Spectroscopy – measuring Intensity vs. Wavelength

Why is spectroscopy important ?

Spectroscopy is used to measure physical properties of objects.

Colors give temperature estimates

Absorption or Emission Lines can identify composition and physical conditions

Spectroscopy measures accurate velocities

Velocity measurements from shifts of lines can tell us about movement.

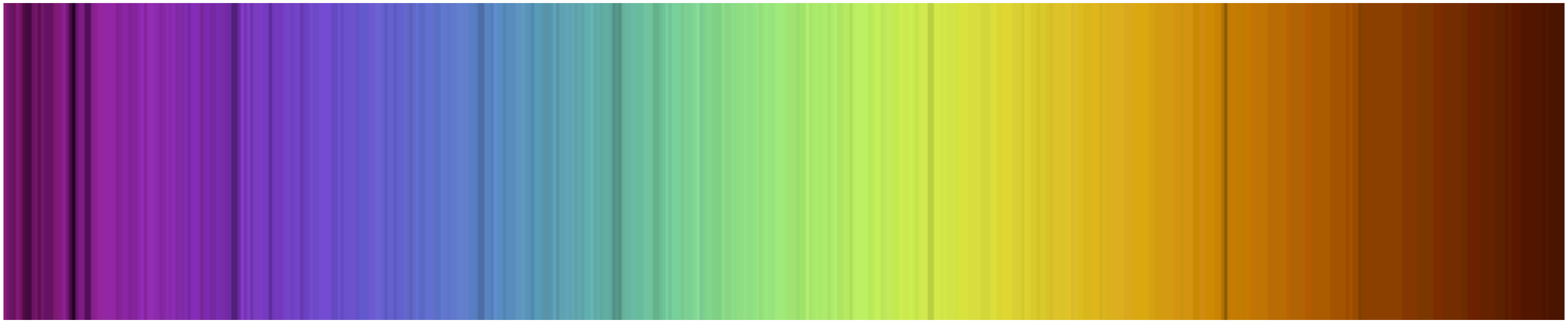
dl/l = v/c

Measure only radial component of velocity (astrometry only in plane of sky).

Example: Radial velocities of Exosolar Planets are measured by their influence on their star.

Jupiter creates a radial velocity variation of ~1 ms/ of the sun.

"Typical" intrinsic width of a stellar absorption line is ~0.005 nm



Spectroscopy – measuring Intensity vs. Wavelength

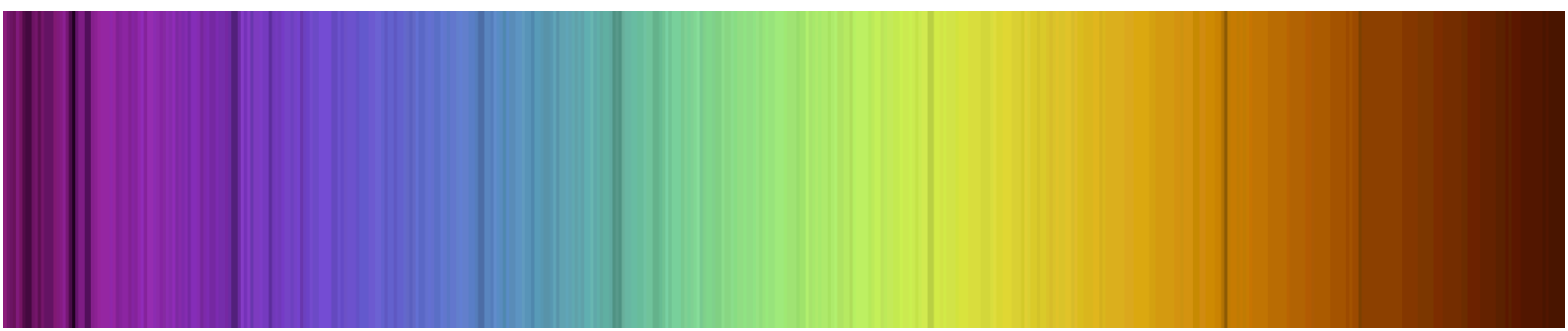
Techniques for Spectroscopy

Use Differential Refraction vs. wavelength of materials(prisms)

High throughput. Efficient.
Compact.
Limited in spectral resolution achievable.
Dispersion is nonlinear.

Use Multiple Interference Effects (Diffraction Gratings)

Can obtain much higher spectral resolution
Dispersion is linear



Some Uses of Spectroscopy

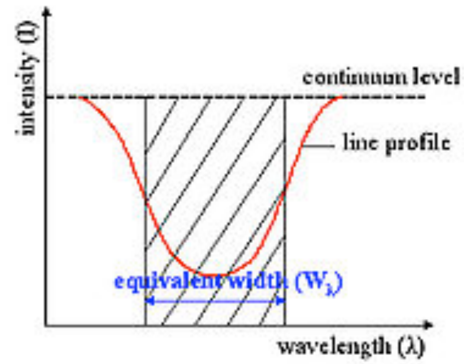
- Stars
  - Used with distance, binaries, etc. to piece together stellar physics
  - Mass Distribution of Star Clusters
  - Radial velocity
- Galaxies
  - Star formation rate, stellar populations
  - Active Galactic Nuclei
  - Quasars as probes of structure
- Reflectance Spectra
  - Asteroids, KBO's

Conventions/Definitions

$$R = \frac{\lambda}{\Delta\lambda}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

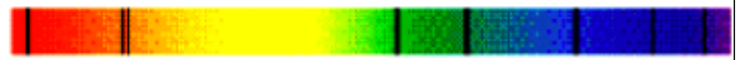
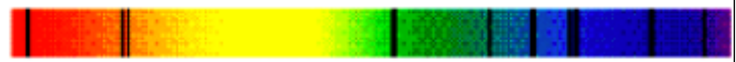
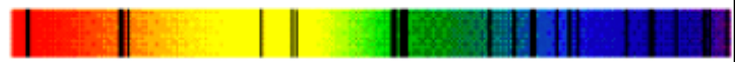
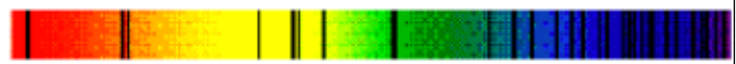
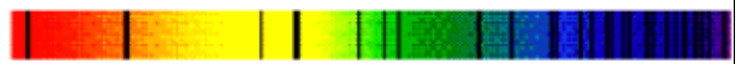
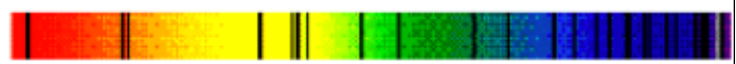
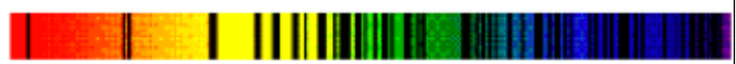
$$v = \frac{c}{R}$$



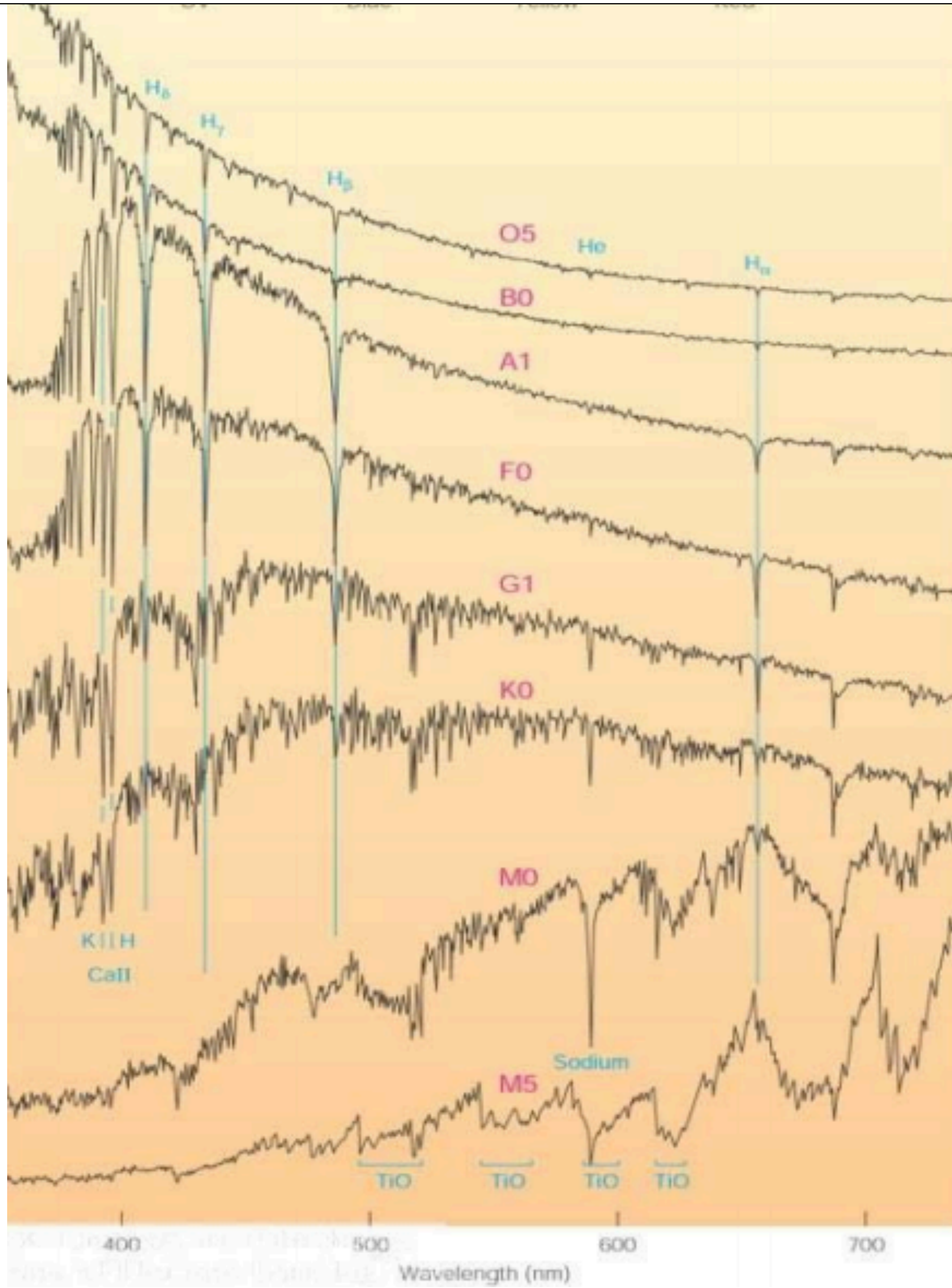
- Spectrometry -observation of the spectrum of an object.
- Spectrophotometry - observation of the intensity vs. wavelength
- Kinematics - determination of the radial velocity of an object.
- Equivalent width - measurement of the strength of an absorption line.
- Redshift,z - shift of lines due to recession velocity in an expanding universe.

$$z = \frac{\Delta\lambda}{\lambda_{emitted}} \qquad z = \frac{\lambda_{observed}}{\lambda_{emitted}} - 1$$

Stars

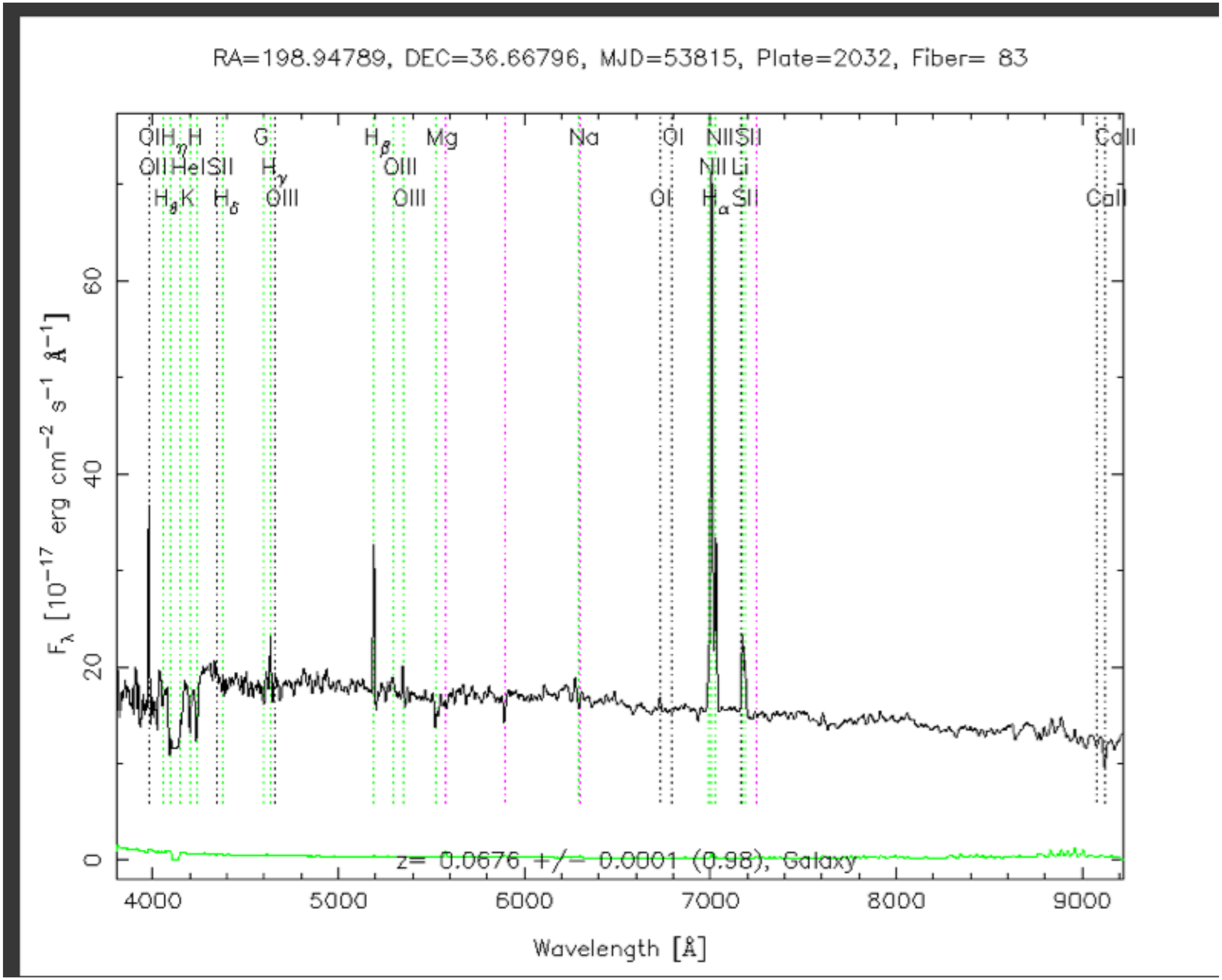
Spectral type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)	Typical Spectrum
O	Stars of Orion's Belt	>30,000 K	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*	
R	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*	
A	Sirius	10,000 K–7,500 K	Very strong hydrogen lines	290–390 nm (violet)*	
F	Polaris	7,500 K–6,000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*	
G	Sun, Alpha Centauri A	6,000 K–5,000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)	
K	Arcturus	5,000 K–3,500 K	Lines of neutral and singly ionized metals some molecules	580–830 nm (red)	
M	Betelguese, Proxima Centauri	<3,500 K	Molecular lines strong	>830 nm (infrared)	

*All stars above 6,000 K look more or less white to the human eye because they emit plenty of rediation at all visible wavelength

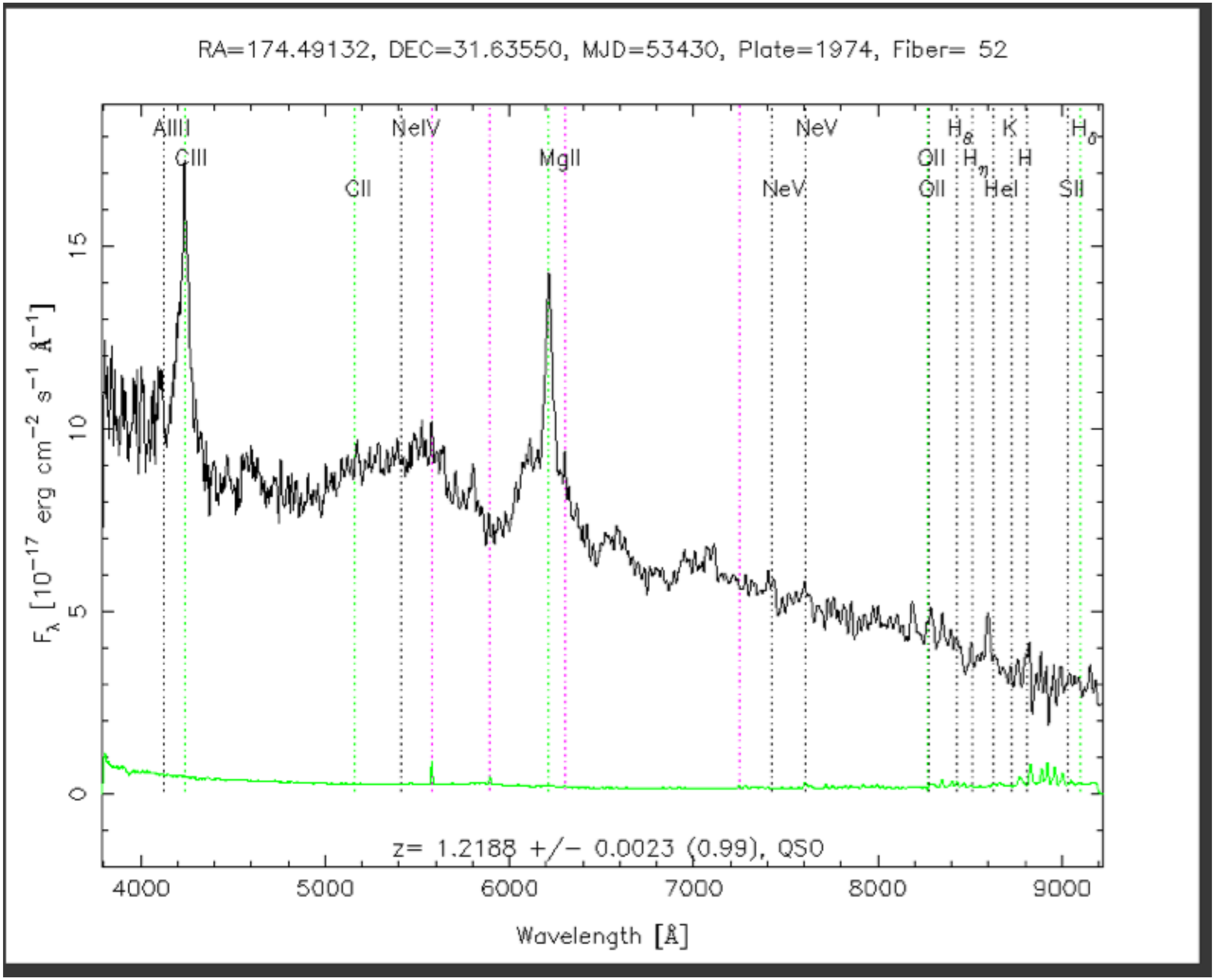


O5
He
B0
A1
F0
G1
K0
M0
K H
CaII
Sodium
M5
TiO
TiO
TiO
TiO
400
500
600
700
Wavelength (nm)

Galaxy Spectra

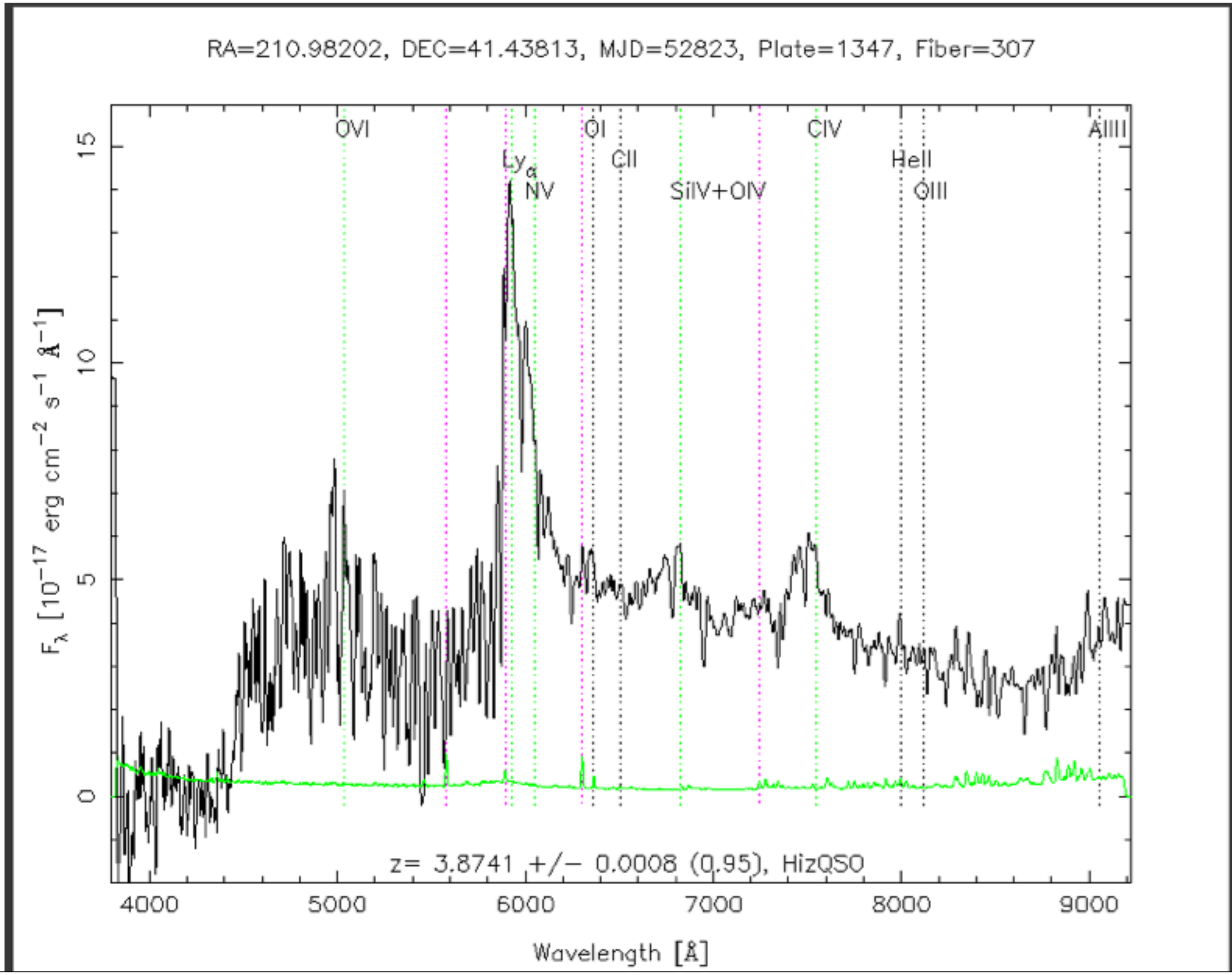


AGN Spectra

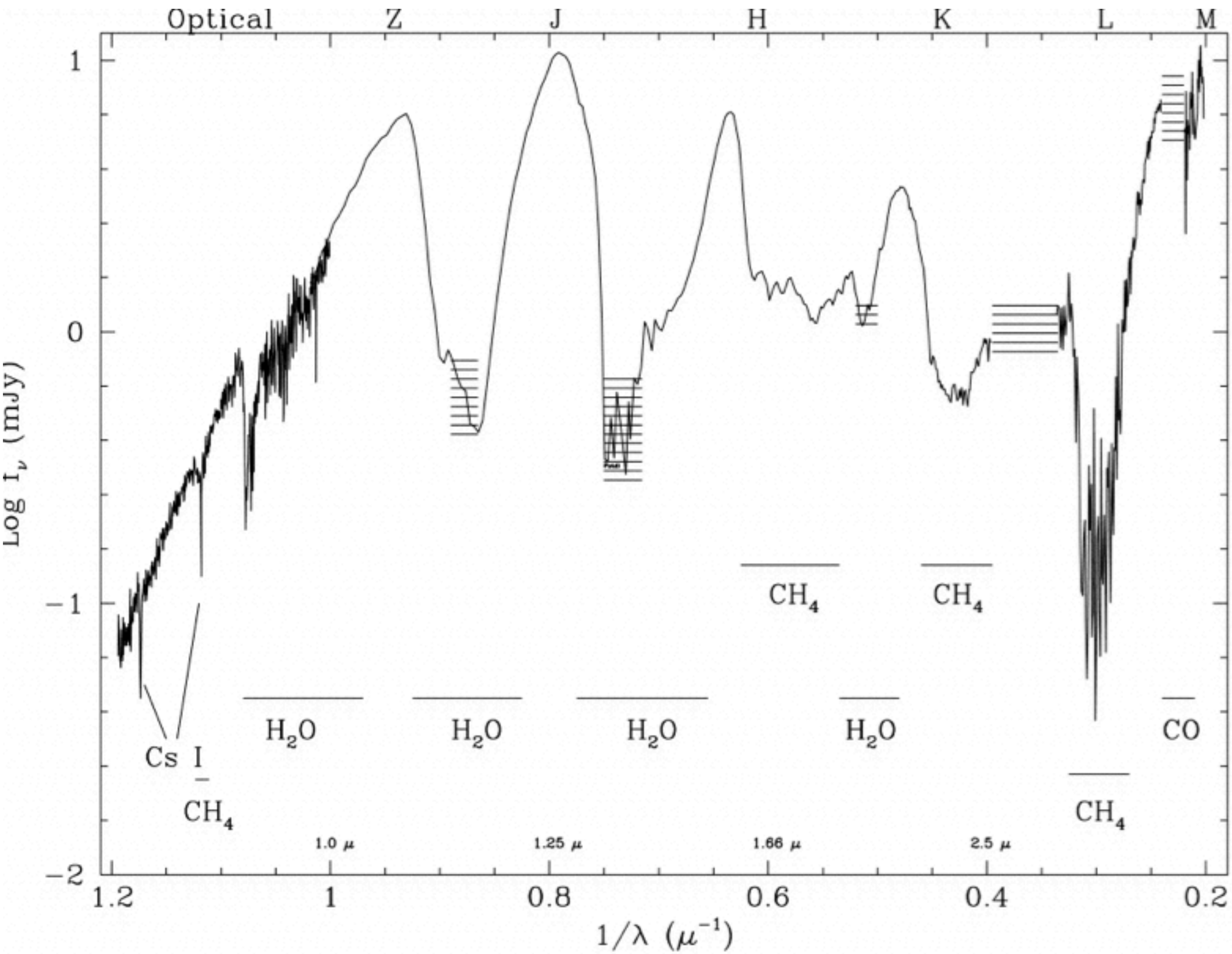


RA=174.49132, DEC=31.63550, MJD=53430, Plate=1974, Fiber= 52
AlIII
CIII
CII
NeIV
MgII
NeV
NeV
OII
OII
Hδ
Hη
K
H
HeI
SII
Hδ
z= 1.2188 +/- 0.0023 (0.99), QSO
Wavelength [Å]
F_λ [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]
0
5
10
15
4000
5000
6000
7000
8000
9000

Quasar Spectra

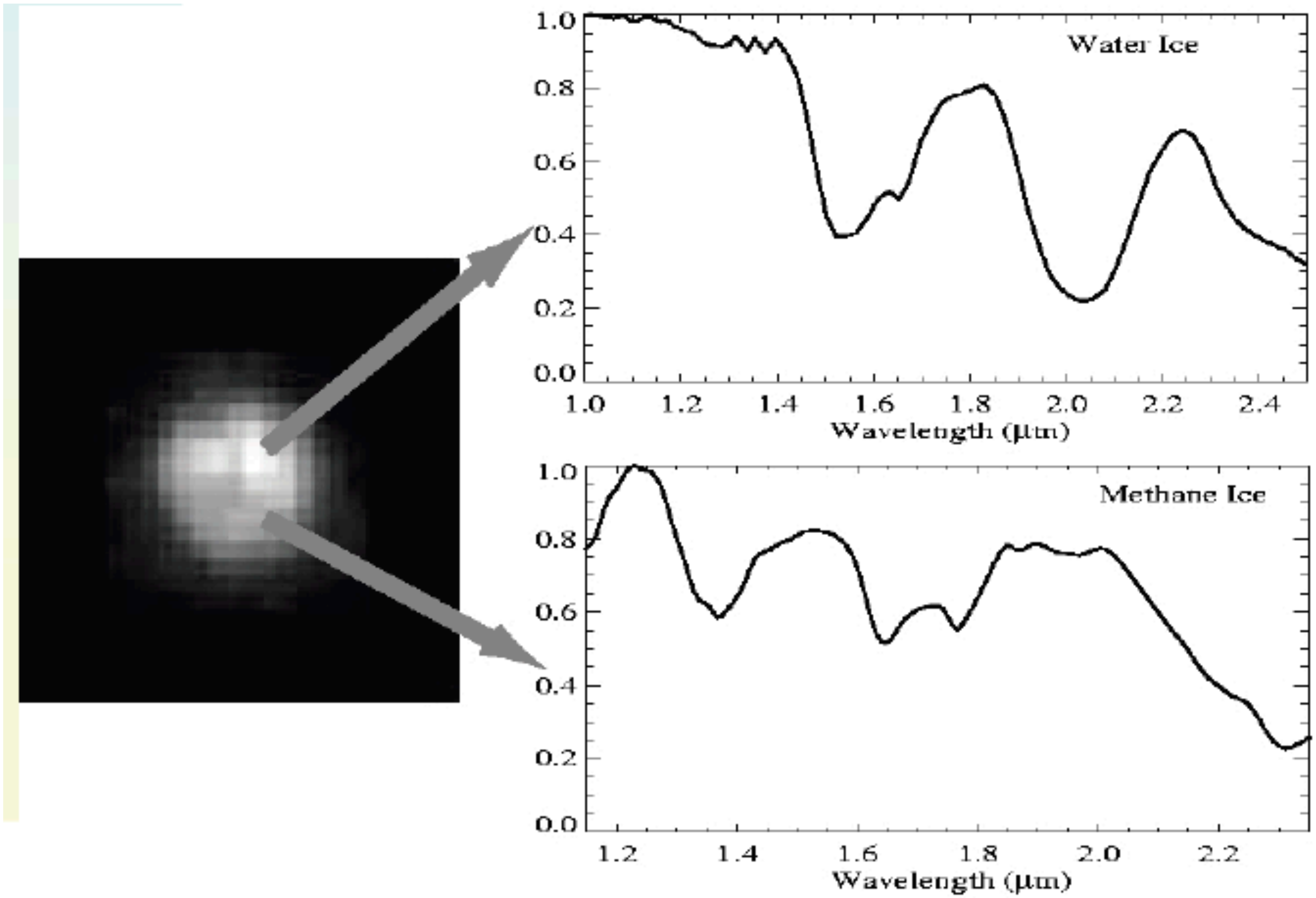


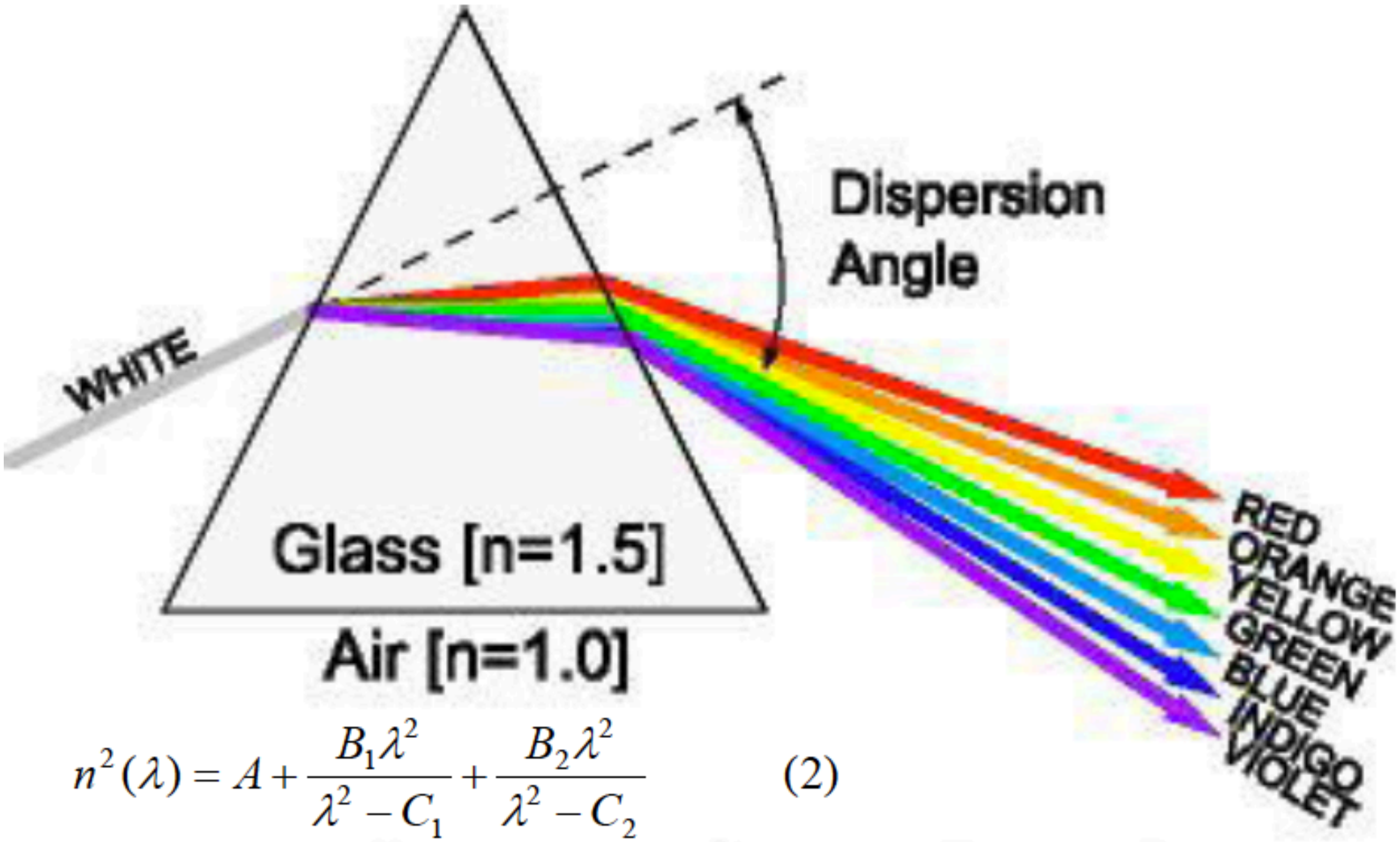
Brown Dwarf



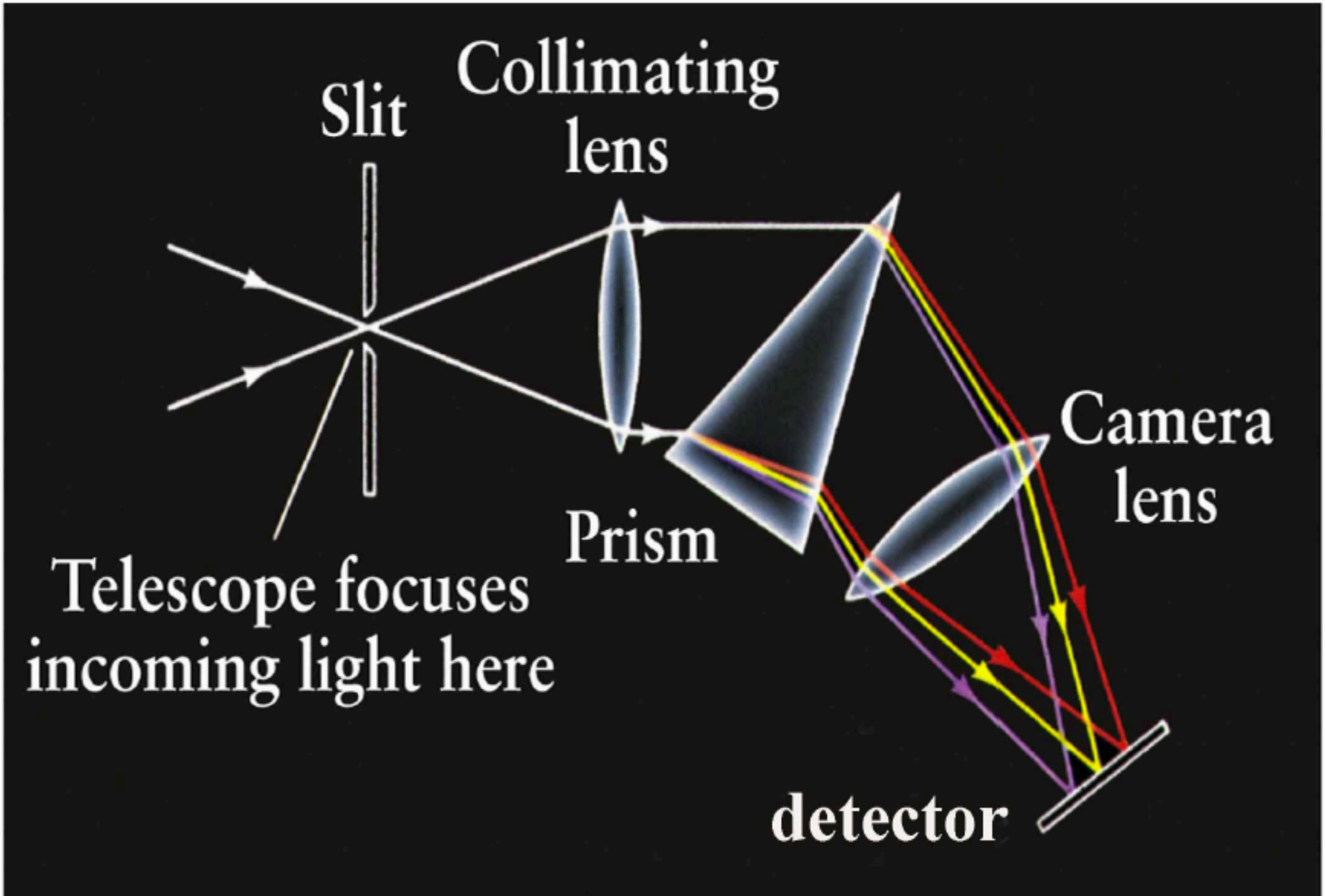
Optical
Z
J
H
K
L
M
Log f_ν (mJy)
1
0
−1
−2
CH_4
CH_4
H_2O
H_2O
H_2O
H_2O
CO
Cs I
CH_4
CH_4
1.0 μ
1.25 μ
1.66 μ
2.5 μ
1.2
1
0.8
0.6
0.4
0.2
$1/\lambda$ (μ^{-1})

Kuiper belt Object (Sedna)



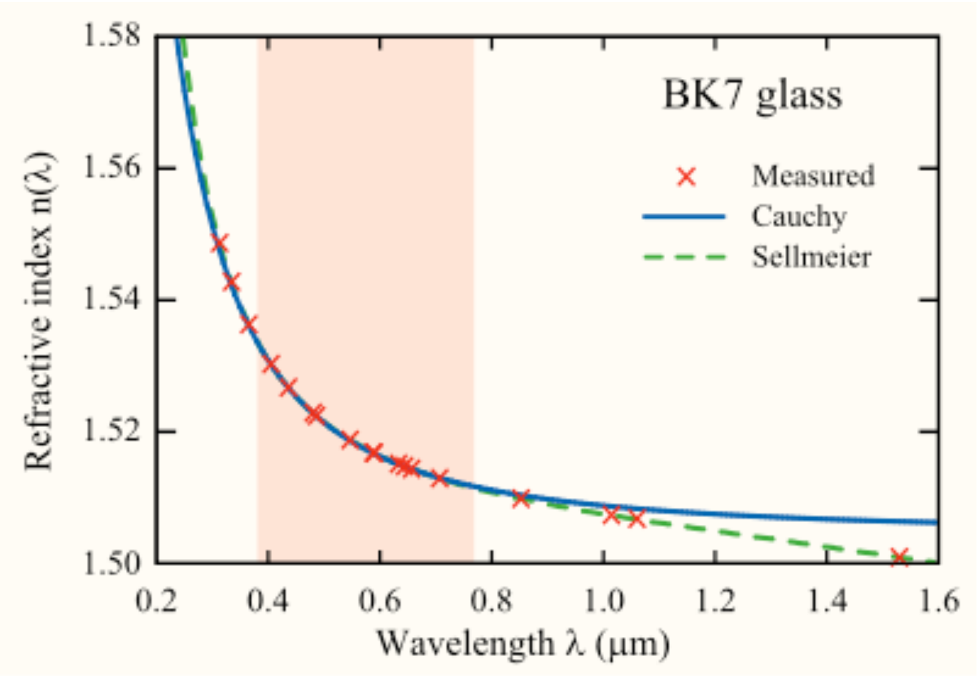


$$n^2(\lambda) = A + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} \qquad (2)$$


Slit
Collimating lens
Camera lens
Prism
Telescope focuses incoming light here
detector

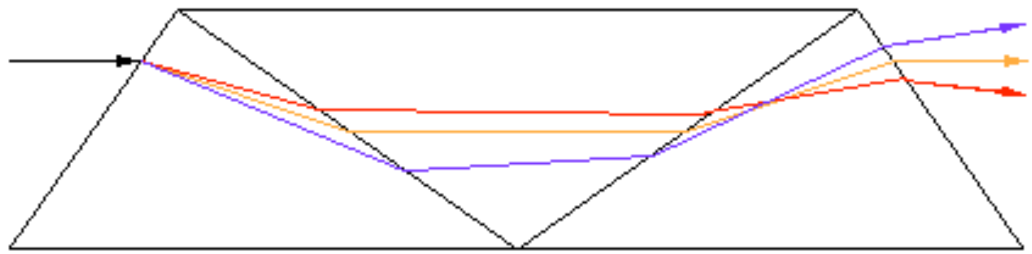
Prisms

- High throughput
- nonlinear dispersion
- Useful for low R
- Have to accommodate deviation of beam

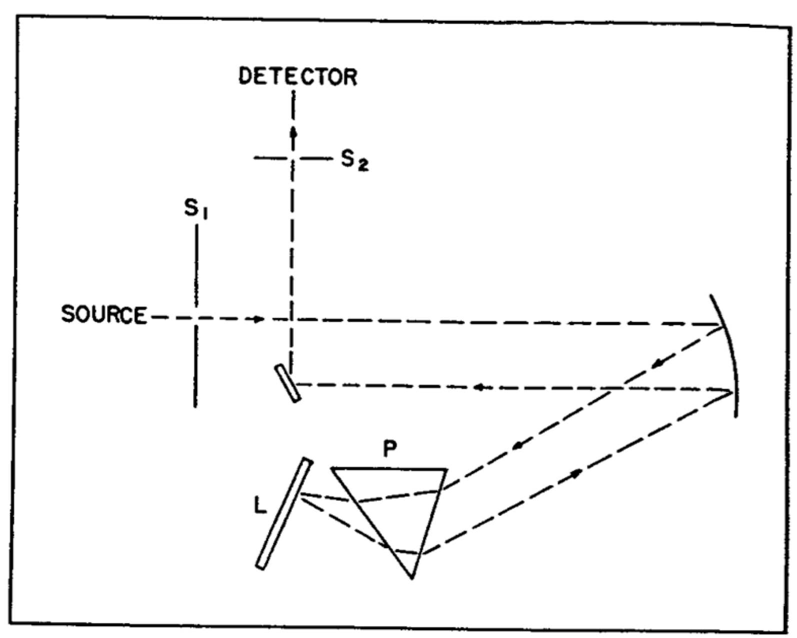


Some Prism designs

- Simple (see previous slides)
- Amici Prism

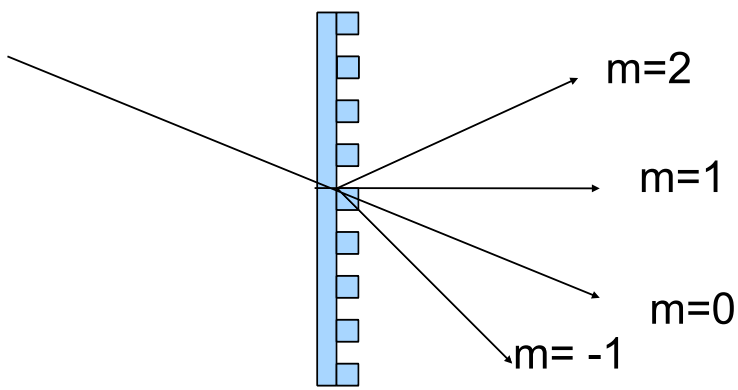


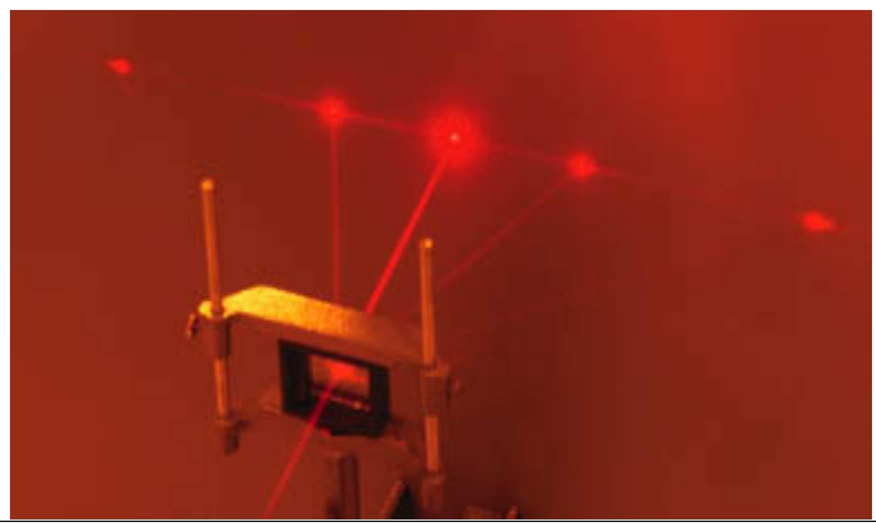
- Littrow configuration



Diffraction Gratings

Phenomenon: Closely spaced patterns of any sort will produce diffraction. If the pattern is regular (either in size or spacing), so is the resulting intensity pattern.

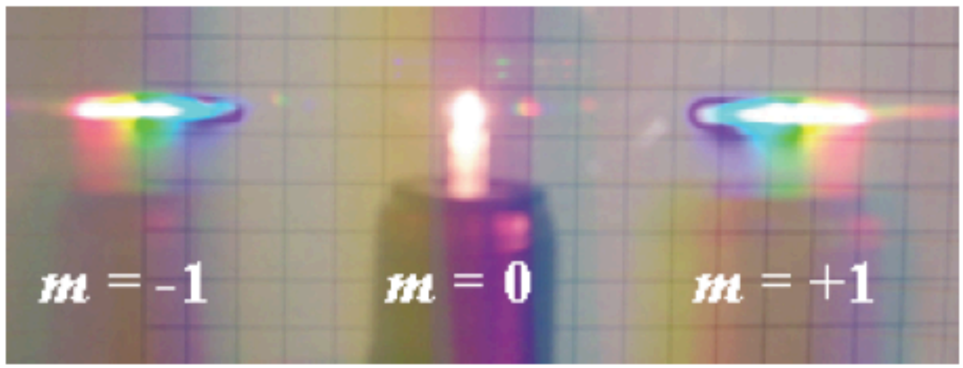




Grating Orders

For light perpendicular on a grating, the light obeys the grating equation:

$$a \sin\theta_m = m\lambda$$



Light incident at an oblique angle satisfies the equation:

$$a(\sin\theta_m - \sin\theta_i) = m\lambda$$

Resolving power of a grating

- The angular extent of a monochromatic source encountering a grating is: $\Delta\theta = \frac{\lambda}{N a \cos(\theta_m)}$

The change in wavelength versus angle can be obtained by differentiating the grating equation:

$$D = \frac{d\theta}{d\lambda} = \frac{m}{a\cos(\theta_m)}$$

$$\Delta\lambda = \frac{a\cos(\theta_m)\,\Delta\theta}{m} = \frac{\lambda}{mN}$$

$$R = \frac{\lambda}{\Delta\lambda} = mN$$

Spectral Range of a Grating

What about successive orders?

Wavelengths of successive orders overlap when they satisfy the equation:

$$a(\sin\theta_m - \sin\theta_i) = (m+1)\lambda = (m)(\lambda + \Delta\lambda)$$

So regions of the spectrum do not overlap if they are less than the free spectral range of the order:

$$\Delta\lambda_{FSR} = \frac{\lambda}{m}$$

Implications for optical setup

- To increase the resolving power you need to either use a higher order of the grating or increase the number of lines.
- For a fixed grating a higher resolving power requires a larger beam.

Grating spacing

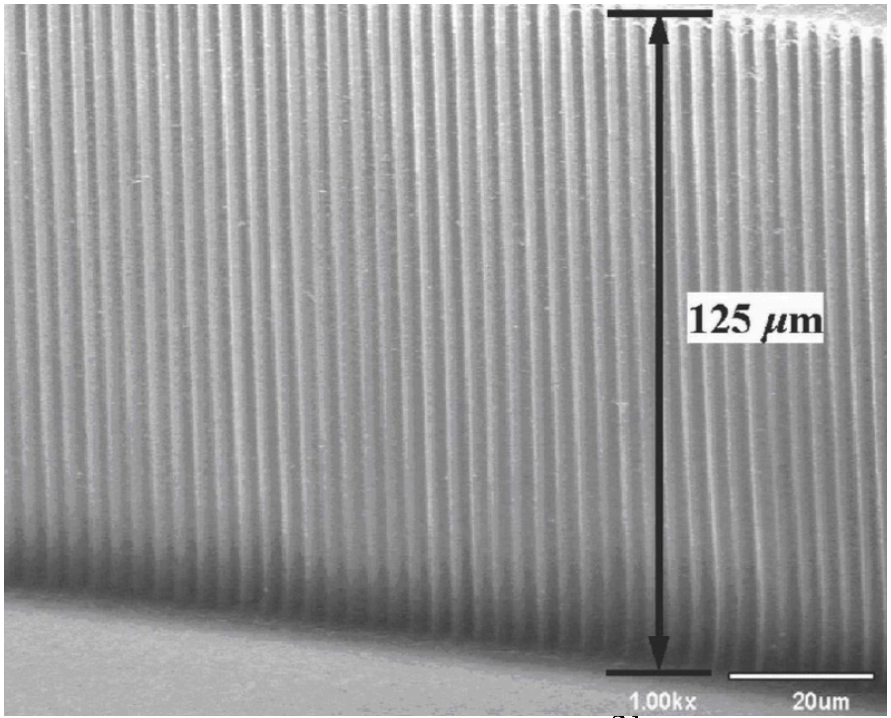
- Grating grooves are typically ~100-1000/ mm.
- The beam diameter on the grating determines the resolving power

Ideal Case:

$$R = \frac{mD}{a}$$

Real World:

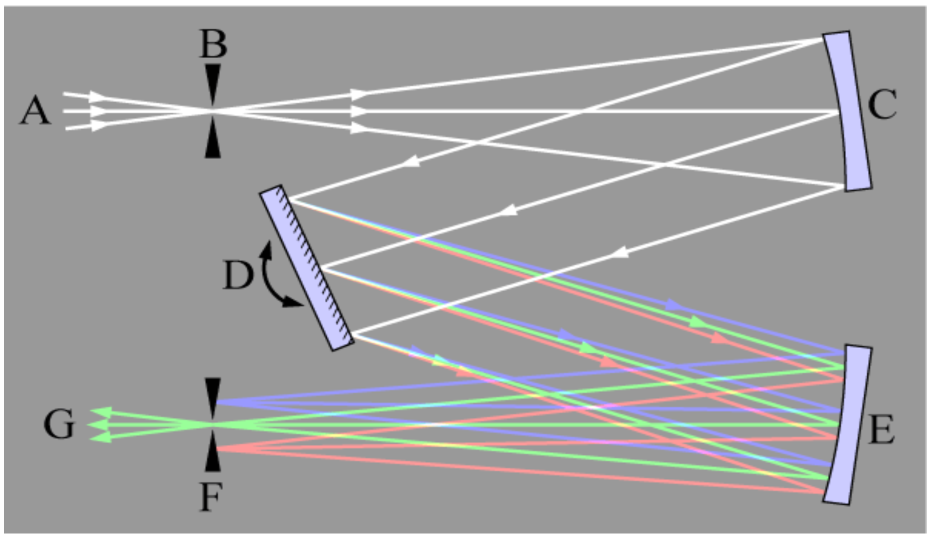
$$R = \frac{mD}{a \cdot slitwidth}$$



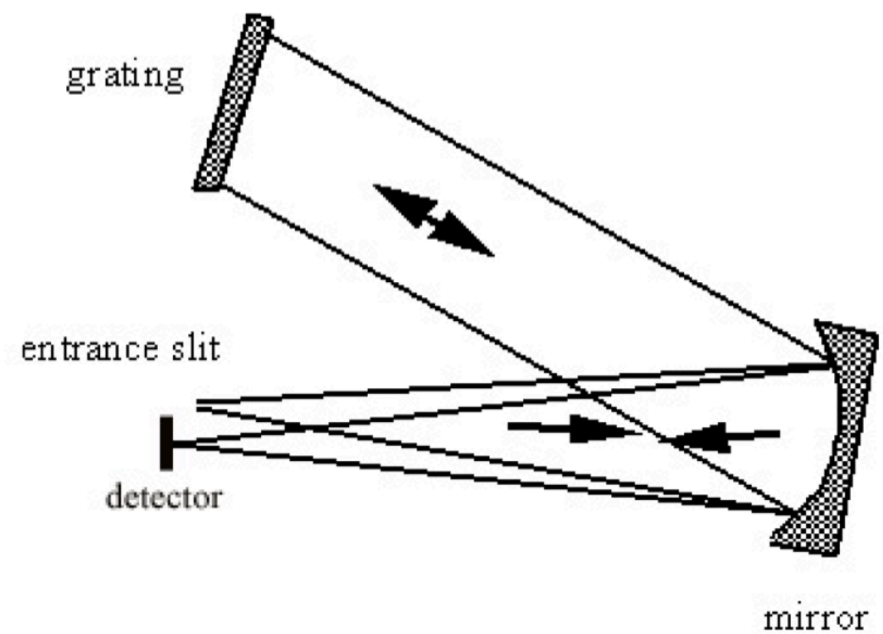
Typical Setup

- Gratings are almost always use in collimated light to avoid aberrations caused by the combination of converging light and diffraction.

Czerny-Turner configuration

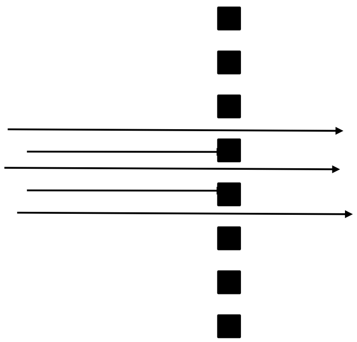


Littrow configuration

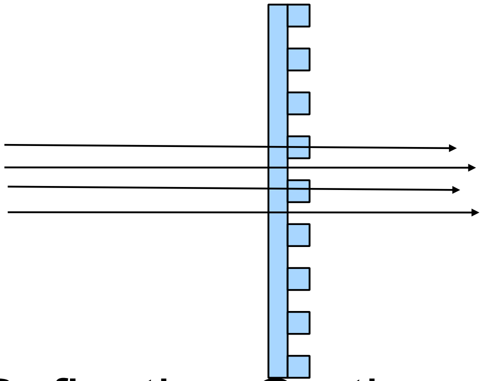


Different types of gratings

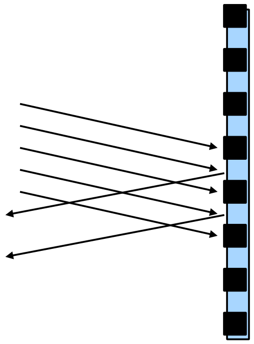
Amplitude Transmission gratings



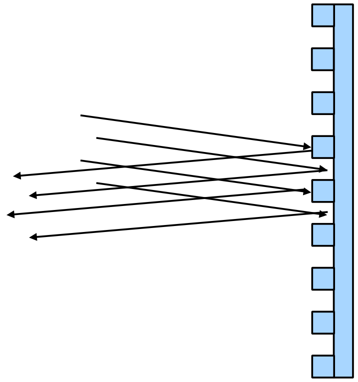
Phase Transmission Gratings



Amplitude Reflection gratings

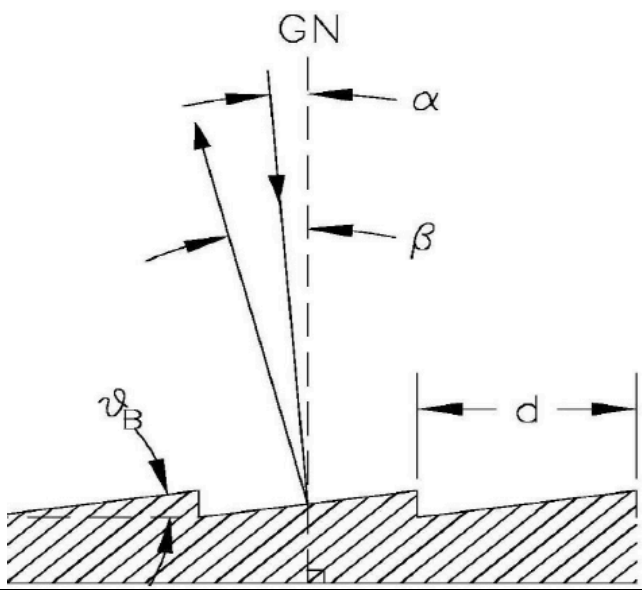


Phase Reflection Gratings

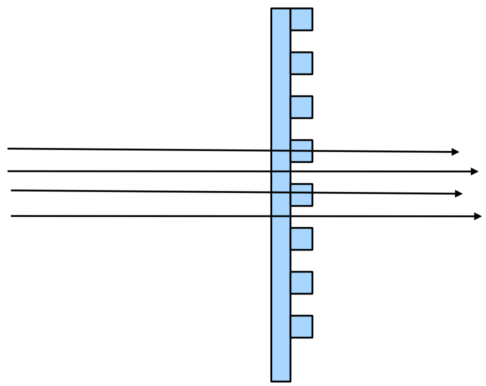


Grating efficiency

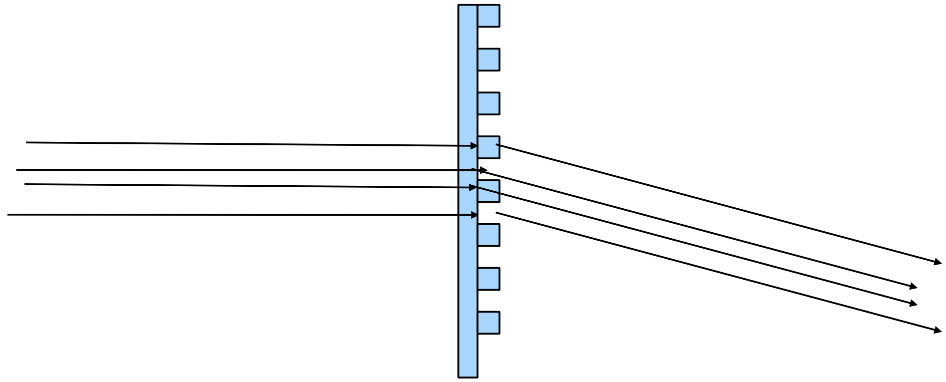
- Grooves diffract light over a scale on the detector which is D/a.
- The faces of these grooves are tilted to center the diffraction at the wavelength of interest.
  - Called the blaze of the grating.
    - Specified as an angle from normal incidence.

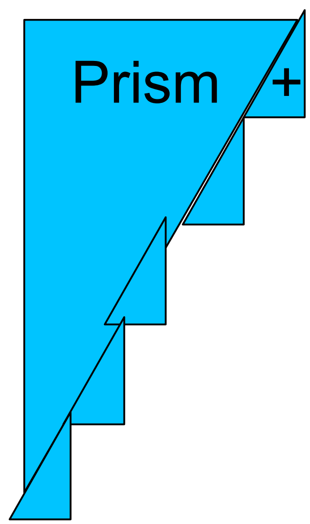


What’s wrong with this transmissive grating?



Dispersion only exists for m ≠ 0





Prism + Grating =Grism (not Prating)