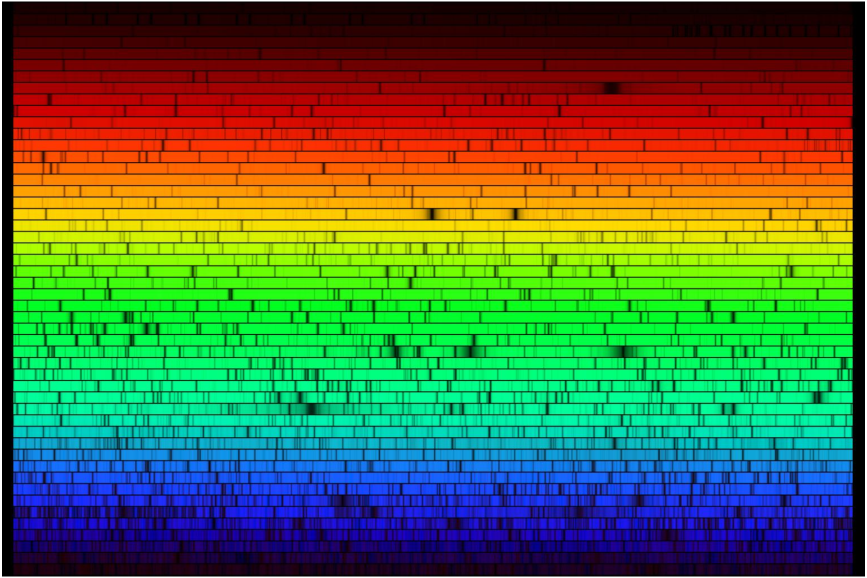
Lecture 3: Optical Spectroscopy

Outline

1. Astrophysical Spectroscopy
2. Broadband Filters
3. Fabry-Perot Filters
4. Interference Filters
5. Prism Spectrograph
6. Grating Spectrograph
7. Fourier Transform Spectrometer

The Solar Spectrum



N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Astrophysical Spectroscopy

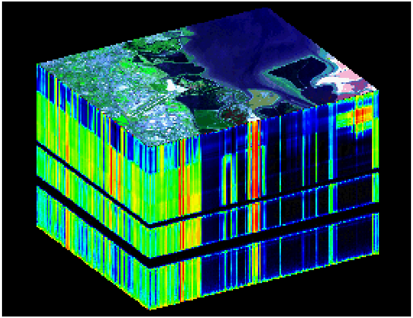
What can we learn from spectra?

Astrophysical Spectroscopy

What can we learn from spectra?

- chemical composition (elemental and molecular abundances)
- velocity (e.g. redshift, exoplanets, gravitational redshift)
- temperature, density, pressure, turbulent velocities
- magnetic and electrical fields
- gravity

Basic Problem of Optical Spectroscopy



www.csr.utexas.edu/projects/rs/hrs/hyper.html

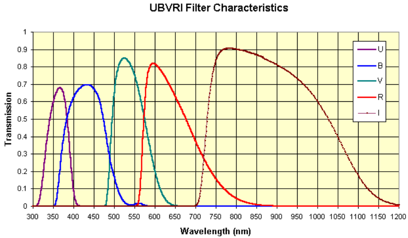
- two spatial/angular dimensions, one wavelength dimension
- detectors are only two-dimensional
- need to slice *hyperspectral cube*
- will have to *scan* in one dimension
- filters: scan in wavelength
- slit spectrograph: scan in one spatial dimension
- or *multi-object spectroscopy* and *integral field units*

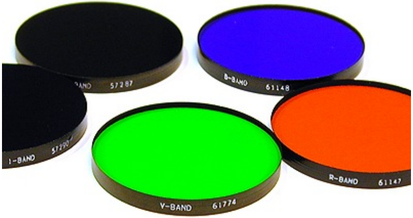
Broadband Filters

Different Types of Color Filters

- dyed gelatin (Kodak Wratten)
  - advantages: thin, cheap, large sizes
  - disadvantages: limited optical quality
- colored glass (Schott, Corning)
  - advantages: stable, rugged, high transmission
  - disadvantages: limited bandpasses, limited sizes
- interference filters
  - advantages: very narrow filters, arbitrary bandpass shape and location
  - disadvantages: expensive, very limited sizes, thermal effects, aging

UBVRI





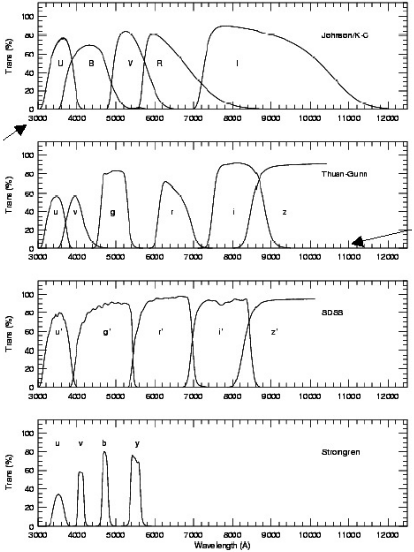
www.sbig.com/products/filters.htm

- UBV by Johnson and Morgan (1953)
- VRIJKLMNQ (infrared) by Johnson (1960)
- (combinations of) glass filters
- invented to classify stars with photomultipliers
- zero point of B-V and U-B color indices defined to be zero for A0 V stars

Limitations of UBVRI Photometry

- limited spectral resolution
- effective central wavelength changes with color of star
- star’s magnitudes and color depend on the star’s color
- short-wavelength side of U filter extends below atmospheric transmission cutoff
- properties of sky define width of bandpass, not filter
- no clean separation of information from different filters
- different detectors have different sensitivities
- today: Bessel or Cron/Cousins UBVRI with CCDs

Other Filter Systems

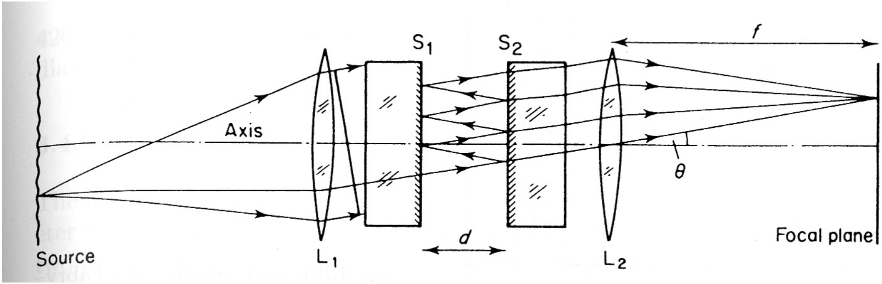


http://www.ucolick.org/b̃olte/AY257/ay257_2.pdf

- other filter systems have less overlap and/or higher transmission
- Johnson system designed to measure properties of stars
- Thuan-Gunn filters for faint galaxy observations
- Stromgren has better sensitivity to stellar properties (metallicity, temperature, surface gravity)
- Sloan Digital Sky Survey (SDSS) for faint galaxy classification

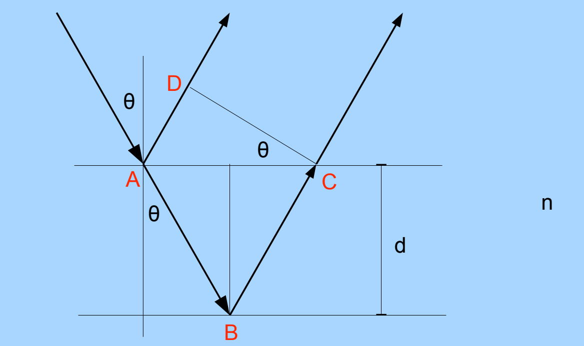
Fabry-Perot Filter

Tunable Filter



- invented by Fabry and Perot in 1899
- interference between partially transmitting plates containing medium with index of refraction *n*
- angle of incidence in material θ, distance *d*
- path difference between successive beams: $\Delta = 2nd\cos\theta$

Plane Wave Path Length for Oblique Incidence



- consider theoretical reflections in single medium
- need to correct for plane wave propagation
- path length for "reflected light": $\bar{AB} + \bar{BC} - \bar{AD}$

$$\frac{2d}{\cos\theta} - 2d\tan\theta \cdot \sin\theta = 2d\frac{1-\sin^2\theta}{\cos\theta} = 2d\cos\theta$$

Fabry Perot continued

- path difference between successive beams: $\Delta = 2nd\cos\theta$
- phase difference: $\delta = 2\pi\Delta/\lambda = 4\pi nd\cos\theta/\lambda$
- incoming wave: $e^{i\omega t}$
- intensity transmission at surface: T
- intensity reflectivity at surface: R
- outgoing wave is the *coherent sum* of all beams

$$Ae^{i\omega t} = Te^{i\omega t} + TRe^{i(\omega t+\delta)} + TR^2 e^{i(\omega t+2\delta)} + ...$$

- write this as

$$A = T(1 + Re^{i\delta} + R^2 e^{i2\delta} + ... = \frac{T}{1 - Re^{i\delta}}$$

Fabry Perot continued

- emerging amplitude

$$A = \frac{T}{1 - Re^{i\delta}}$$

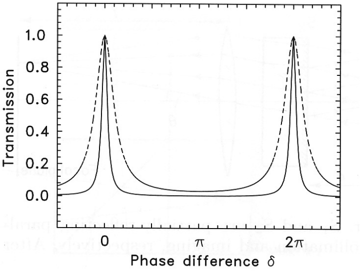
- emerging intensity is therefore

$$I = AA^* = \frac{T^2}{1 - 2R\cos\delta + R^2} = \frac{T^2}{(1-R)^2 + 4R\sin^2\frac{\delta}{2}}$$

- with $I_{\max} = T^2/(1-R)^2$

$$I = I_{\max}\frac{1}{1 + \frac{4R}{(1-R)^2}\sin^2\frac{\delta}{2}}$$

Fabry Perot Properties



$$I = I_{\max} \frac{1}{1 + \frac{4R}{(1-R)^2} \sin^2 \frac{\delta}{2}}$$

- transmission is periodic
- distance between transmission peaks, *free spectral range*

$$\mathrm{FSR} = \frac{\lambda_0^2}{2nd\cos\theta}$$

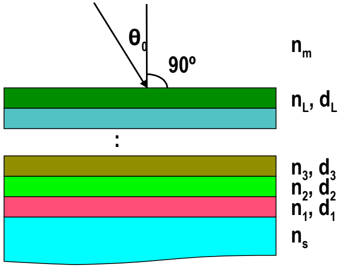
- Full-Width at Half Maximum (FWHM) $\Delta\lambda$

$$\Delta\lambda = \mathrm{FSR}/F$$

- *finesse F*

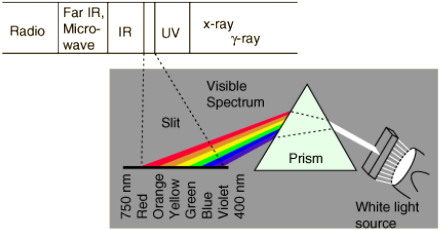
$$F = \frac{\pi\sqrt{R}}{1-R}$$

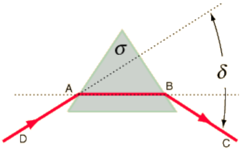
Interference filters



- *thin film*:
  - layer with thickness $\lesssim \lambda$
  - extends in 2 other dimensions $\gg \lambda$
- reflection, refraction at all interfaces
- layer thickness $d_i \lesssim \lambda \Rightarrow$ interference between reflected and refracted waves
- L layers of thin films like Fabry-Perots: *thin film stack*
- *substrate* (index n_s) and incident medium (index n_m) have infinite thickness
- produced by evaporating material in vacuum and depositing on glass
- can be taylored to almost any specifications
- sensitive to temperature, humidity, angle of incidence

Prism Spectrograph





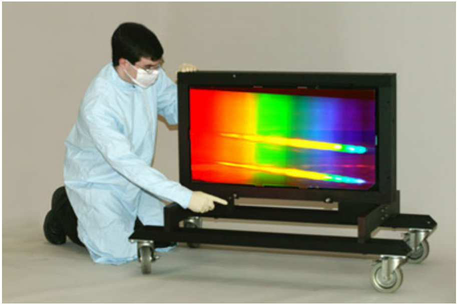
$$\frac{n_{prism}}{n_0} = \frac{\sin\frac{1}{2}(\sigma+\delta)}{\sin\frac{1}{2}\sigma}$$

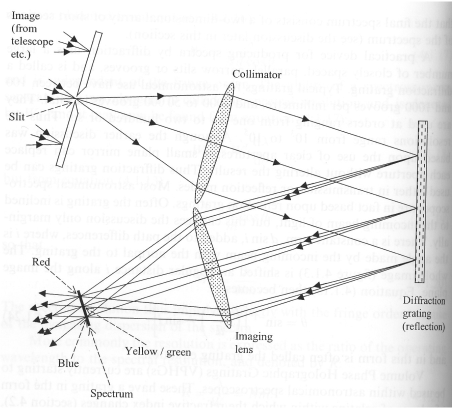
hyperphysics.phy-astr.gsu.edu/Hbase/geoopt/prism.html

- first type of spectrograph because prism is easy to make
- needs glass with high dispersion (large index of refraction variation with wavelength
- limited spectral resolution, wavelength coverage
- used as *predisperser* or *cross-disperser*

Diffraction Grating

Introduction



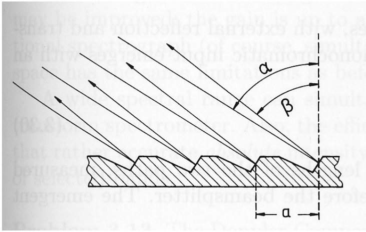


- first produced by American astronomer David Rittenhouse in 1785, but had no further impact
- reinvented by Joseph von Frauenhofer in 1821

Reflection Gratings

- Fraunhofer gratings good enough to see solar absorption lines
- Fraunhofer labeled absorption lines with letters (A,B,C,D, ...)
- since 1950, Richardson Grating Laboratory has produced large gratings of exceptional quality with replication process

Grating Equation



- grating equation: $m\lambda = a(\sin\alpha + \sin\beta)$
- m is order of diffraction
- angular dispersion

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

- *blazed* to maximize intensity in one direction
- typical grating: 632 lines per mm, used at 60 degrees

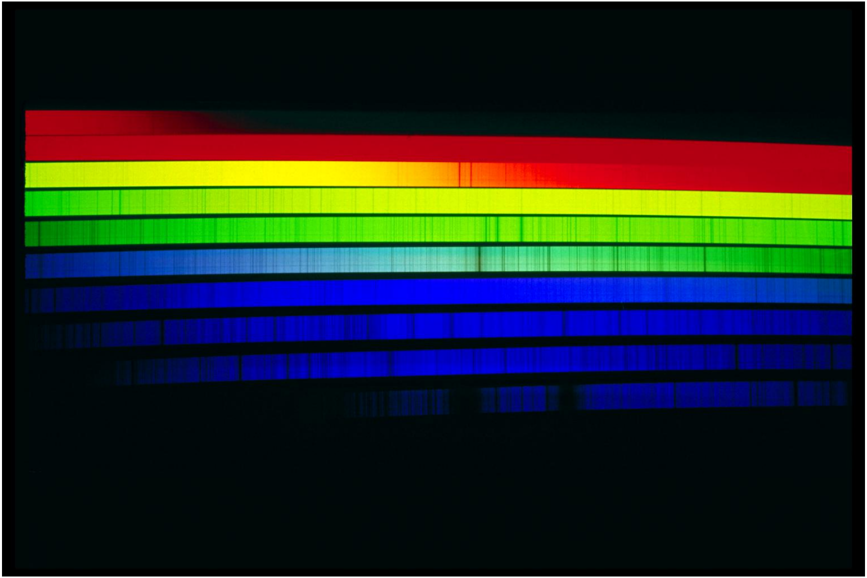
Grating Resolving Power

- resolving power is

$$\frac{\lambda}{\delta\lambda} = nm$$

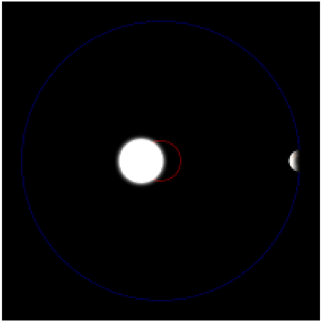
  where n is the total number of grooves
- Echelle gratings are used in high orders (e.g. m=42)
- many orders and wavelengths combine to the same angle ⇒ overlapping grating orders

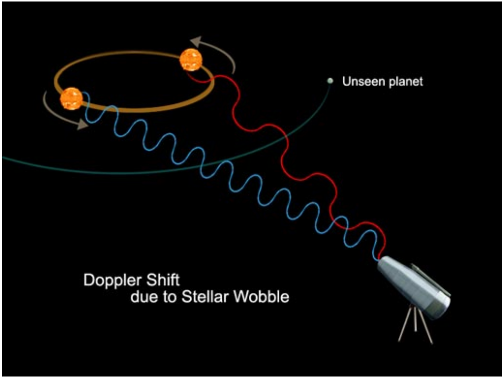
Cross-Dispersed Echelle



Solar Spectrum, NSO/AURA/NSF

Radial Velocity Detection of Exoplanets





en.wikipedia.org/wiki/Extrasolar_planet

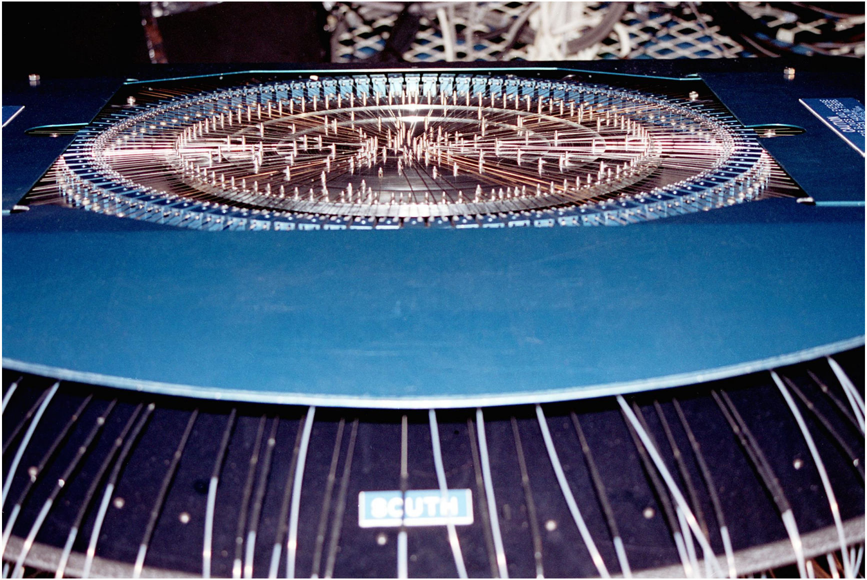
- Star, planet move around common center of mass
- Doppler effect: $\frac{\delta\lambda}{\lambda} = \frac{v}{c}$
- Look for periodic variations in stellar velocity

HARPS: Highly Stable Spectrograph for Exoplanet Detection

obswww.unige.ch/Instruments/Harps/gallery/Integration_LSO

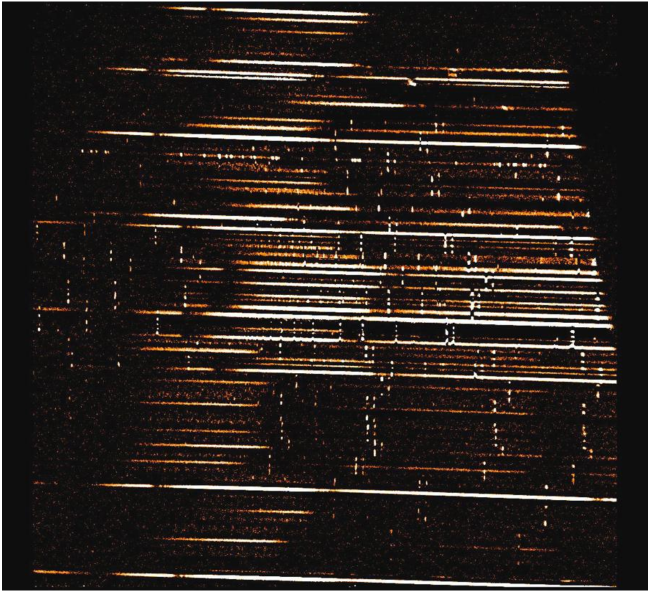
- fiber head(s) at Cassegrain focus of 3.6-m ESO telescope
- fibers lead to spectrograph, does not move
- designed and assembled add-on polarimeter here in Utrecht

Multi-Object Spectrographs



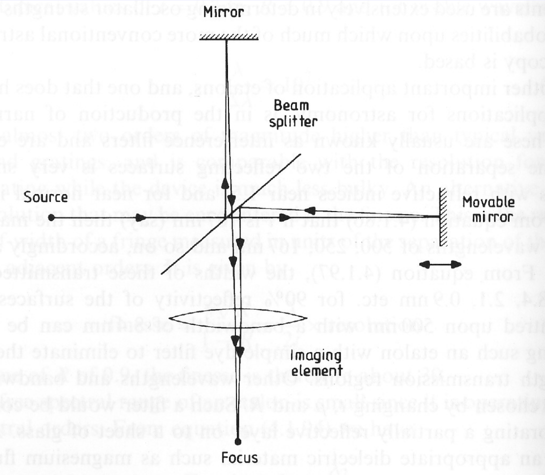
Hydra fiber-fed bench spectrograph, NSO/AURA/NSF

Multi-Object Spectrograms



Near-infrared FLAMINGOS spectra, NSO/AURA/NSF

Fourier Transform Spectrometer (FTS)



Operating Principle

- Michelson interferometer with variable path length difference
- monochromatic input wave with $k = 2\pi/\lambda$

$$e^{i(\omega t - kx)}$$

FTS continued ...

- at output for balanced beams and perfect mirrors, beam splitters

$$A = \frac{1}{2} e^{i\omega t}\left(e^{-ikx_1} + e^{-ikx_2}\right)$$

- measured intensity at output is

$$AA^* = \frac{1}{2}\left(1 + \cos k(x_2 - x_1)\right)$$

- with $x = x_2 - x_1$ and I_0 term that is independent of x, *incoherent sum* of intensities and intensity distribution $B(k)$

$$I(x) = I_0 + \frac{1}{2}\int_0^\infty B(k)\cos kx dk$$

- recover $B(k)$ by measuring $I(x)$ and cosine transform of $I(x) - I_0$
- either change path length with constant velocity or by step-scanning

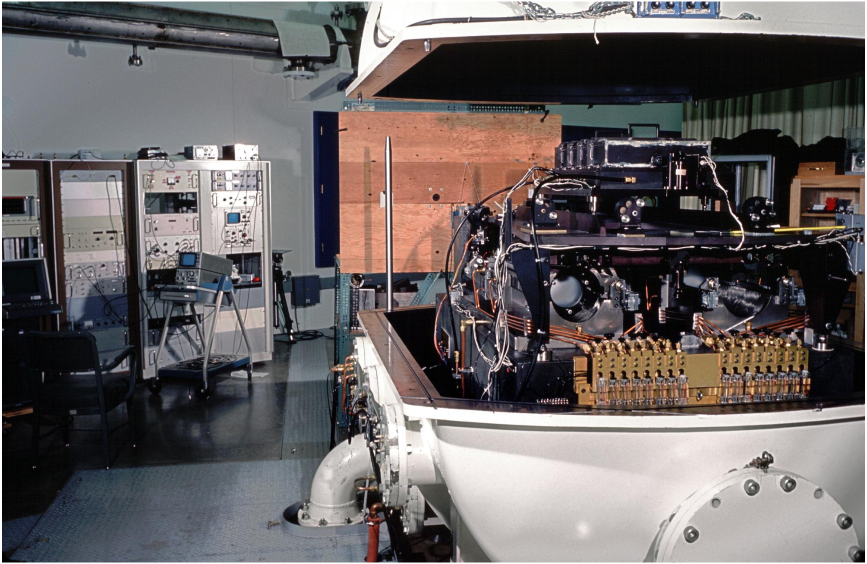
FTS Properties

- imaging Fourier Transform spectrometer is possible
- path length is measured with stabilized laser interferometers
- yields absolute wavelength of spectral lines, limited only by accuracy of path length measurement
- spectral resolution given by largest path-length difference

$$\Delta k = 2\pi/L$$

- 1-m path length difference: $\lambda/\Delta\lambda = 2 \cdot 10^6$
- high spectral resolution independent of aperture size
- wide spectral range is observed simultaneously

1-m Kitt Peak FTS



Tom Eglin, Mark Hanna, NOAO/AURA/NSF