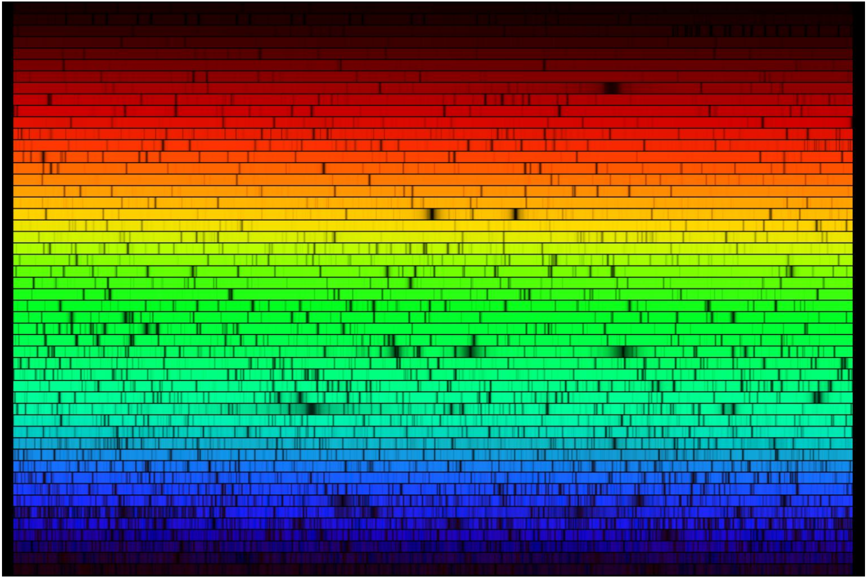
Lecture 9: Spectrographs 1

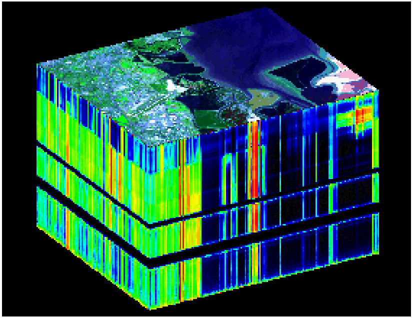
Outline

The Solar Spectrum



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

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*

Spectrograph Requirements

- wavelength range
- simultaneous wavelength coverage
- spectral resolution $R = \lambda/\Delta\lambda$
- spectral profile (point-spread function)
- scattered light (far wings of spectral profile)
- wavelength stability
- wavelength accuracy

Broadband Filters

Different Types of Color Filters

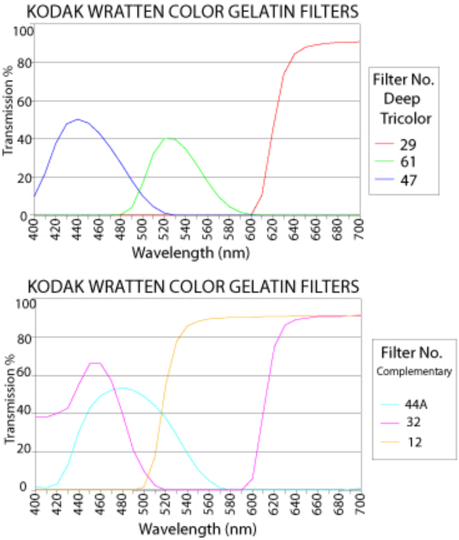
- dyed gelatin (Kodak Wratten)
  - advantages: thin, cheap, large sizes
  - disadvantages: limited optical quality, heat-sensitive
- colored glass (Schott, Corning)
  - advantages: stable, rugged, high transmission
  - disadvantages: limited bandpasses, limited sizes
- interference filters
  - advantages: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

Wratten Filters

www.edmundoptics.com/onlinecatalog/displayproduct.cfm?productid=1326

- colored plastic sheets
- named after Frederick Wratten, manufactured by Kodak for about 100 years
- recently: Wratten 2
- up to 100 mm by 300 mm
- can be used for experiments
- improved performance when put between glass plates

Typical Wratten Filters

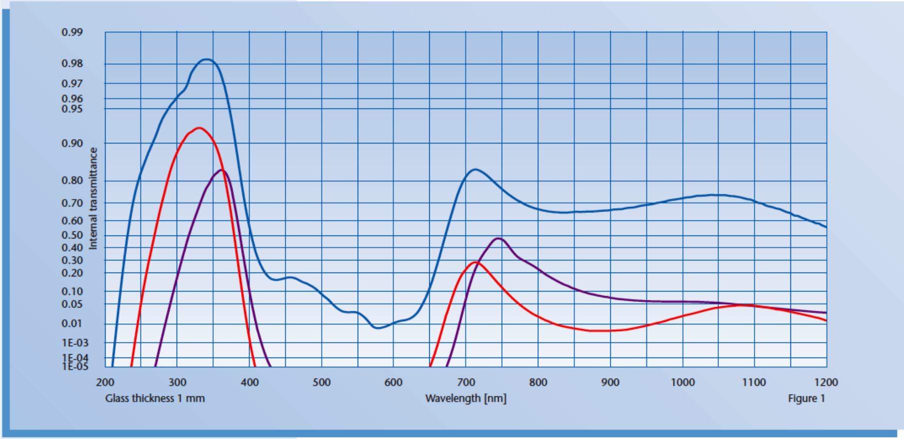


www.edmundoptics.com/onlinecatalog/displayproduct.cfm?productid=1326

Colored Glass

- typically useful from 200 - 1000 nm
- Schott
  - UG: Black and blue glasses, UV transmitting
  - BG: Blue, blue-green, and multi-band glasses
  - VG Green glass
  - GG: Nearly colorless to yellow glasses, IR transmitting
  - OG: Orange glasses, IR transmitting
  - RG:Red and black glasses, IR transmitting
  - NG:Neutral density glasses with uniform attenuation in the visible range
  - N-WG: Colorless glasses with different cutoffs in the UV, transmitting in the visible range and the IR
  - KG: Virtually colorless glasses with high transmission in the visible and effective absorption in the IR (heat protection filters)
- Corning
- Hoya

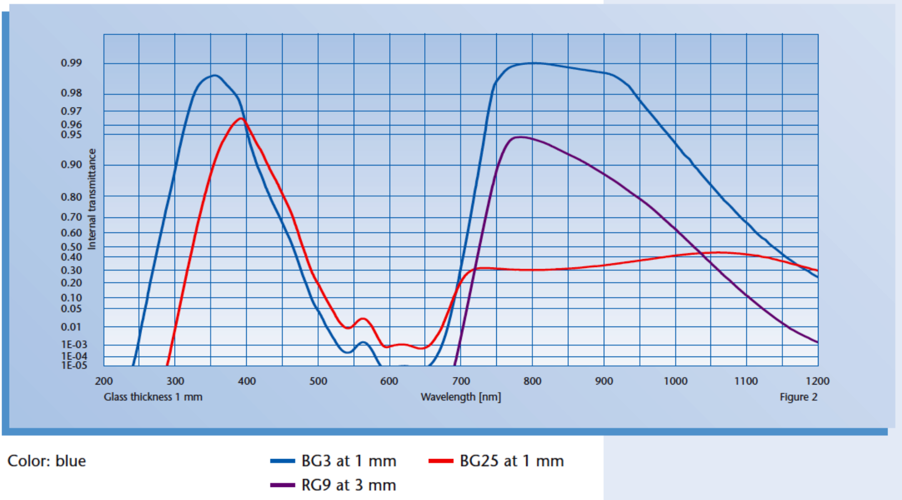
Schott Colored Glass



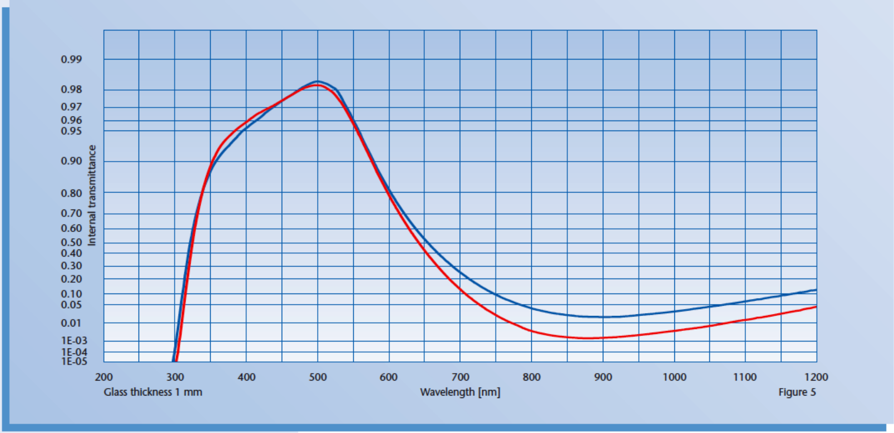
Color: dark violet-black (UG1)
dark violet (UG5)
dark red-black (UG11)

UG5 UG11
UG1

Schott Colored Glass

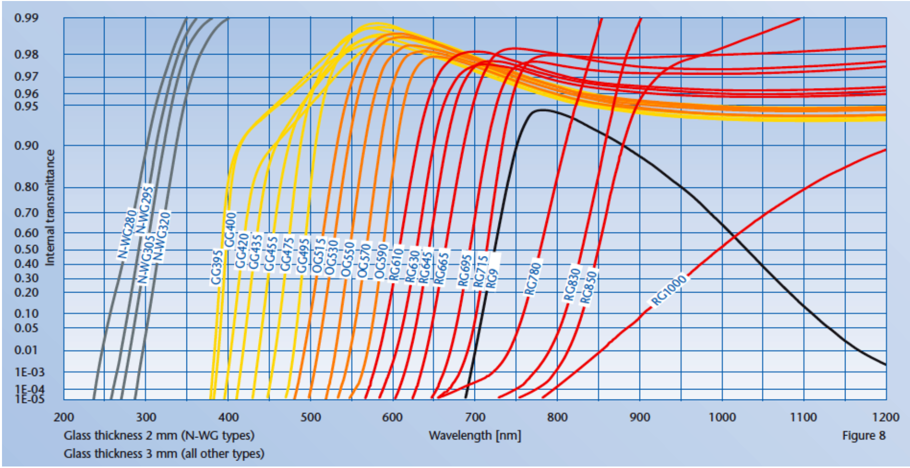


Schott Colored Glass

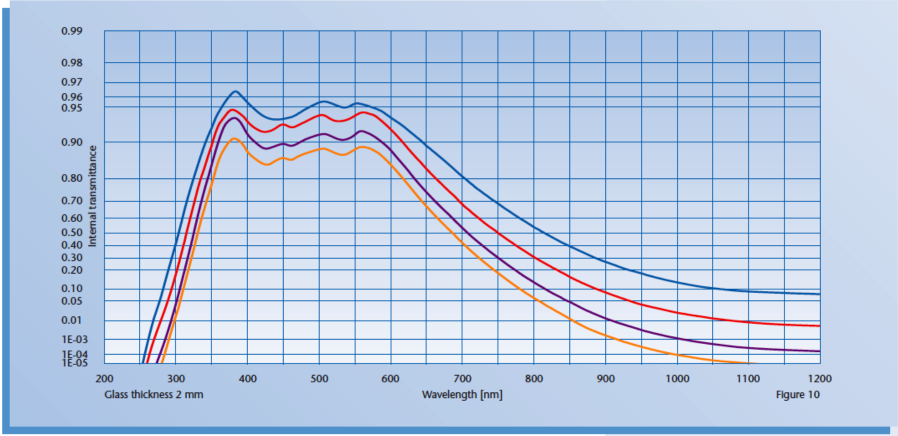


Color: bright blue-green — BG38 at 1 mm — BG40 at 1 mm

Schott Colored Glass



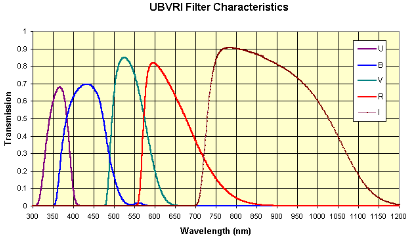
Schott Colored Glass

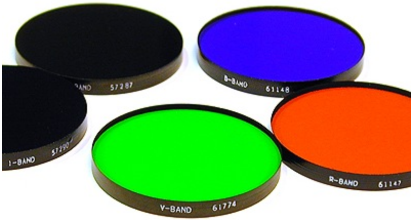


Color: nearly clear
(light greenish tint)

KG2 KG1
KG3 KG5

UBVRI





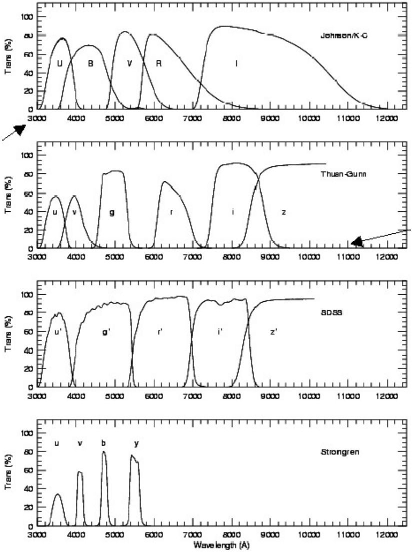
www.sbig.com/products/filters.htm

- 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

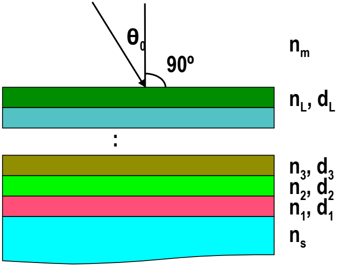
Other Filter Systems



http://www.ucolick.org/˜bolte/AY257/ay257_2.pdf

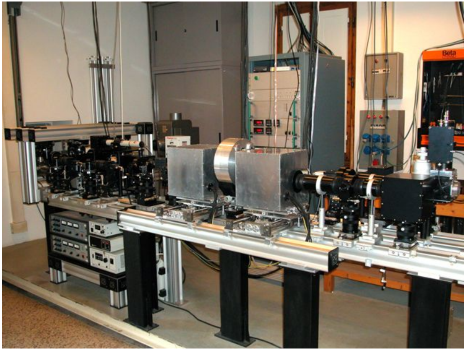
- other filter systems have less overlap and/or higher transmission
- Johnson system designed to measure properties of stars
- Thuan-Gunn filters for faint galaxy observations
- Stromgren has better sensitivity to stellar properties (metallicity, temperature, surface gravity)
- Sloan Digital Sky Survey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

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
- can be taylored to almost any specifications
- sensitive to temperature, humidity, angle of incidence
- can tune filter in wavelength by changing temperature and angle of incidence

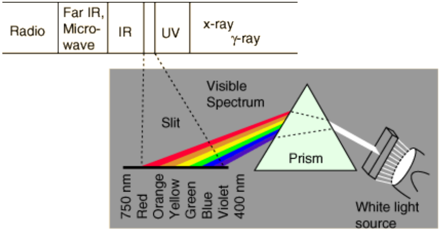
Fabry-Perot Tunable Filter

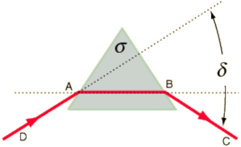


http://www.arcetri.astro.it/science/solare/IBIS_photo.jpeg

- main ingredient is Fabry-Perot with tunable plate separation
- stability of cavity spacing is critical
- often combine two or more tunable elements
- always need interference prefilter

Prism Spectrograph



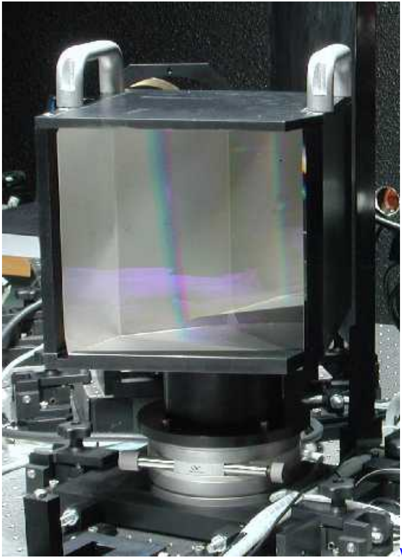


$$\frac{n_{prism}}{n_0} = \frac{\sin \frac{1}{2}(\sigma + \delta)}{\sin \frac{1}{2}\sigma}$$

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

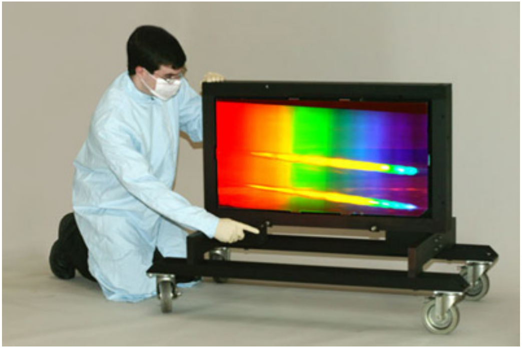
- first type of spectrograph because prism is easy to make
- needs glass with high dispersion (large index of refraction variation with wavelength
- limited spectral resolution, wavelength coverage
- used as order sorter: *predisperser* or *cross-disperser*
- materials from 200 nm to 10um (KCl, ZnSe)

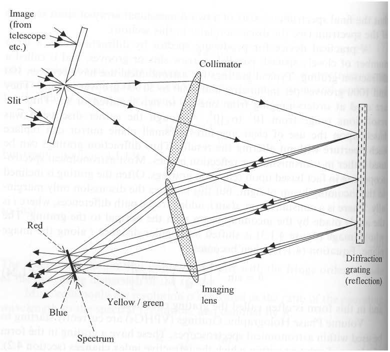
Cross-Disperser for Espadons



www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/IMAGES/PhotoPri

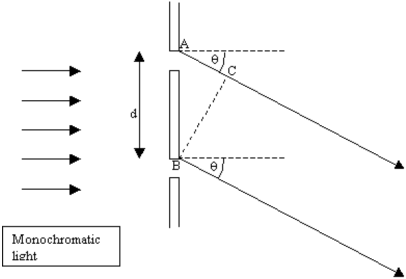
Introduction





- first produced by American astronomer David Rittenhouse in 1785, but had no further impact
- reinvented by Joseph von Frauenhofer in 1821
- excellent free literature: Richardson Grating Laboratory's Diffraction Grating Handbook

Basic Grating Principle



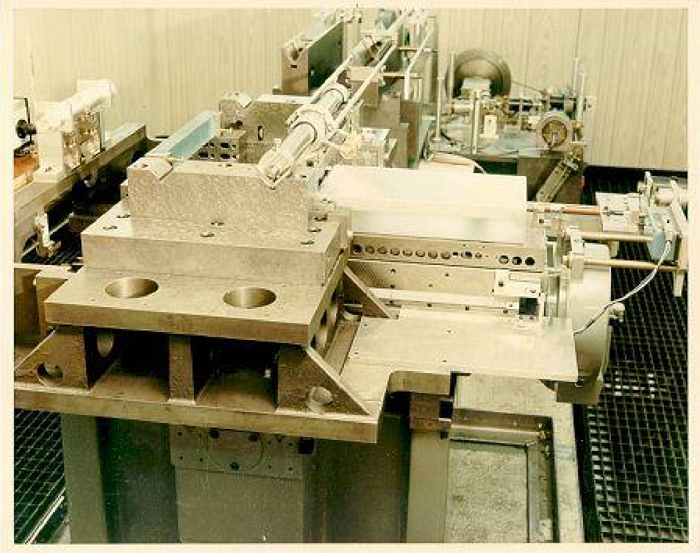
sciwebhop.net/sci_web/physics/a-level/as_module1/diffraction.htm

- flat wavefront goes through periodic structure
- periodic structure changes wavefront amplitude and/or transmission
- phase grating has highest transmission
- phase change in reflection or transmission

Reflection Gratings

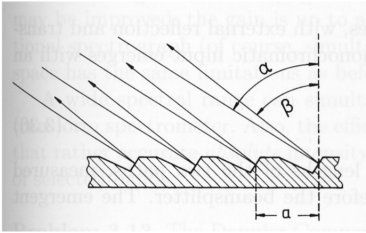
- Fraunhofer gratings good enough to see solar absorption lines
- Fraunhofer labeled absorption lines with letters (A,B,C,D, ...)
- since 1950, Richardson Grating Laboratory has produced large gratings of exceptional quality with replication process

Ruling Engine



gratings.newport.com/information/handbook/chapter3.as

Grating Equation

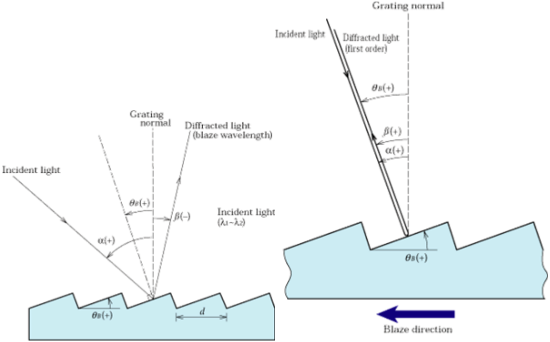


- grating equation: $m\lambda = a(\sin\alpha + \sin\beta)$
- m is order of diffraction
- angular dispersion

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

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

Blaze Angle and Wavelength

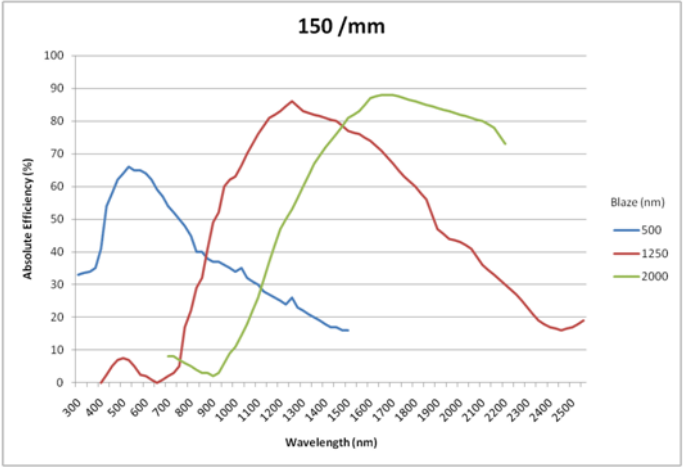


www.shimadzu.com/products/opt/oh80jt0000001uz0.html

- increase grating efficiency for a particular wavelength and order with saw-tooth shaped grooves
- blaze angle and wavelength

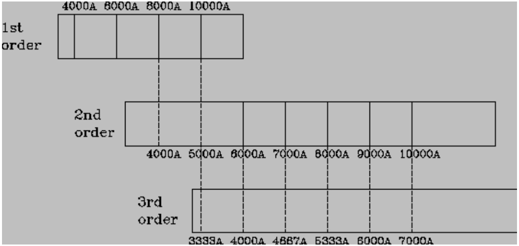
$$\theta_B = \frac{\alpha + \beta}{2} \quad \lambda_B = \frac{2}{nm} \sin\theta_B \cos(\alpha - \theta_B)$$

Grating Efficiency



bwtek.com/technical/index.html#grating$_t$*ab*

Grating Resolving Power



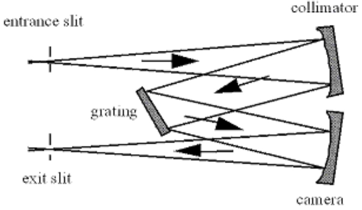
www.noao.edu/kpno/manuals/l2mspect/node24.html

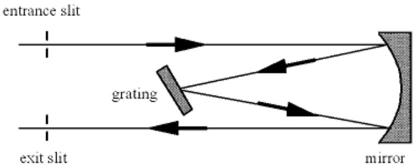
- resolving power is

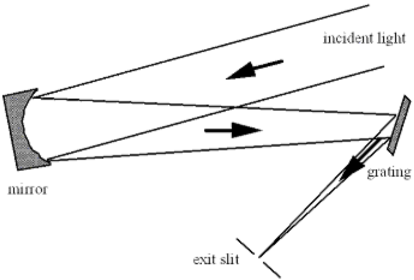
$$\frac{\lambda}{\delta\lambda} = nm$$

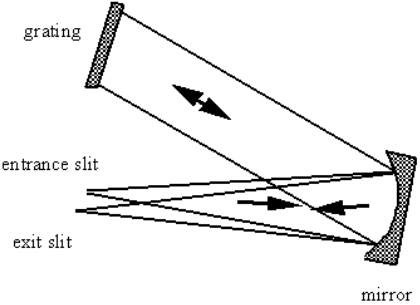
  where *n* is the total number of grooves
- Echelle gratings are used in high orders (e.g. m=42)
- many orders and wavelengths combine to the same angle ⇒ overlapping grating orders

Spectrograph Configurations



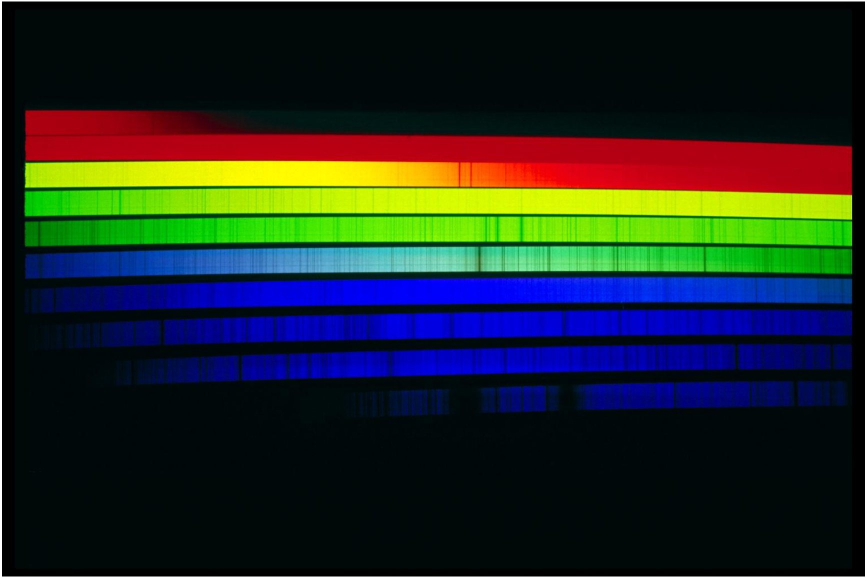






gratings.newport.com/information/handbook/chapter6.asp

Cross-Dispersed Echelle



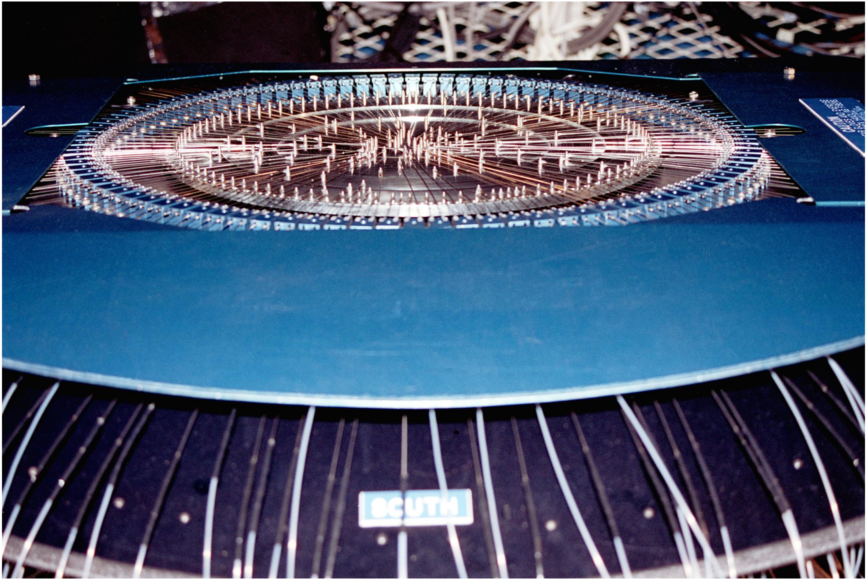
Solar Spectrum, NSO/AURA/NSF

HARPS: Highly Stable Spectrograph for Exoplanet Detection

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

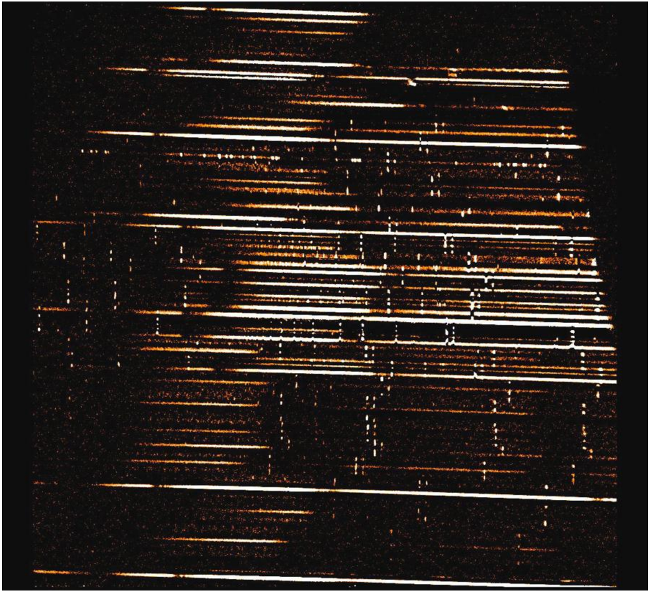
- fiber head(s) at Cassegrain focus of 3.6-m ESO telescope
- fibers lead to spectrograph, does not move
- designed and assembled add-on polarimeter here in Utrecht

Multi-Object Spectrographs



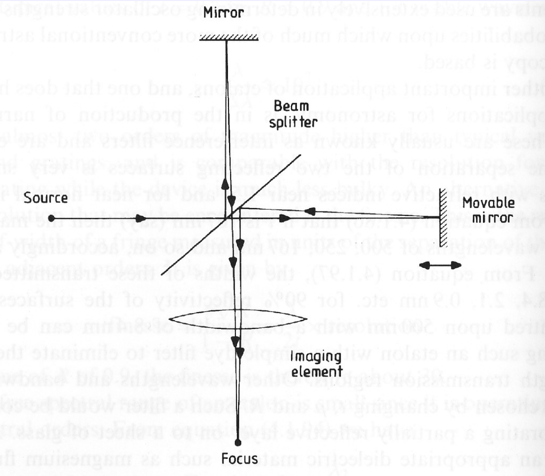
Hydra fiber-fed bench spectrograph, NSO/AURA/NSF

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

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

- 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

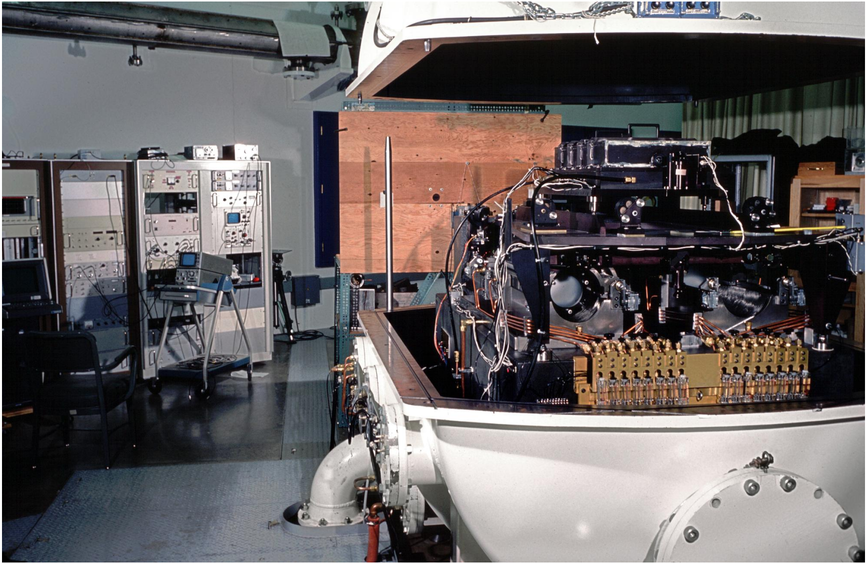
FTS Properties

- 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 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