

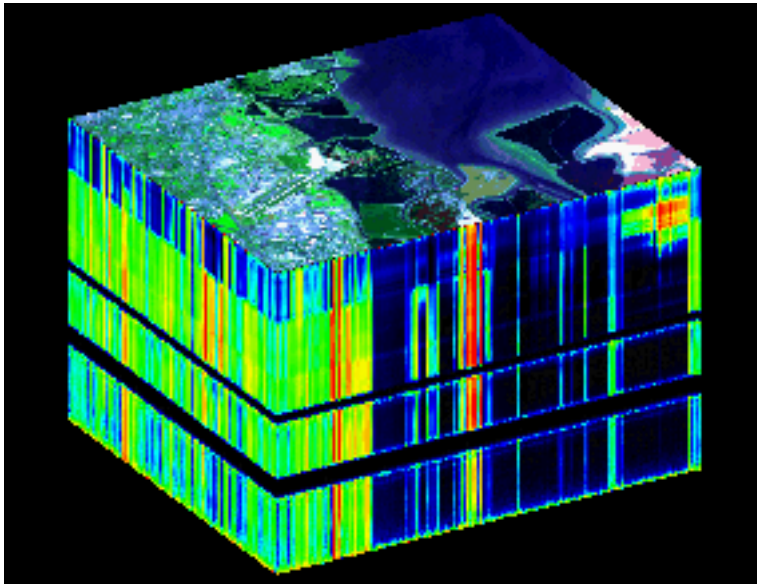
Lecture 12: Imaging

Christoph U. Keller

Overview

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 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

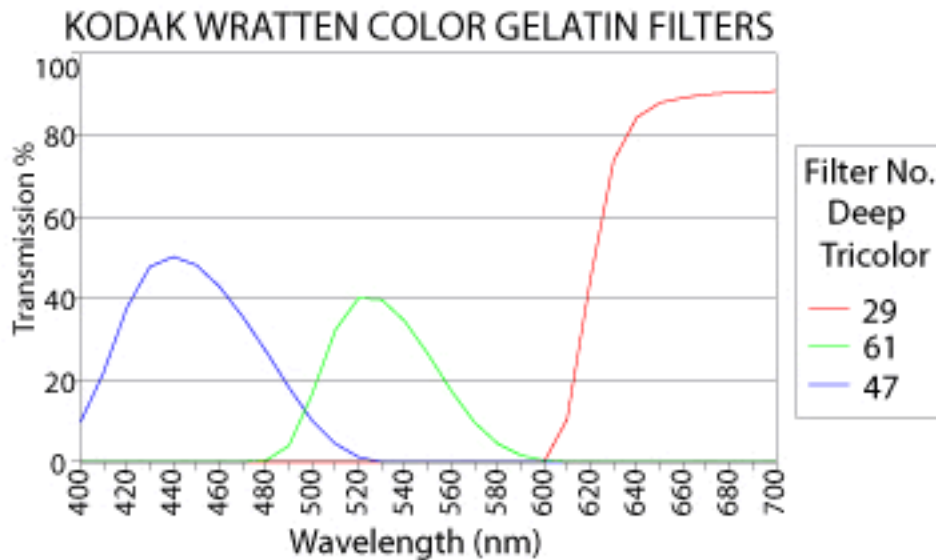
Wratten Filters



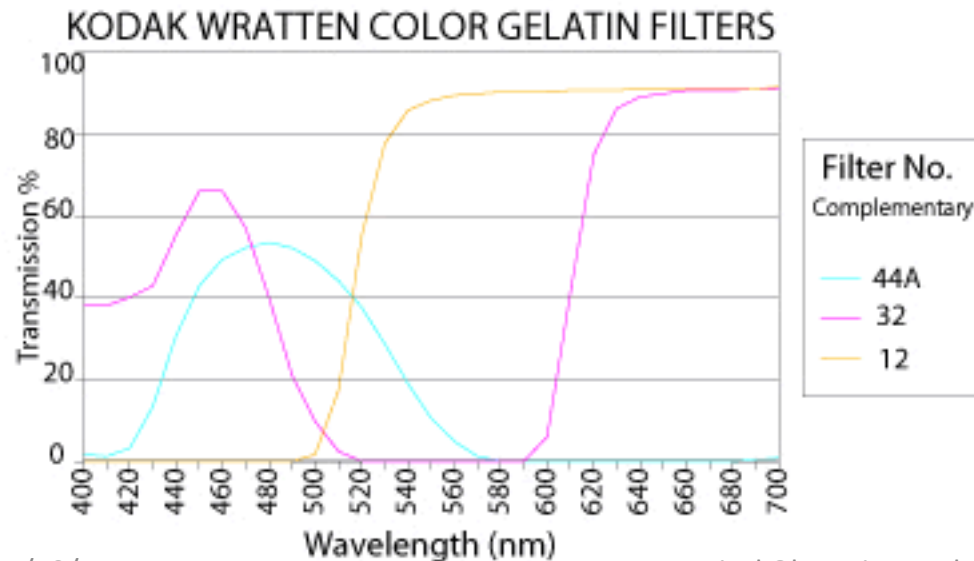
[www.edmundoptics.com/
onlinecatalog/displayproduct.cfm?
productid=1326](http://www.edmundoptics.com/onlinecatalog/displayproduct.cfm?productid=1326)

- 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



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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)
- other glasses from Corning, Hoya

Schott Colored Glass 1

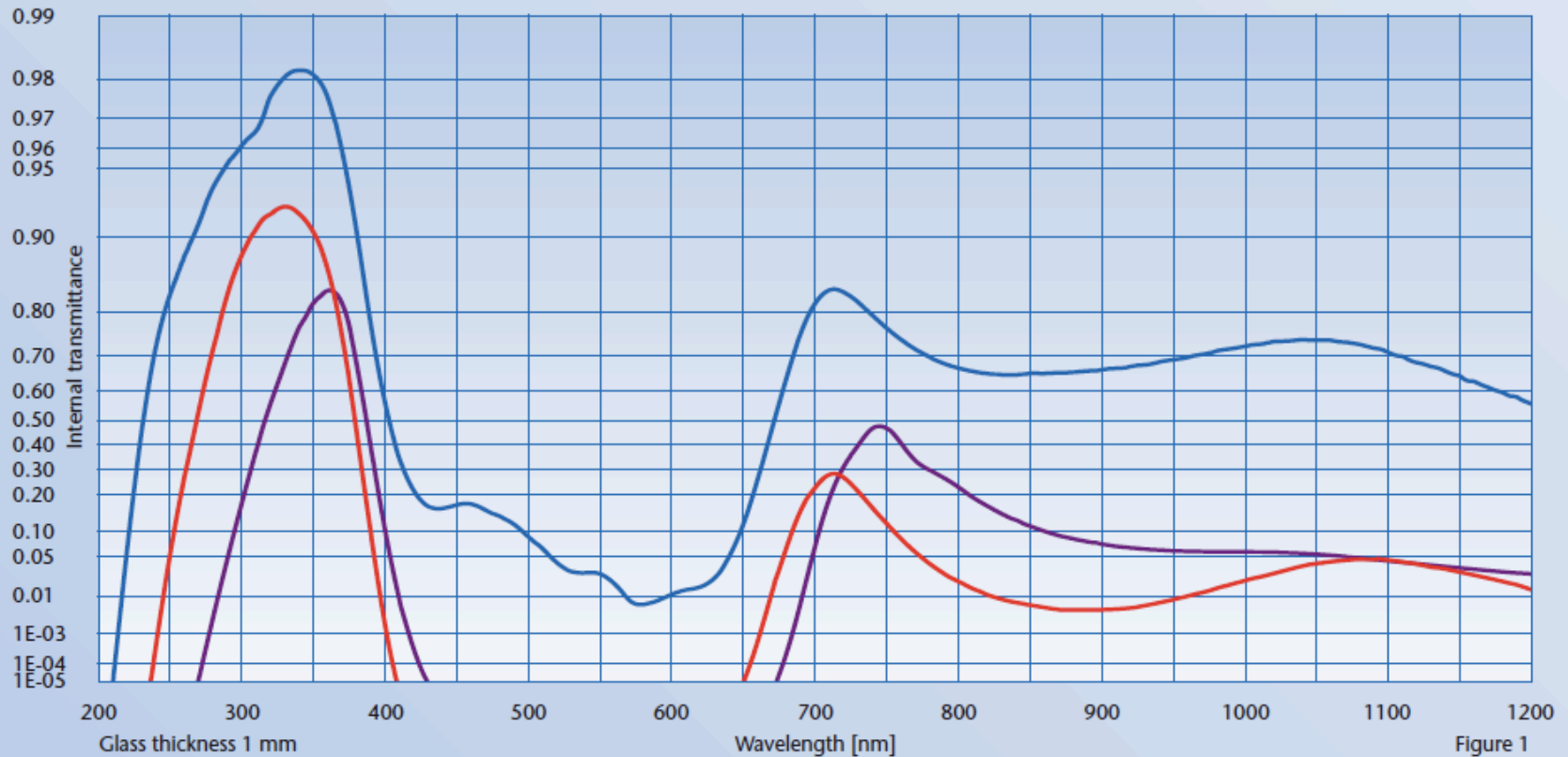


Figure 1

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

— UG5
— UG1

— UG11

Schott Colored Glass 2

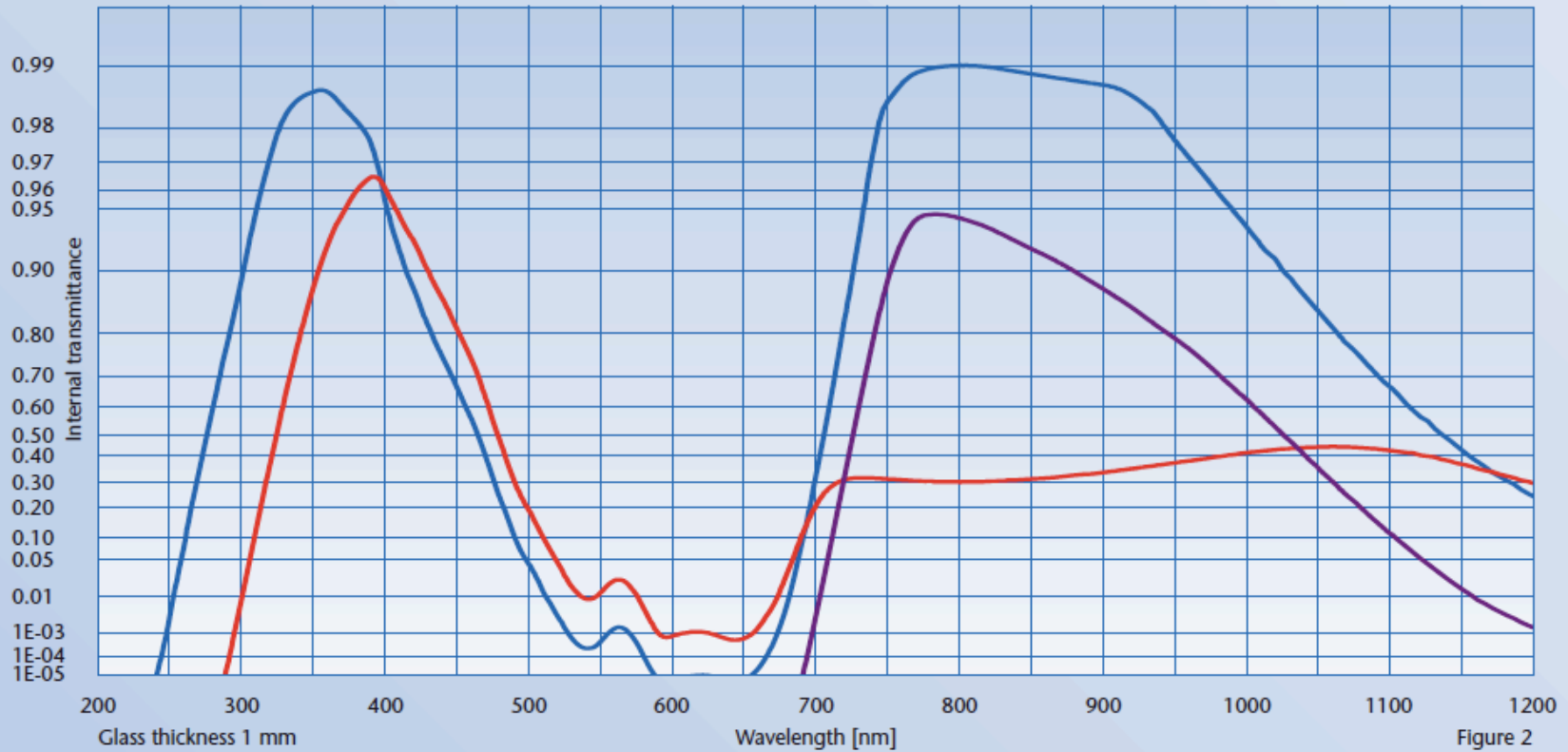
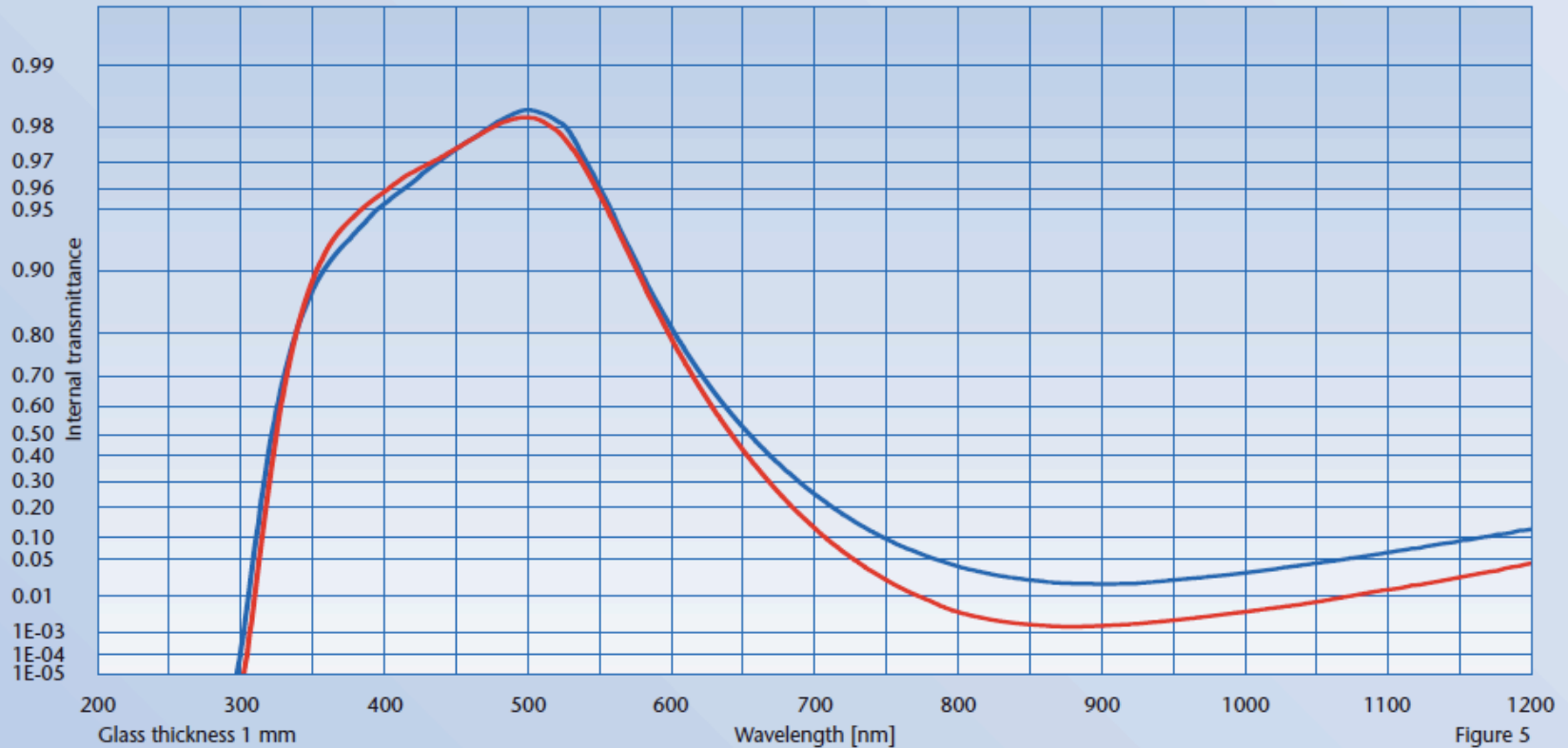


Figure 2

Color: blue

- BG3 at 1 mm
- BG25 at 1 mm
- RG9 at 3 mm

Schott Colored Glass 3

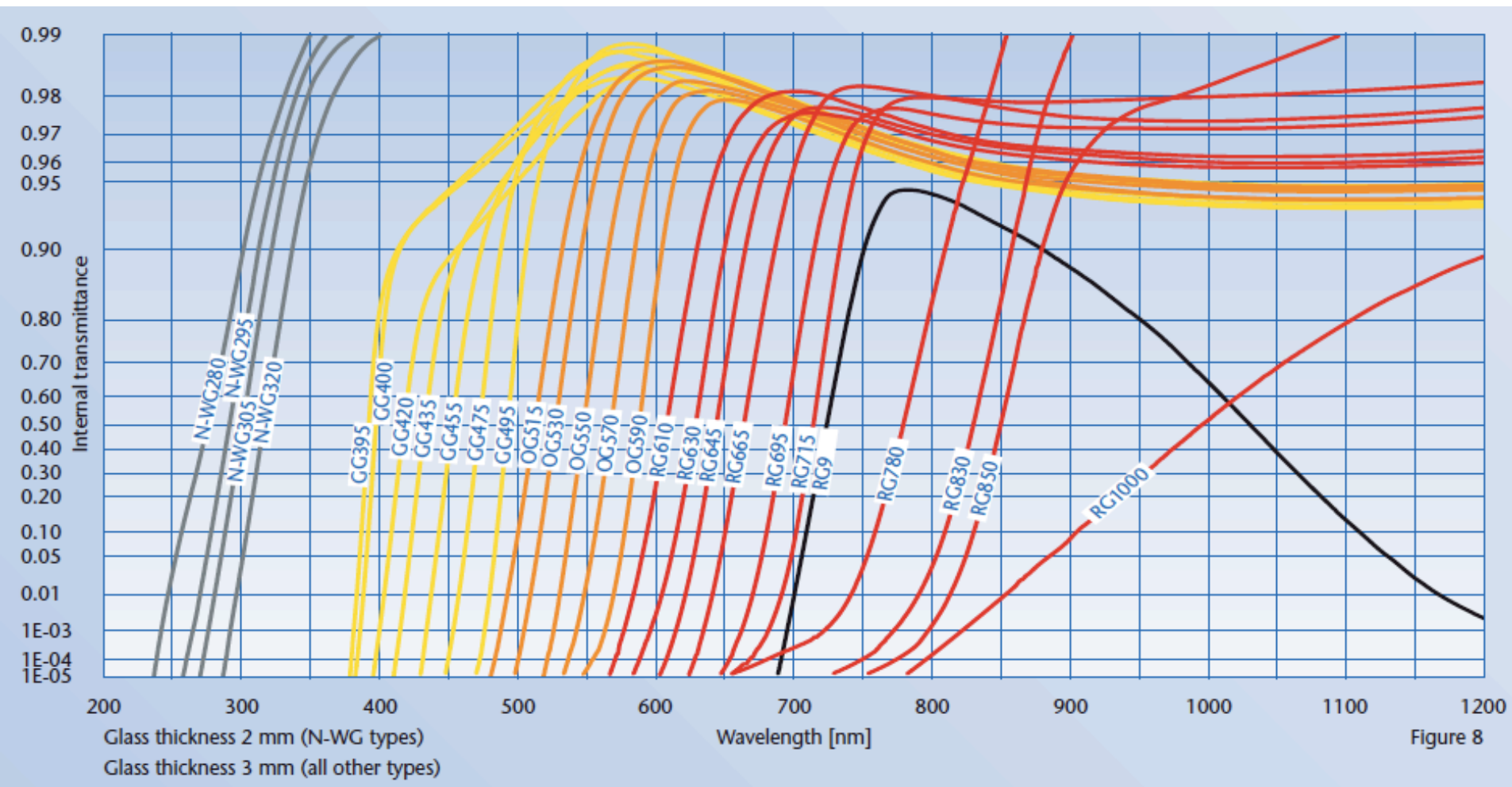


Color: bright blue-green

— BG38 at 1 mm

— BG40 at 1 mm

Schott Colored Glass 4



Schott Colored Glass 5

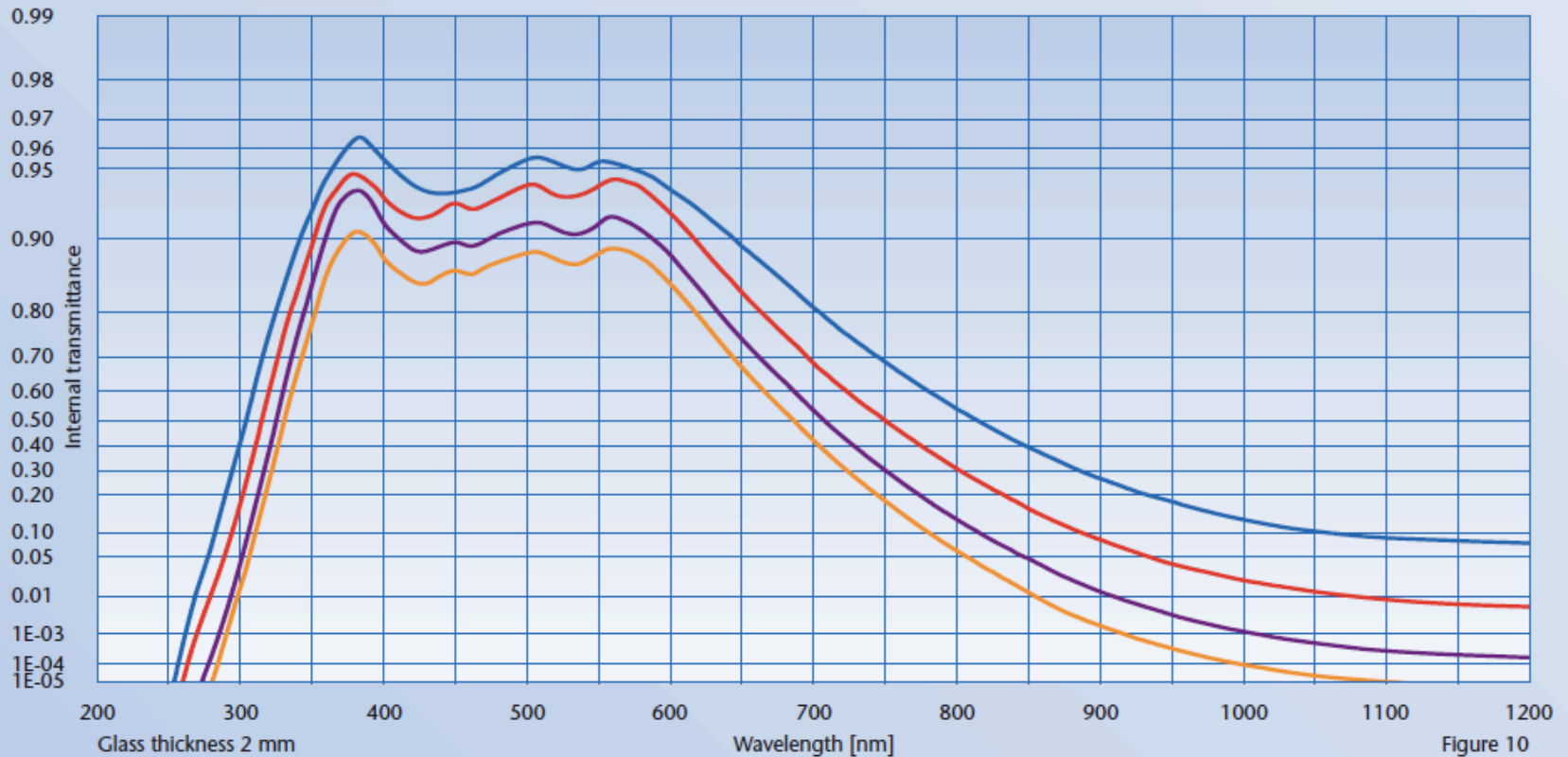
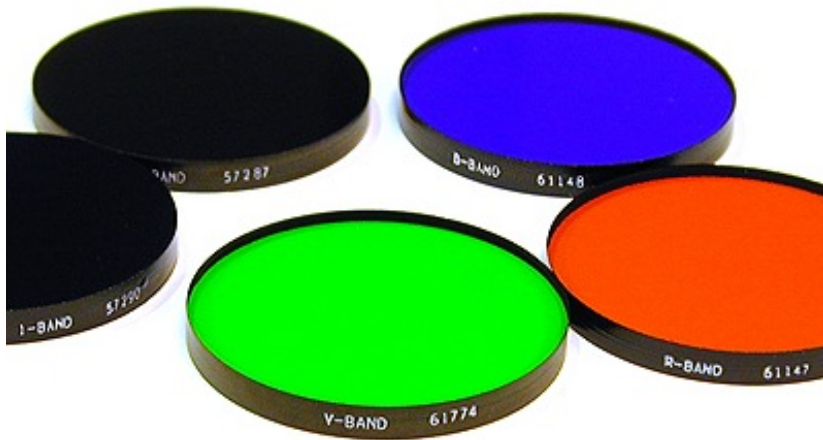


Figure 10

Color: nearly clear
(light greenish tint)

— KG2 — KG1
— KG3 — KG5

UBVRI

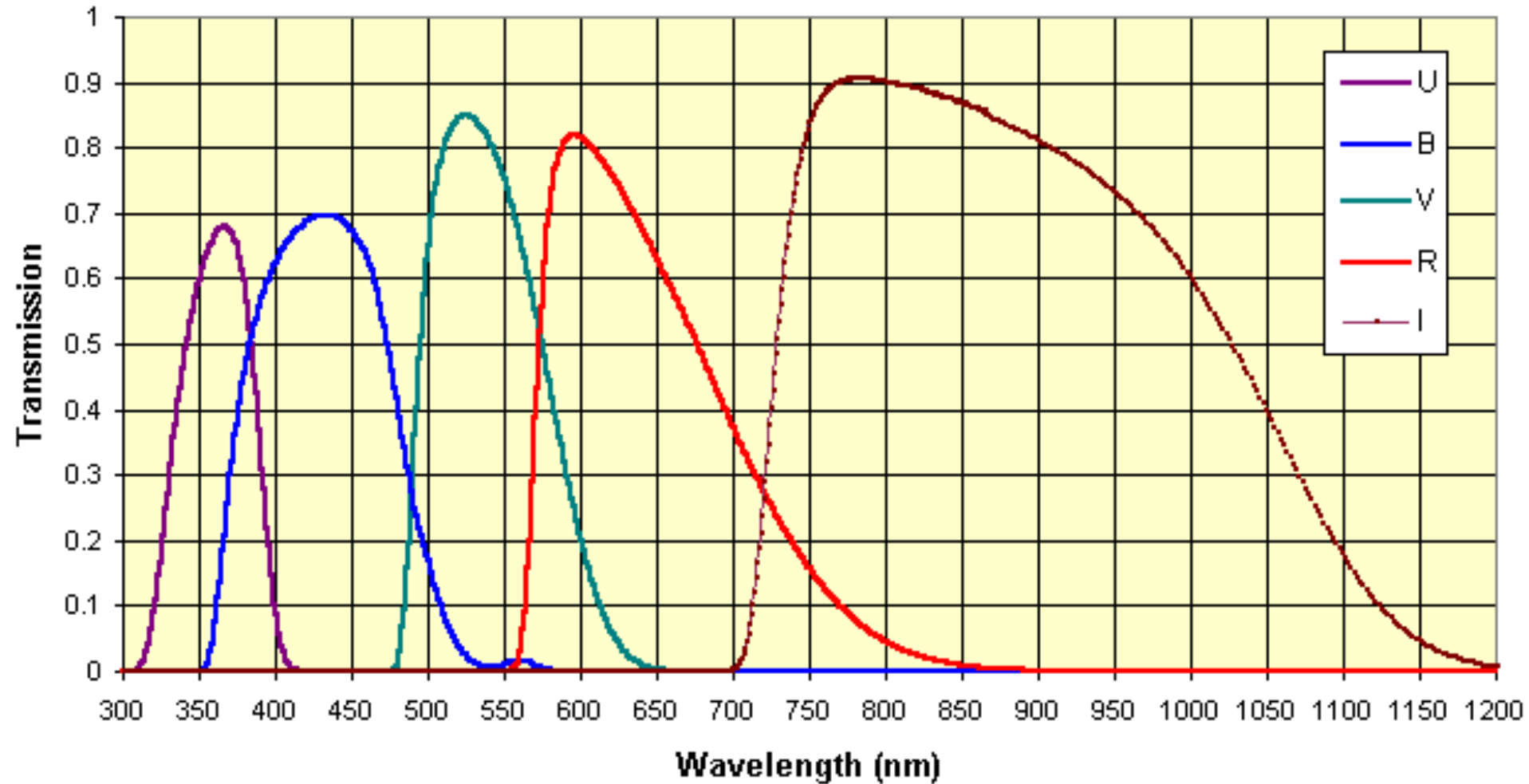


www.sbig.com/products/filters.htm

- 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

(Old) UBVRI

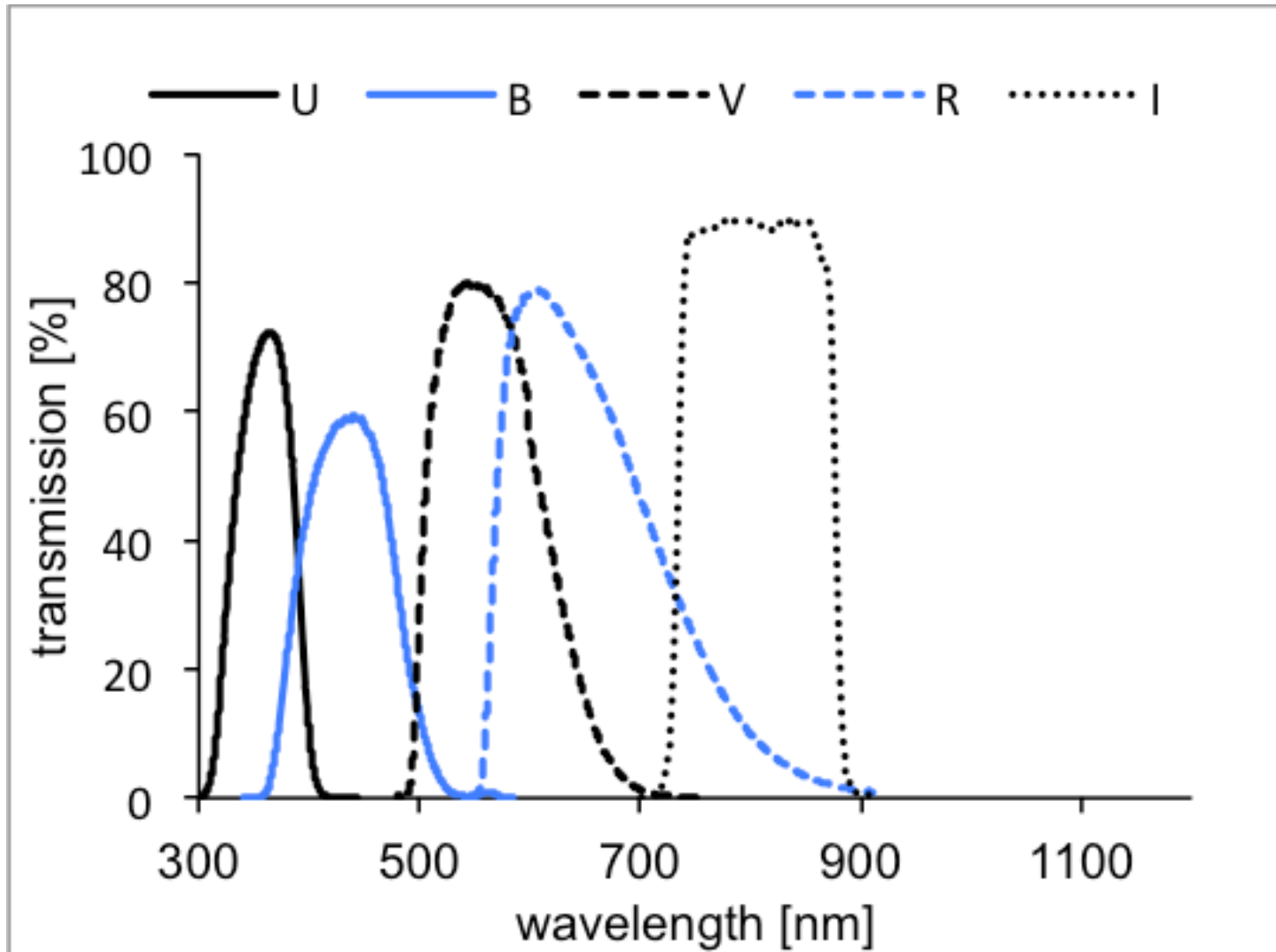
UBVRI Filter Characteristics



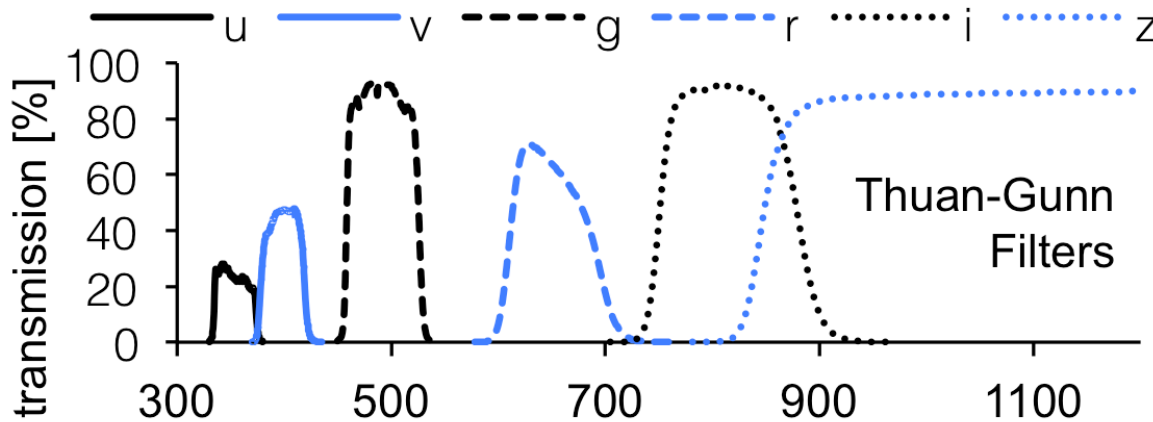
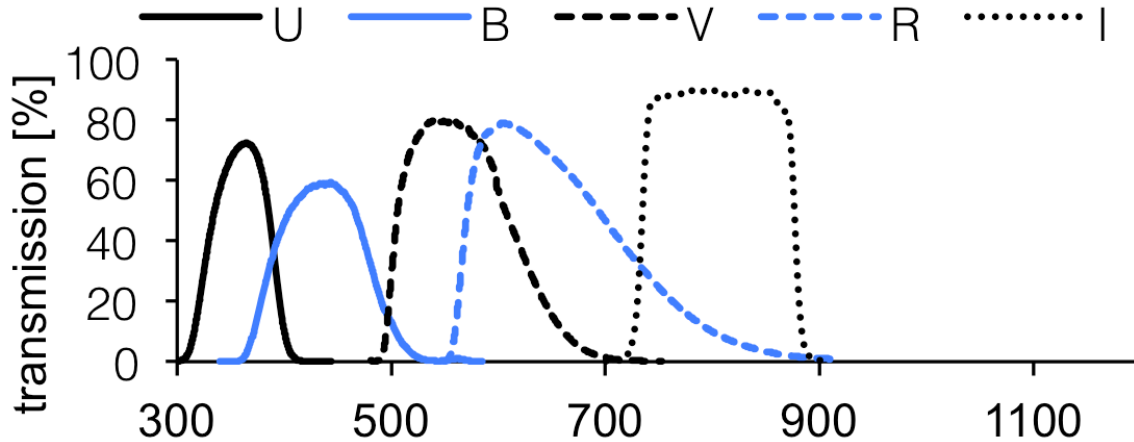
Limitations of UBVRI Photometry

- 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

UBVRI

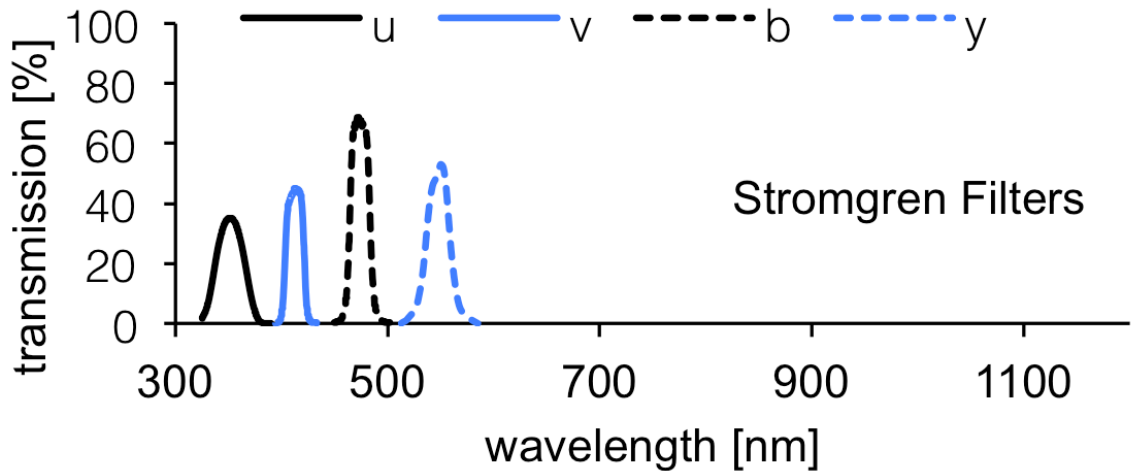
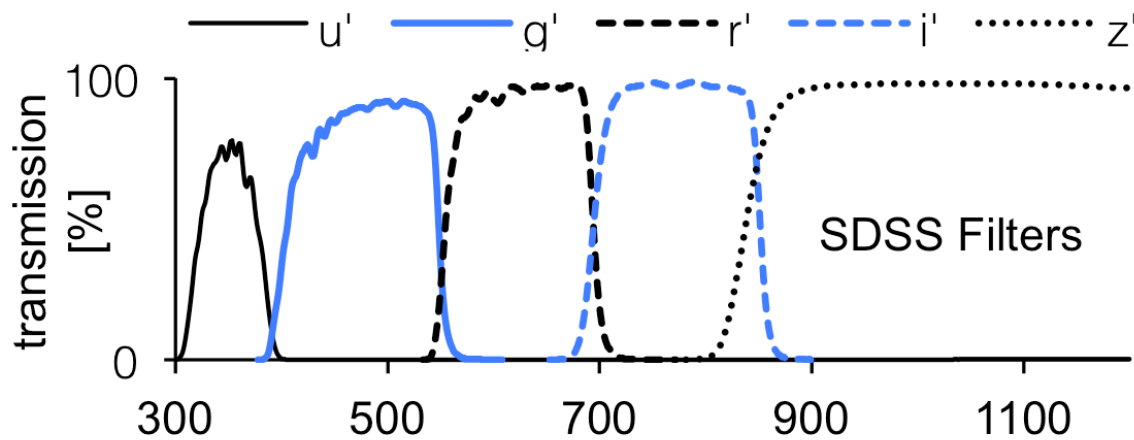


Other Filter Systems



- 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

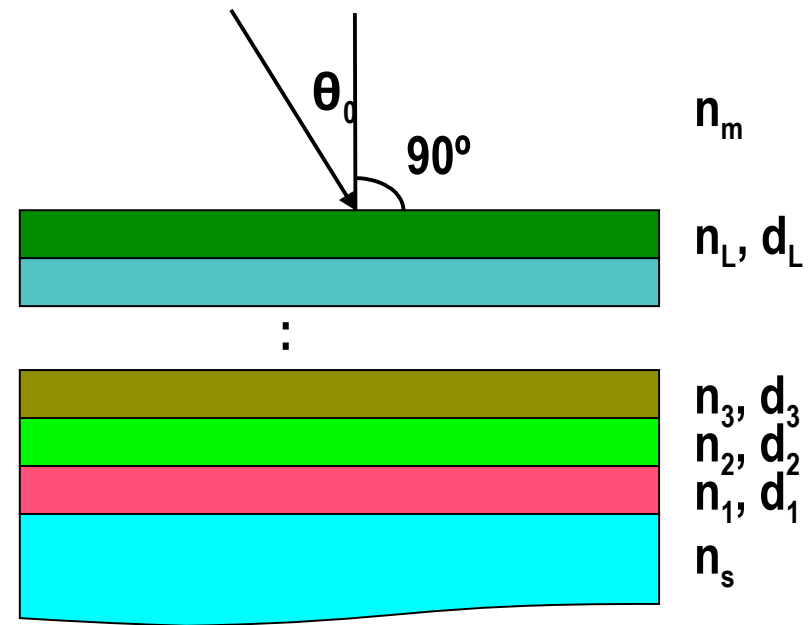
Other Filter Systems



- Sloan Digital Sky Survey (SDSS) for faint galaxy classification
- Stromgren has better sensitivity to stellar properties (metallicity, temperature, surface gravity)

Interference Filters

- thin film:
 - layer with thickness $\leq \lambda$
 - extends in 2 other dim. $\gg \lambda$
- reflection, refraction at all interfaces
- layer thickness $d_i \leq \lambda \rightarrow$ interference between reflected and refracted waves
- L layers of thin films like Fabry-Perots: thin film stack
- substrate (index n_s), incident medium (index n_m) have infinite thickness
- can be tailored to almost any specifications
- sensitive to temperature, humidity, angle of incidence
- tune in wavelength with temperature, angle of incidence



Fabry-Perot Tunable Filter



www.arcetri.astro.it/science/solare/IBISphoto.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

A night sky over La Palma, showing a starry sky with a prominent yellowish-white nebula or comet tail in the center. The foreground is dark, with silhouettes of trees and a building on a hillside.

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

A long-exposure photograph of a clear night sky in the Alps. The Milky Way galaxy is the central focus, appearing as a dense, glowing band of stars and dust that curves from the lower right towards the upper left. The sky is filled with numerous individual stars of varying brightness. In the foreground, the dark, jagged silhouettes of mountain peaks are visible against the starry background. The overall scene is a testament to the clarity and darkness of the night sky in high-altitude regions.

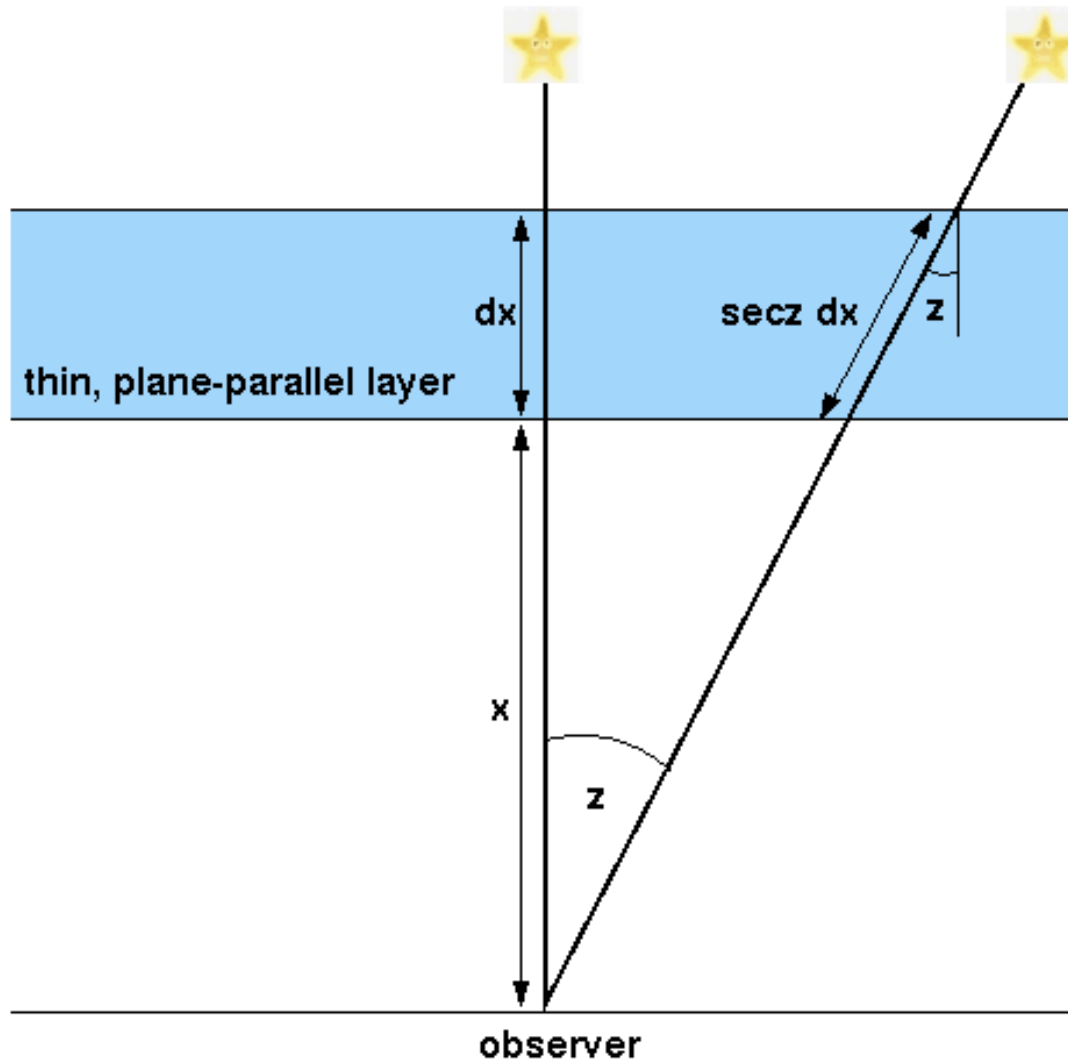
Bright Sky in the Netherlands



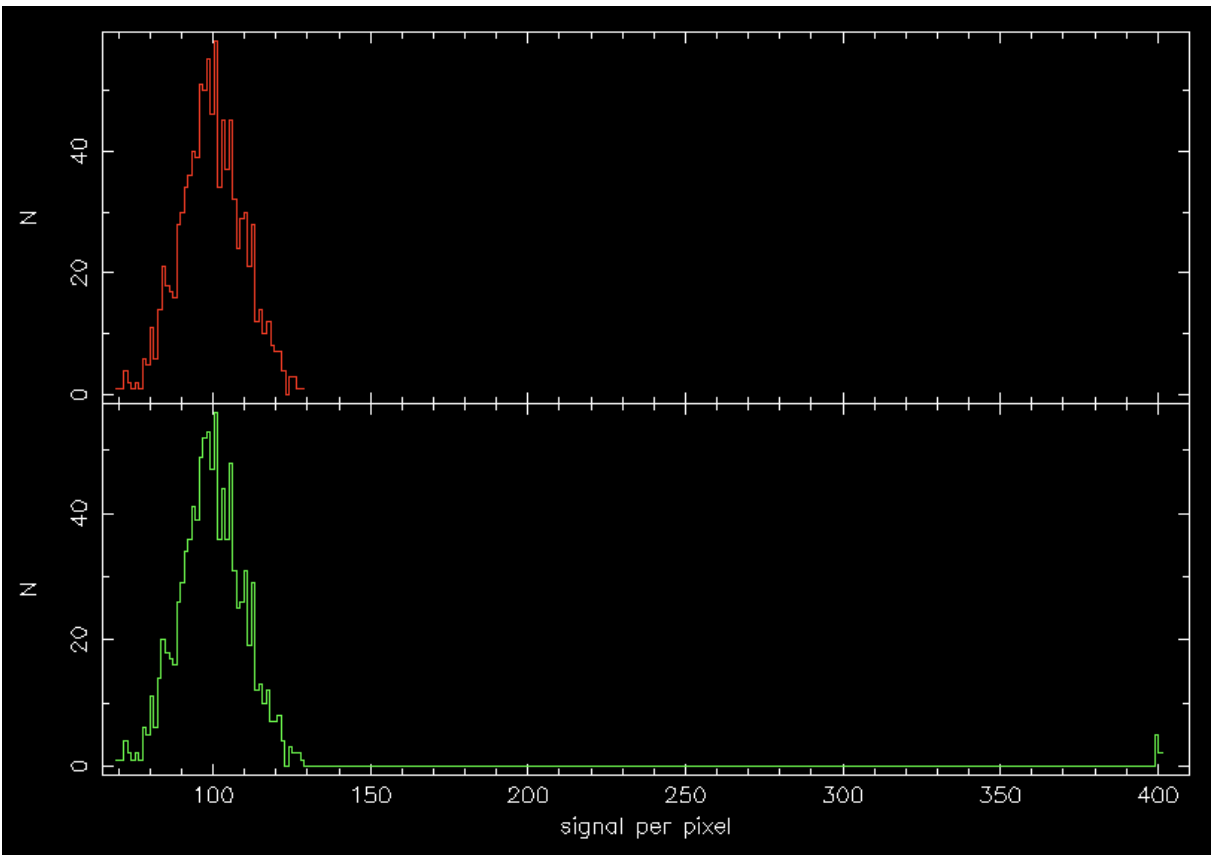
Photometric Observations

- 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 with **aperture photometry**
- calculate **instrumental magnitudes**: $m_{inst} = -2.5 \log(f_i/t_{exp})$
- calibrate instrumental magnitude for zero airmass:
 $m_0 = m_{inst} - K \sec z$
- zero point from standard stars: $m_{zp} = m_{std} - m_{std,inst}$
- remove zero point: $m = m_{zp} + m_{inst}$
- absolute photometry: determine actual magnitudes with **transfer equations** derived from standard stars
- differential photometry does not require calibrations

Airmass

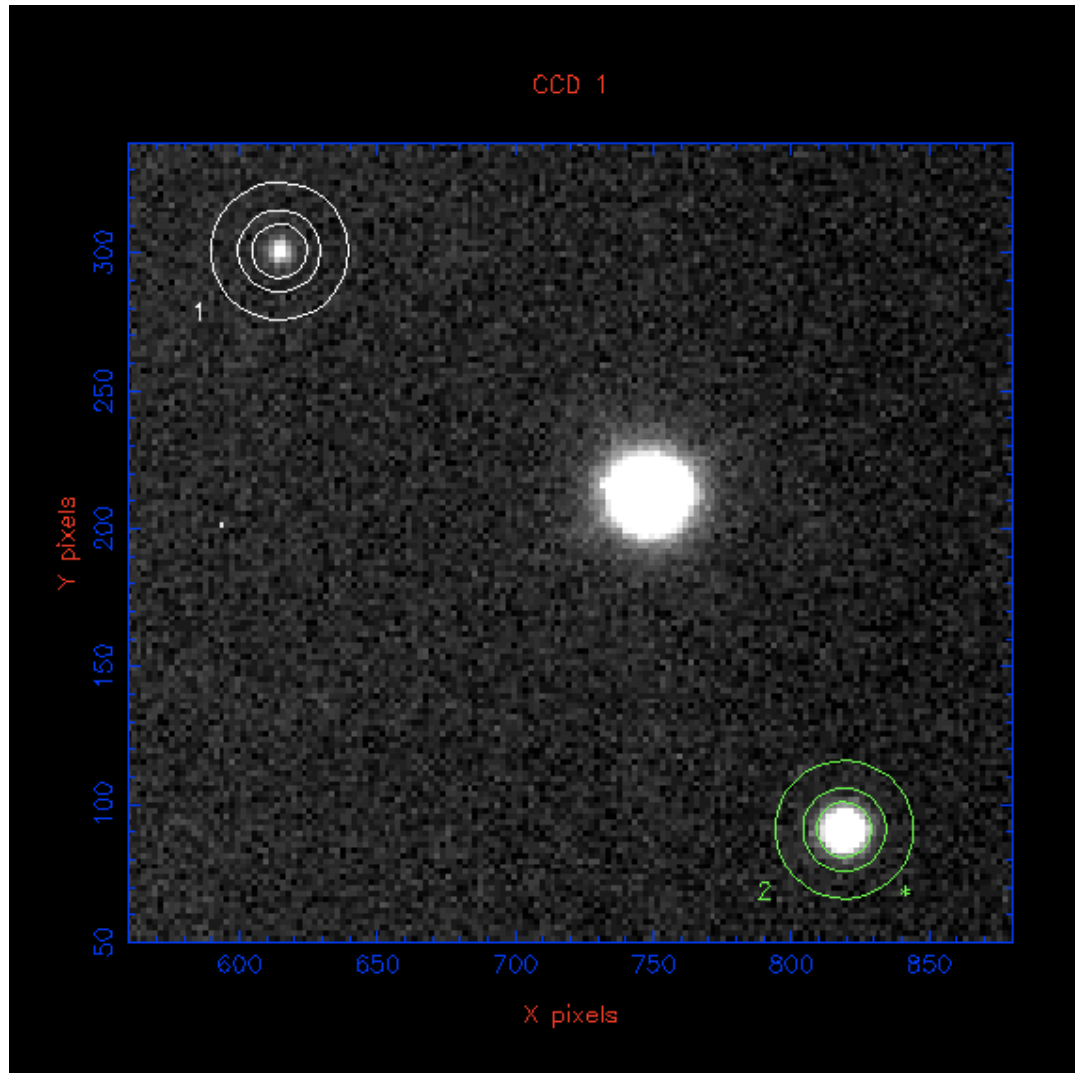


Sky Background



- 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 $m_{target} - m_{std}$

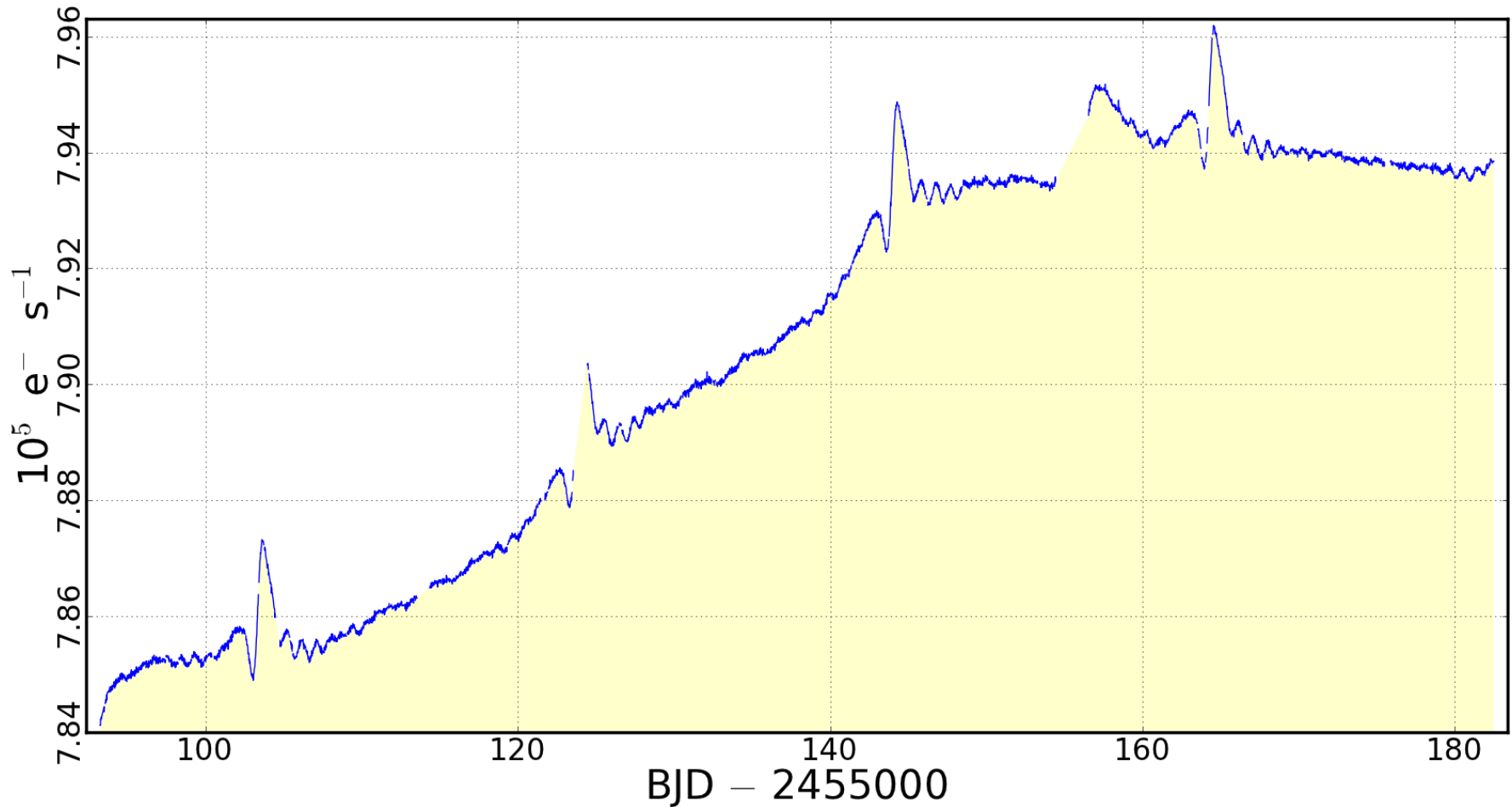
Color Correction

- 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)

Extreme Photometry

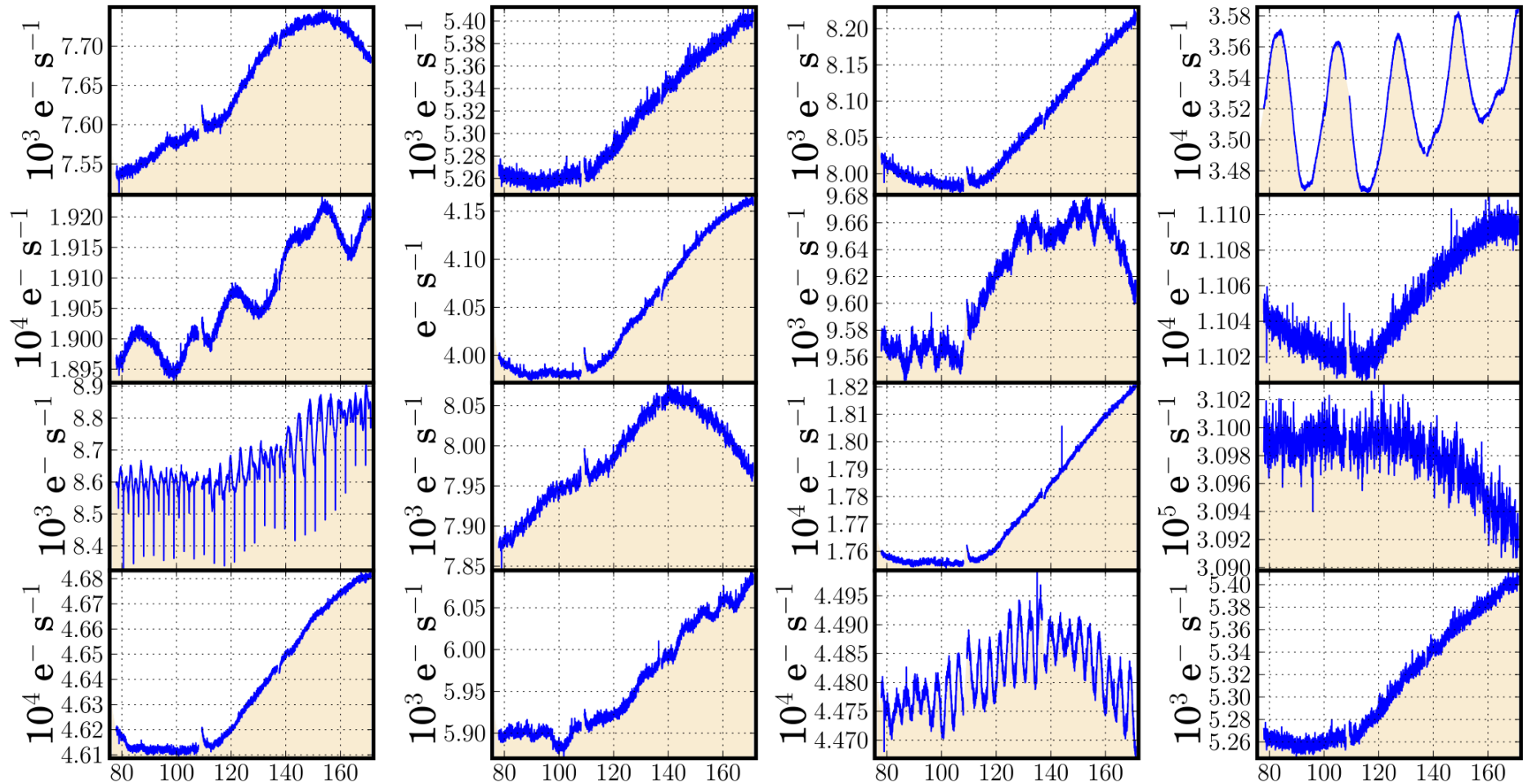


keplerscience.arc.nasa.gov/PyKEprimerWalkthroughC.shtml
90-day long-cadence Kepler SAP light curve of KIC 3749404.

Subtle Instrumental Effects

- Thermal changes in optics, electronics
- Small guiding errors coupled with sub-pixel gain variations
- Cotrending Basis Vectors (CBV): Instrumental parameters that have been shown to correlate with photometry of standard stars

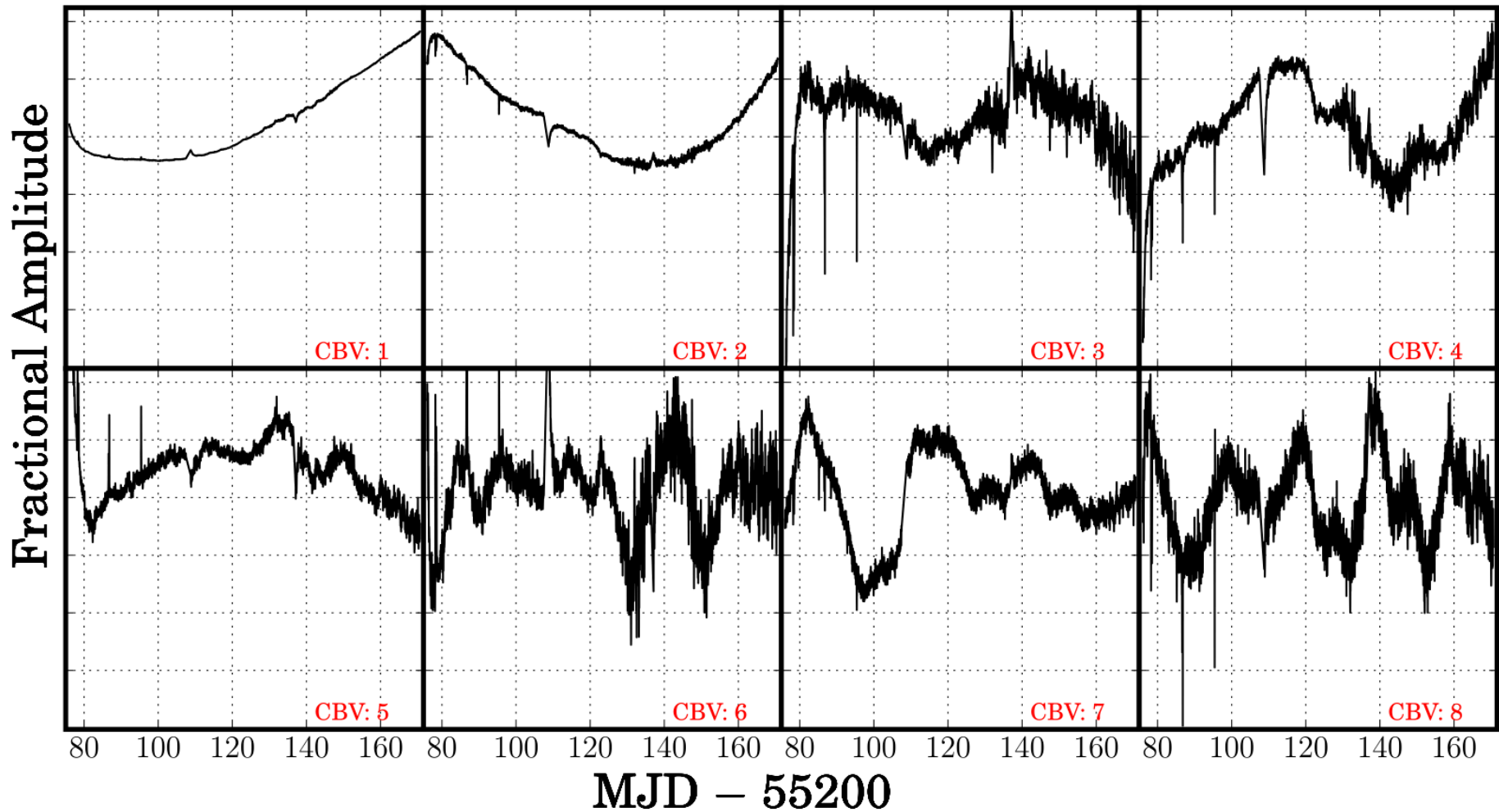
16 Kepler Light Curves



BJD - 2455200

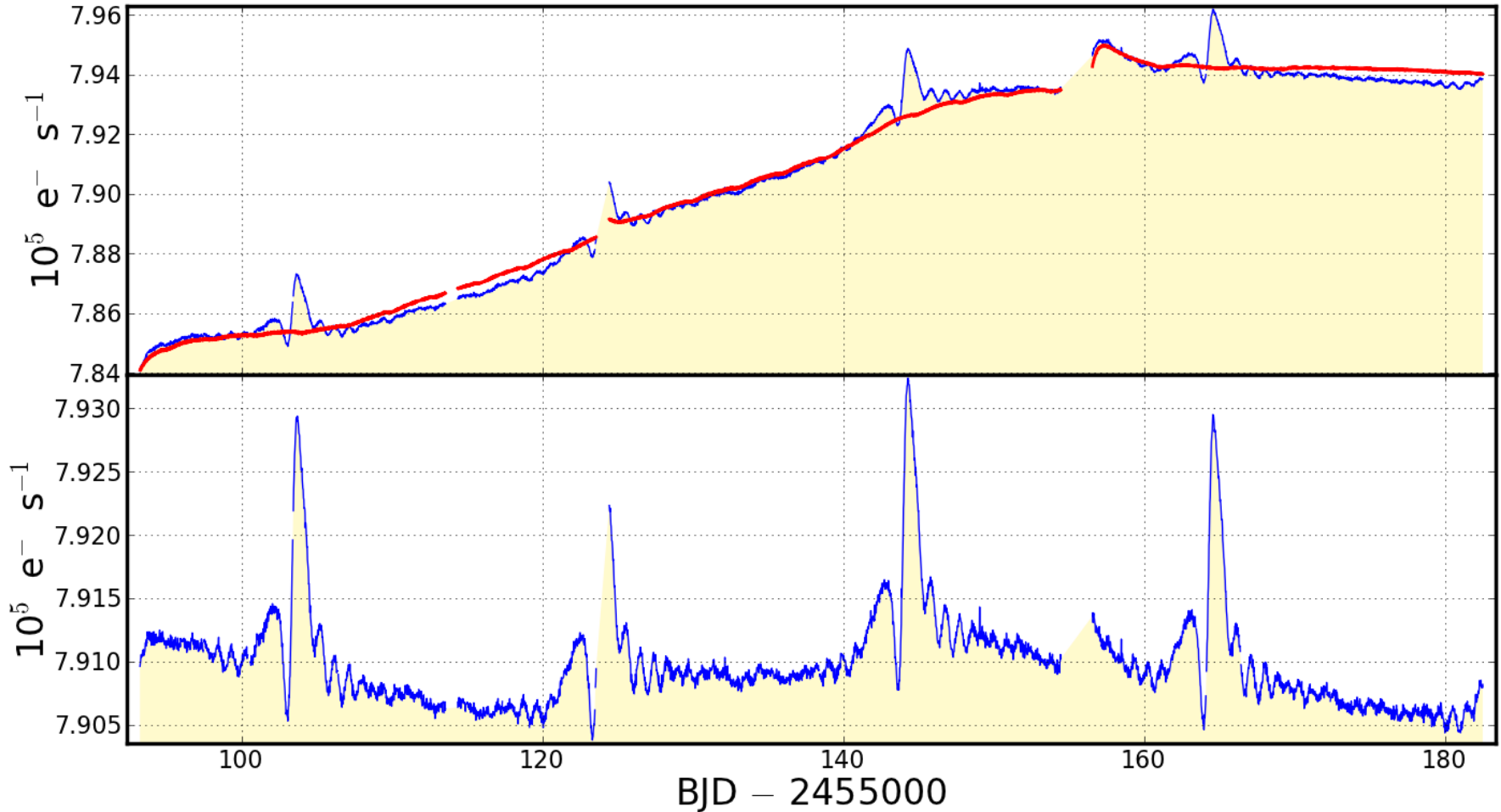
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Cotrending Basis Vectors



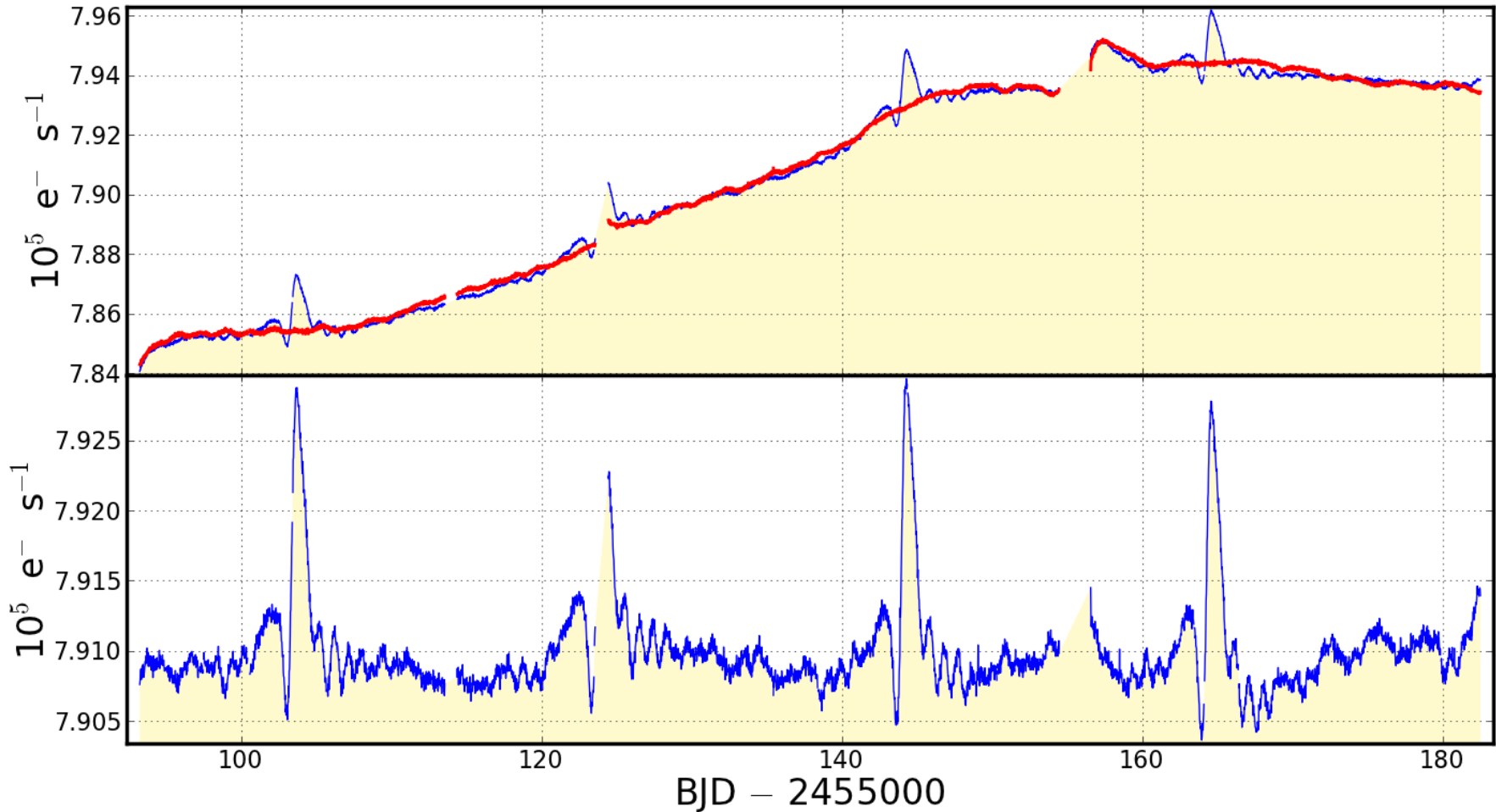
keplerscience.arc.nasa.gov/images/PyKE/PyKEprimerFig3.png

Subtraction of 2 CBVs



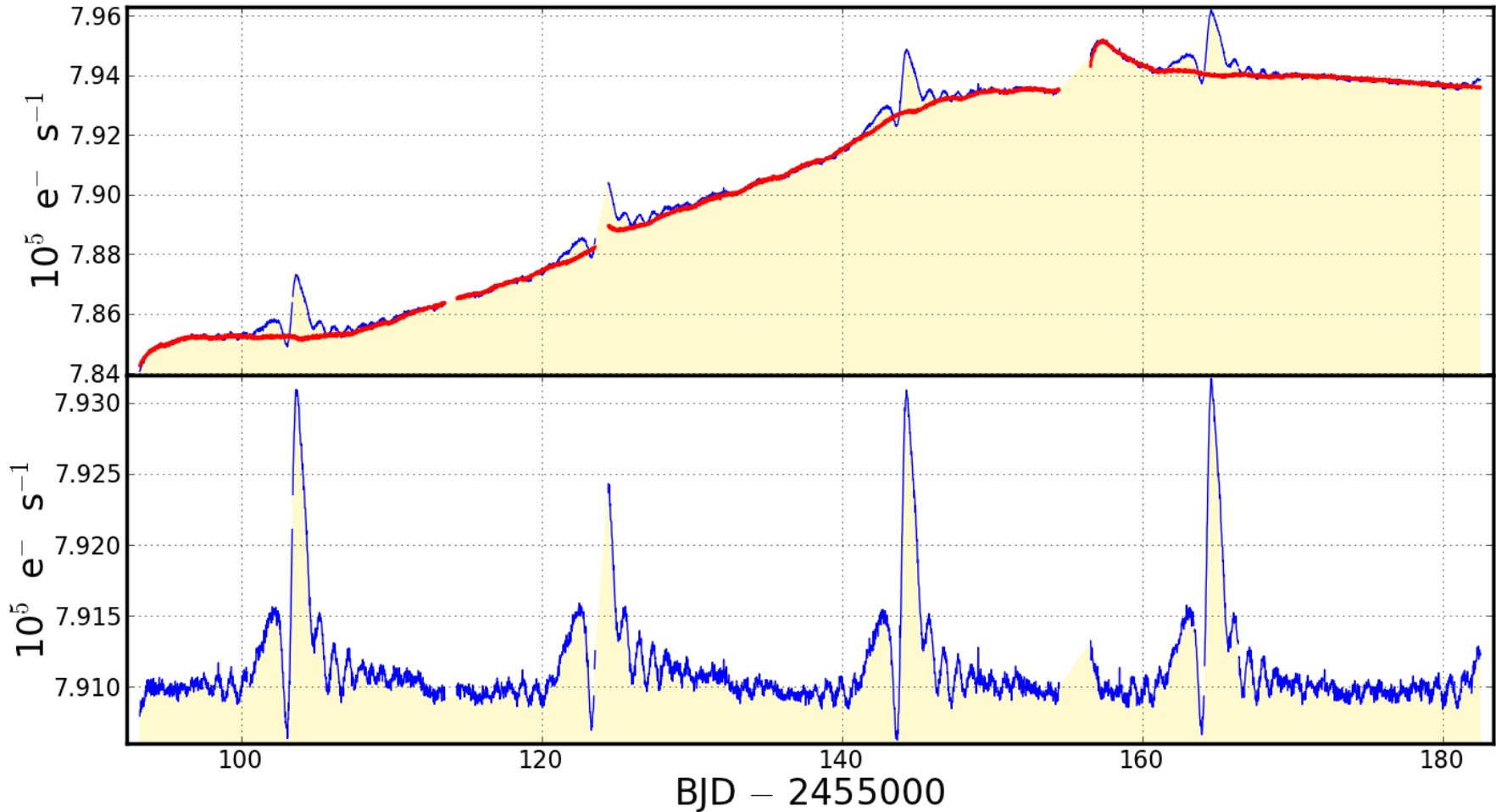
keplerscience.arc.nasa.gov/PyKEprimerWalkthroughC.shtml
90-day long-cadence Kepler SAP light curve of KIC 3749404.

Subtraction of 8 CBVs



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90-day long-cadence Kepler SAP light curve of KIC 3749404.

No CBV Fitting During Eclipses



keplerscience.arc.nasa.gov/PyKEprimerWalkthroughC.shtml
90-day long-cadence Kepler SAP light curve of KIC 3749404.