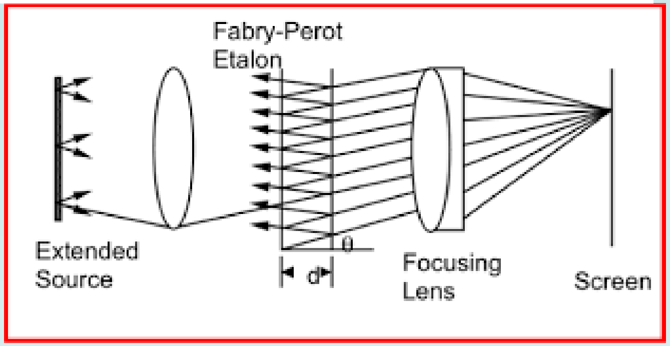


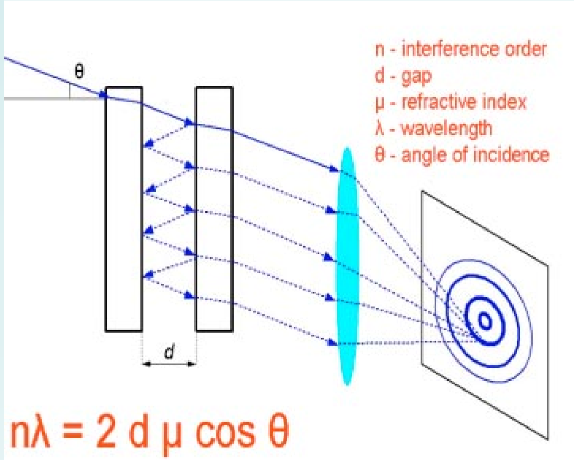


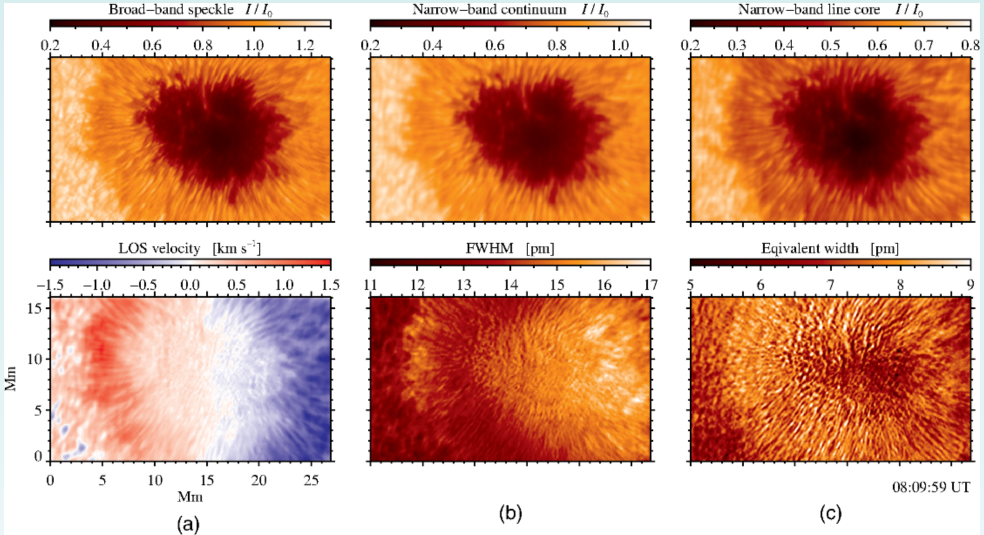
Fabry-Perot Interferometry

- Fabry-Perot interferometry uses parallel mirrors to create interference from incoming sources.

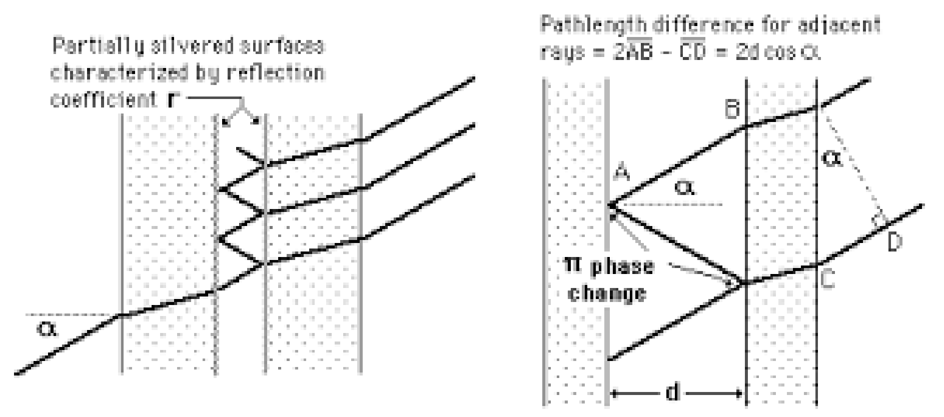








Etalon Fundamentals



- Effective Transmission
- $T_e = \frac{(1-r)^2}{1+r^2-2r\cos(4\pi n d \lambda^{-1}\cos\gamma)}$
  - Where:
  - r is the reflectivity of the mirrors
  - d is the spacing between the mirrors
  - n is refractive index in the space between mirrors

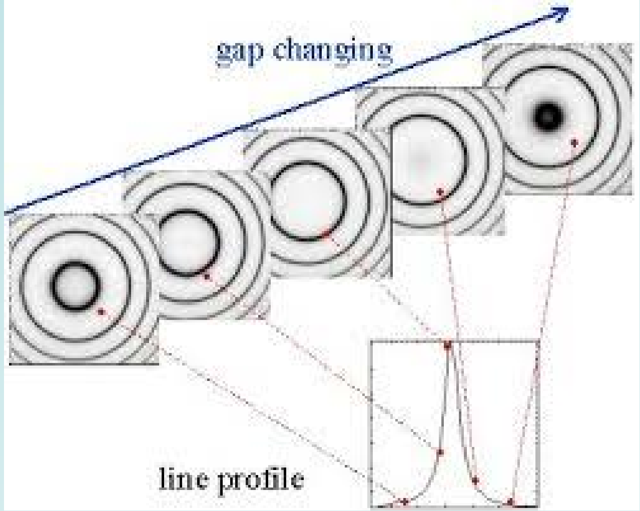
- Transmission maxima at λ:
  - $2nd\cos\alpha = m\lambda$
- Free Spectral Range
- $FSR = \lambda_m - \lambda_{m-1};\ m \gg 1$
- $T_e(min)$ when
  - $2nd\cos\alpha = (2m+1)\,\lambda/2$

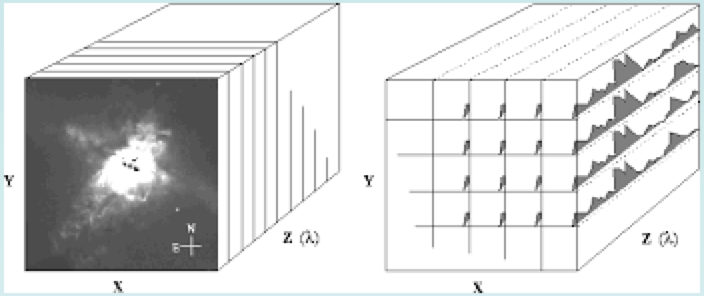
- Finesse of an etalon
- $\mathcal{F} = \frac{FSR}{w_{1/2}} = \frac{\pi r^{1/2}}{1-r}$
  - $w_{1/2}$= FWHM of maximum

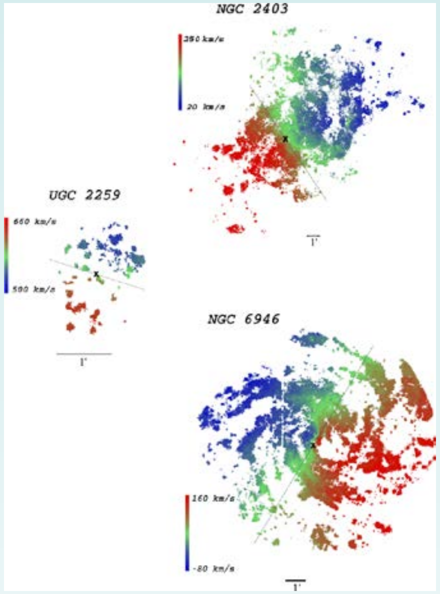
- Resolution
  - $\boldsymbol{R = \frac{\lambda}{\Delta\lambda} = \mathcal{F}m}$

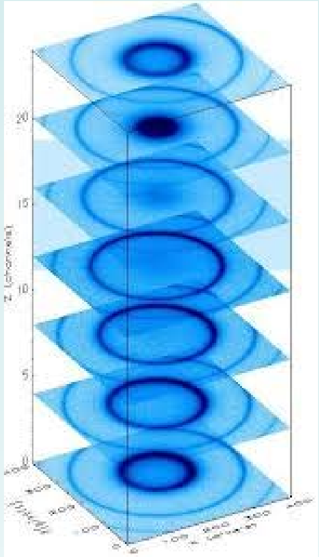
Fabry-Perot Data Cube

- Produce a data cube by scanning the spacing between the reflective plates









FT Interferometry

- Fourier Transform:
- $F(u) = \int_{-\infty}^{\infty} I(x) e^{-2i\pi ux}\, dx$
- Single detector
  - Fellget Advantage
  - E.g. very high resolution IR spectroscopy