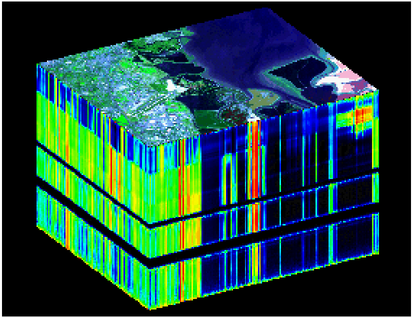
Lecture 12: Imaging

Outline

1. Spectroscopy
2. Filters
3. Photometry

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

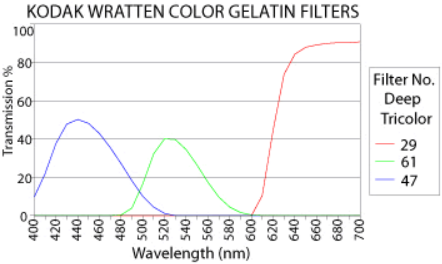
- dyed gelatin (Kodak Wratten)
  - advantages: thin, cheap, large sizes
  - disadvantages: limited optical quality, heat-sensitive
- colored glass (Schott, Corning)
  - advantages: stable, rugged, high transmission
  - disadvantages: limited bandpasses, limited sizes
- interference filters
  - advantages: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

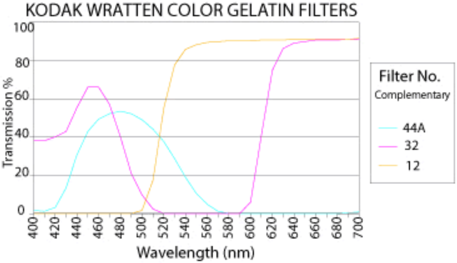
Wratten Filters

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



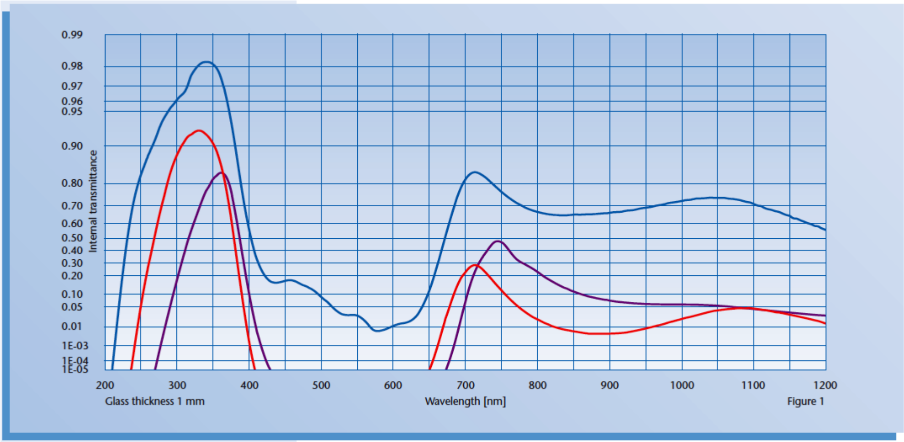


www.edmundoptics.com/onlinecatalog/displayproduct.cfm?productid=1326

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

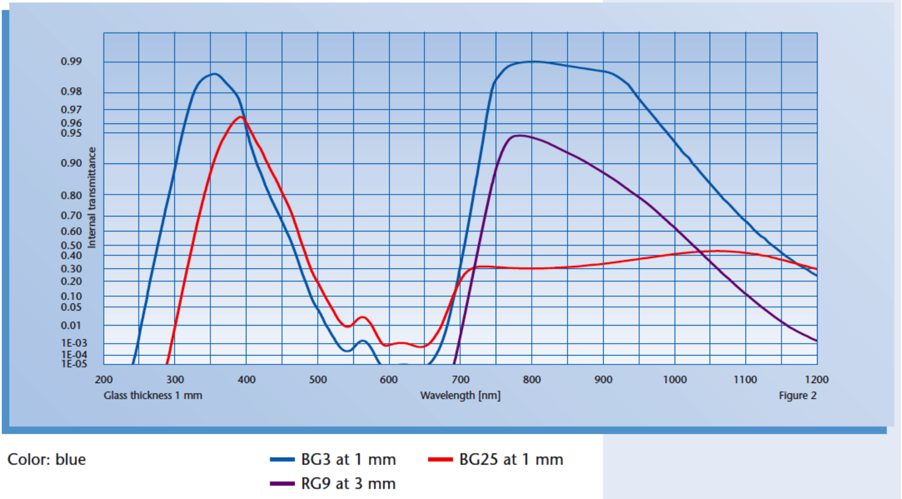
Schott Colored Glass



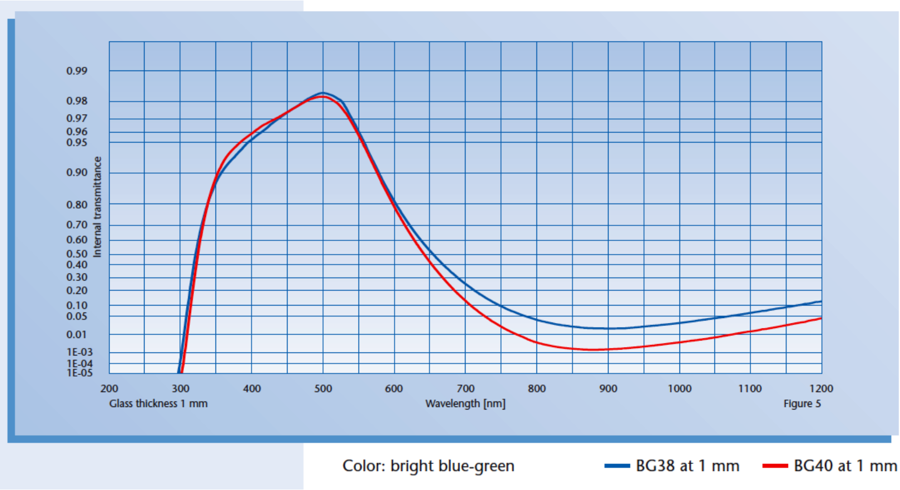
Color: dark violet-black (UG1)
dark violet (UG5)
dark red-black (UG11)

UG5	UG11
UG1	

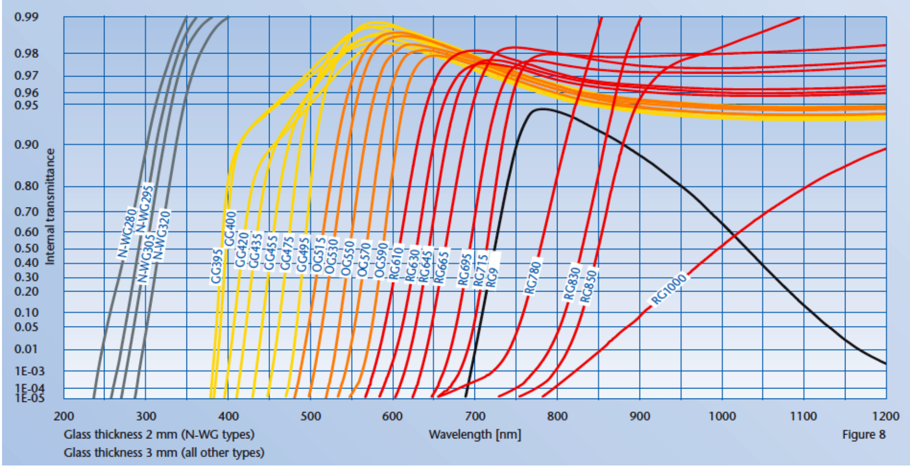
Schott Colored Glass



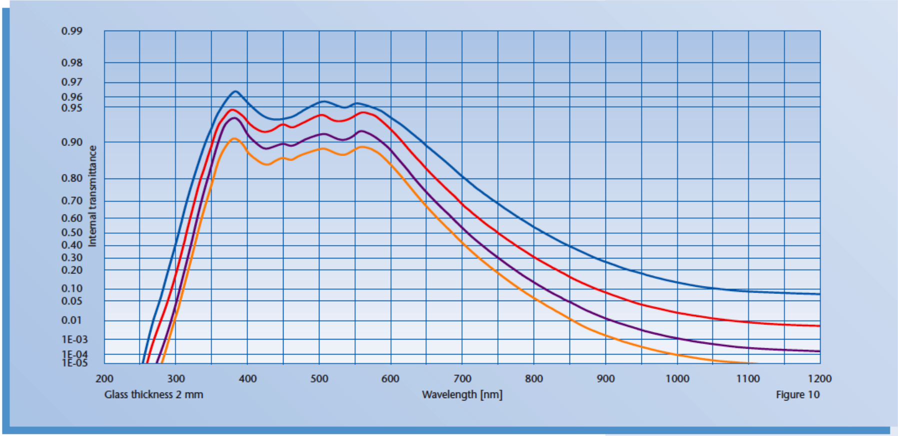
Schott Colored Glass



Schott Colored Glass

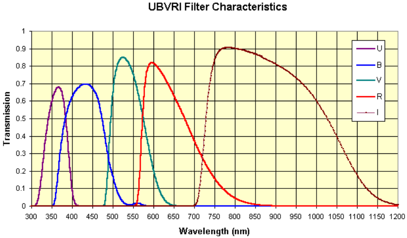


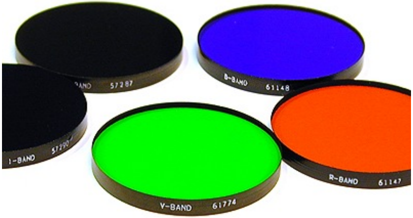
Schott Colored Glass



Color: nearly clear
(light greenish tint)

UBVRI





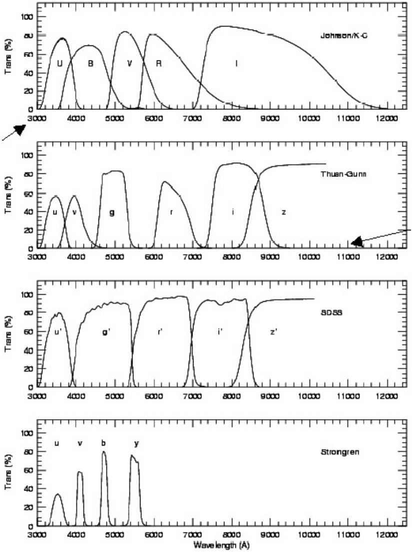
www.sbig.com/products/filters.htm

- 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

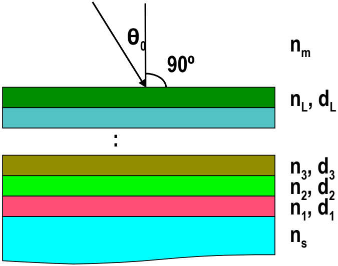
Other Filter Systems



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

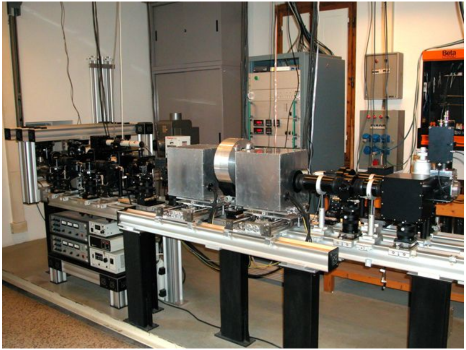
- other filter systems have less overlap and/or higher transmission
- Johnson system designed to measure properties of stars
- Thuan-Gunn filters for faint galaxy observations
- Stromgren has better sensitivity to stellar properties (metallicity, temperature, surface gravity)
- Sloan Digital Sky Survey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

Photometry

- goal: determine flux of an astronomical object in well-defined wavelength range
- problems:
  - seeing
  - extinction
  - sky background
  - telescope, instrument, detector
- calibration with (standard) stars
- *all-sky photometry*: compare objects all over the sky
- *differential photometry*: compare objects on same CCD exposure

Sky over La Palma

Atmosphere

- *photometric night* = uniform, stable sky conditions
- thin clouds and cirrus are hard to see at night
- *bright*, *grey* and *dark* observing time
- seeing defines size of stellar image for large telescopes
- image = convolution of source and Point-Spread Function (PSF)
- integral over image = integral over source

Air Mass

- extinction due to atmosphere proportional to amount of air along line-of-sight
- *airmass* = amount of air one looks through
- at zenith ($z = 0$): airmass=1.0
- *absorption coefficient* $K = 2.5 \log(f(z)/f(z = 0)$ where $f(z)$ is measured flux as function of zenith distance z
- $K\Delta X = \Delta m$ change in magnitude is absorption coefficient times change in airmass
- measure magnitude for different airmasses and extrapolate to zero airmass (no atmosphere!)

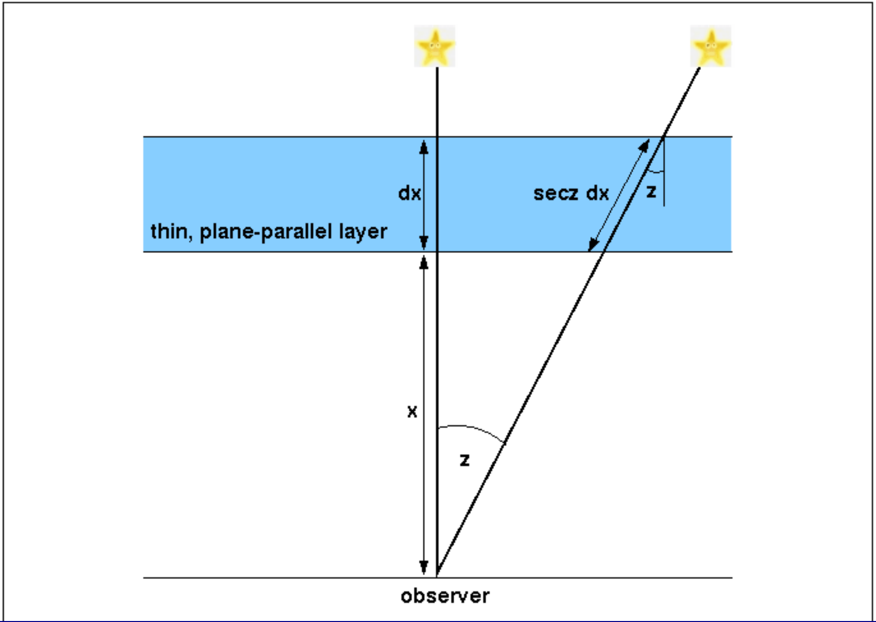
Dark Sky in Alps

Bright Sky in the Netherlands

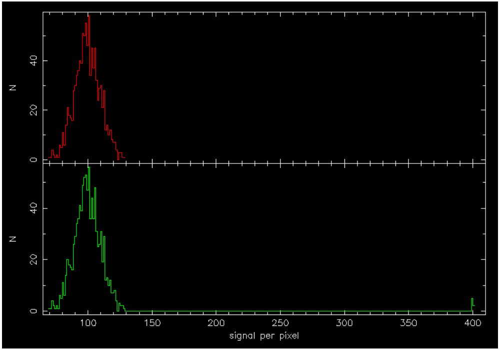
Photometric Observations

- observe object and standard stars with different colors
- observe standard stars at low and high airmass to determine their (color-dependent) extinction coefficients
- reduce images with bias, dark, flat field
- measure fluxes f_i with *aperture photometry*
- calculate *instrumental magnitudes*: $m_{\mathrm{inst}} = -2.5 \log_{10}(f_i / t_{\mathrm{exp}})$
- calibrate instrumental magnitude for zero airmass: $m_0 = m_{\mathrm{inst}} - K \sec z$
- *zero point* from standard stars: $m_{\mathrm{zp}} = m_{\mathrm{std}} - m_{\mathrm{std,inst}}$
- remove zero point: $m = m_{\mathrm{zp}} + m_{\mathrm{inst}}$
- absolute photometry: determine actual magnitudes with *transfer equations* derived from standard stars
- differential photometry does not require calibrations

Airmass: about sec *z*

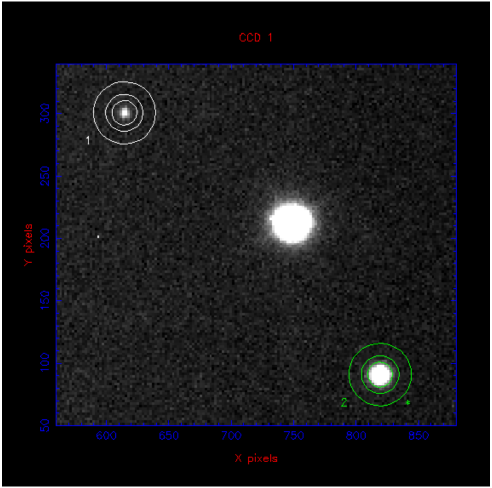


Sky Background



- use annulus around star
- use median instead of mean to neglect cosmic rays

Aperture Photometry



- determine location of star by fitting 2-D Gaussian or Moffat PSF model
- determine and remove sky background

Aperture Photometry (continued)

- optimum aperture size depends on brightness of star
- trade-off between capturing more starlight and adding noise from sky background, detector etc.
- plot result as function of increasing aperture and estimate asymptotic value
- for variability measurements (e.g. exoplanet transit) with differential photometry (standard star in same image):
    - use fixed and identical apertures for target and reference star(s)
    - optimum aperture minimizes scatter in constant parts of $m_{\mathrm{target}} - m_{\mathrm{std}}$

Color Correction

- extinction depends strongly on wavelength (color)
- measured flux through broad filter depends on stellar spectrum
- additional correction: $m = m_0 + k \sec z + k_2 C \sec z$ where C is color index (e.g. $C = B - V$)