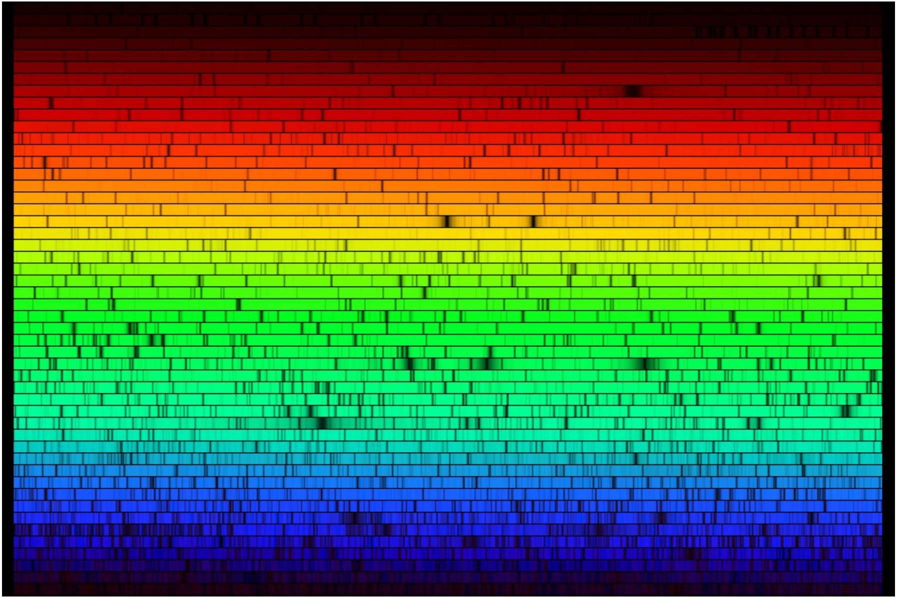
Lecture 12: Spectroscopy

Outline

1. Astrophysical Spectroscopy
2. Broadband Filters
3. Diffraction Gratings
4. Fabry-Perot Filters
5. Interference Filters
6. Fourier Transform Spectrometer

The Solar Spectrum



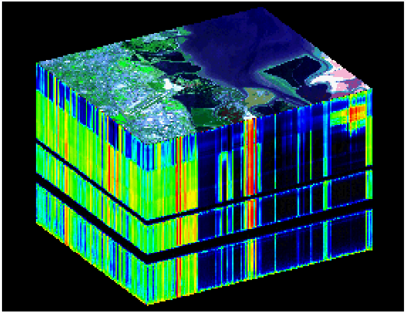
N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Astrophysical Spectroscopy

What can we learn from spectra?

- chemical composition (elemental and modulecular 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

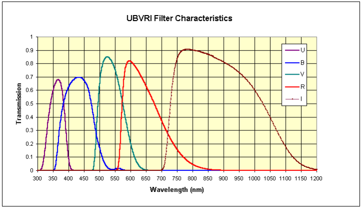
- two spatial/angular dimensions, one wavelength dimension
- detectors are only two-dimensional
- need to slice hyperspectral cube
- will have to scan in third dimension

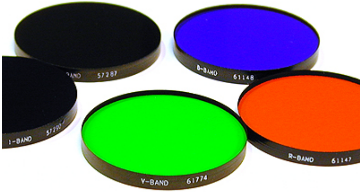
Broadband Filters

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

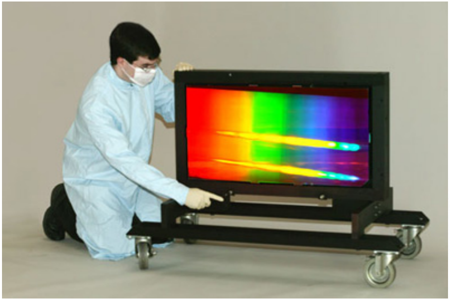
- UBV by Johnson and Morgan (1953)
- VRIJKLMNQ by Johnson (1960)
- (combinations of) glass filters
- invented to classify stars
- zero point of B-V and U-B color indices defined to be zero for A0 V stars

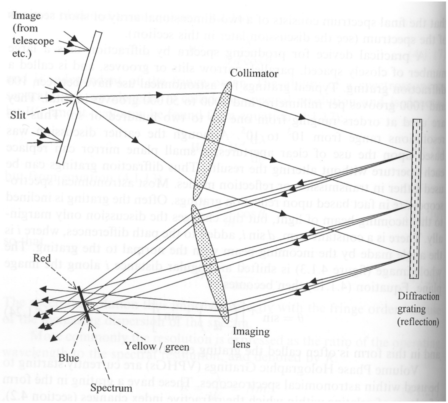
Limitations of UBVRI Photometry

- 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: Bessell (1990) UBVRI with CCDs

Diffraction Grating

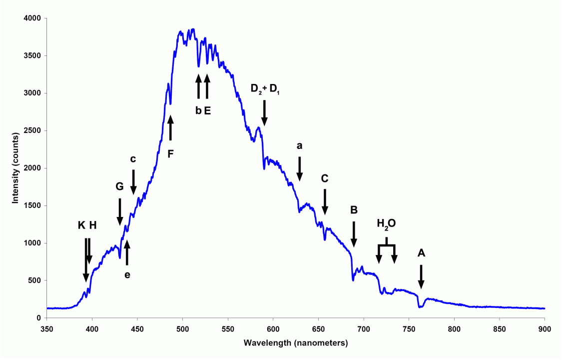
Introduction





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

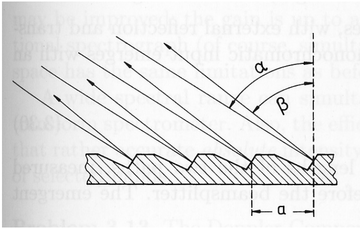
Reflection Gratings



en.wikipedia.org/wiki/Image:Spectrum_of_blue_sky.png

- Frauenhofer gratings good enough to see solar absorption lines
- Frauenhofer 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

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

- typical grating: 632 lines per mm, used at 60 degrees

Grating Resolving Power

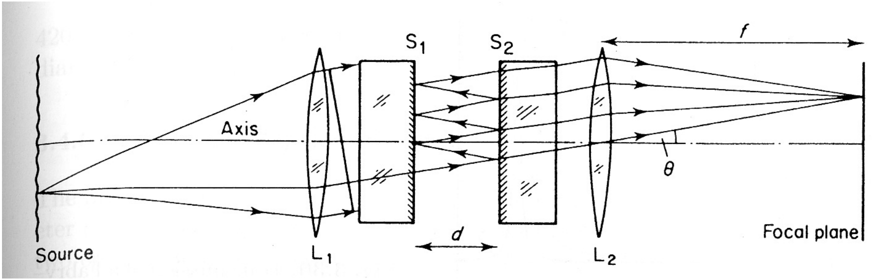
- resolving power is

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

  where n is the total number of grooves
- Echelle gratings are used in high orders (e.g. m=42)

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

$$\Delta = 2nd \cos\theta$$

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

$$e^{i\omega t}$$

- outgoing wave is the *coherent sum* of all beams

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

- write this as

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

Fabry Perot continued

- emerging amplitude

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

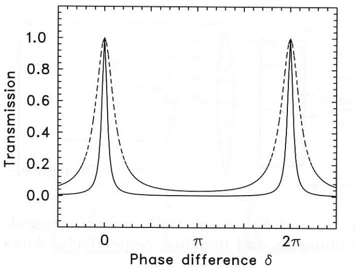
- emerging intensity is therefore

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

- 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 is given by

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

- Finesse F is given by

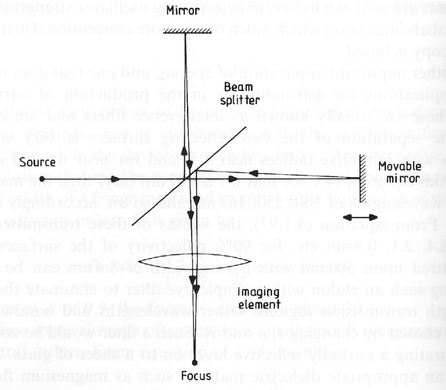
$$F = \frac{\pi\sqrt{R}}{1-R}$$

Interference filters

- multiple stacks of thin films that act as fixed Fabry-Perot filters
- produced by evaporating material in vacuum and depositing it on glass
- typical thickness is less than one wavelength
- can be taylored to almost any specifications
- tend to be sensitive to temperature and humidity

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

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

- measured intensity at output is

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

- 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

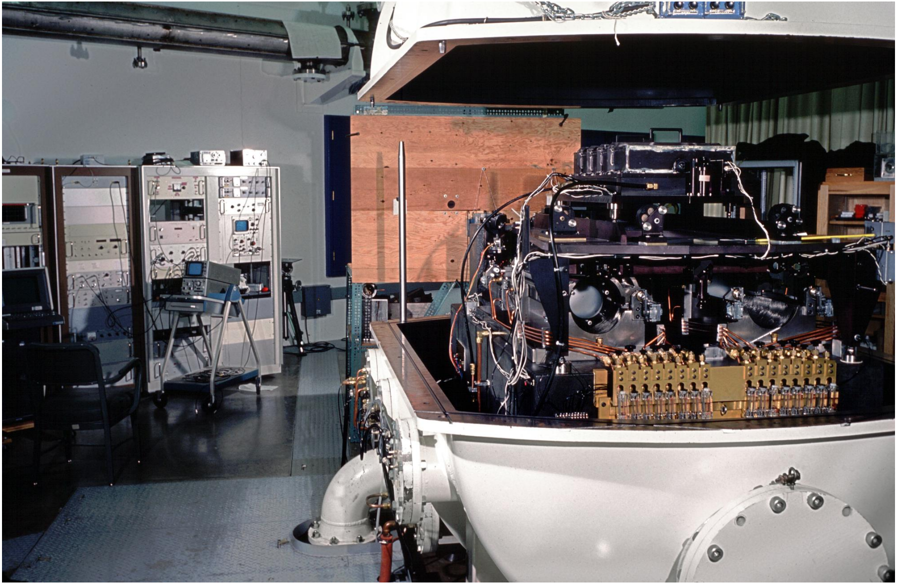
FTS Properties

- 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 reslution 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