Introduction to photometry/spectroscopy

Research workshop on evolved stars

Matti Dorsch

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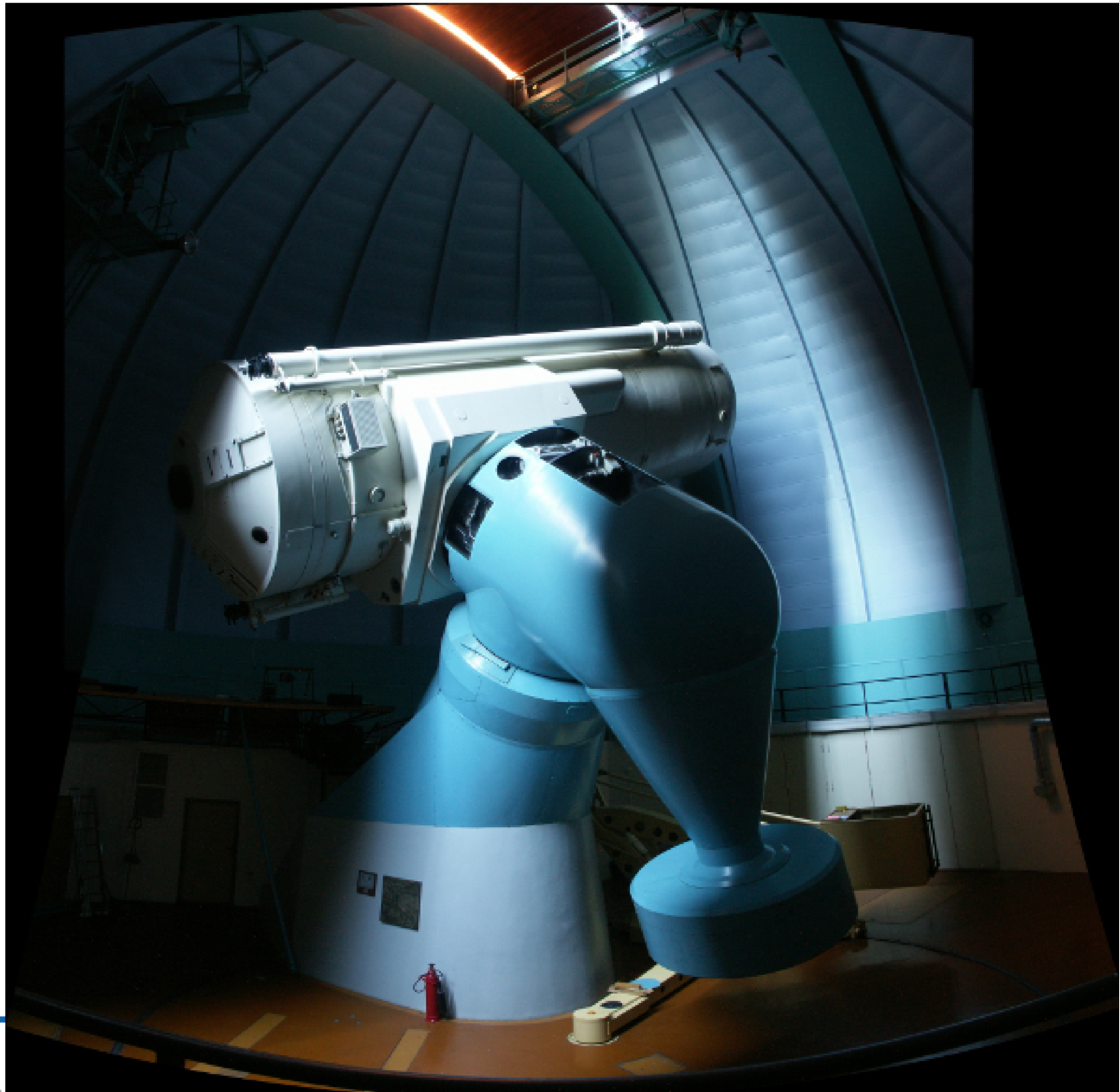
Institute for Physics and Astronomy

Email: matti.dorsch@fau.de

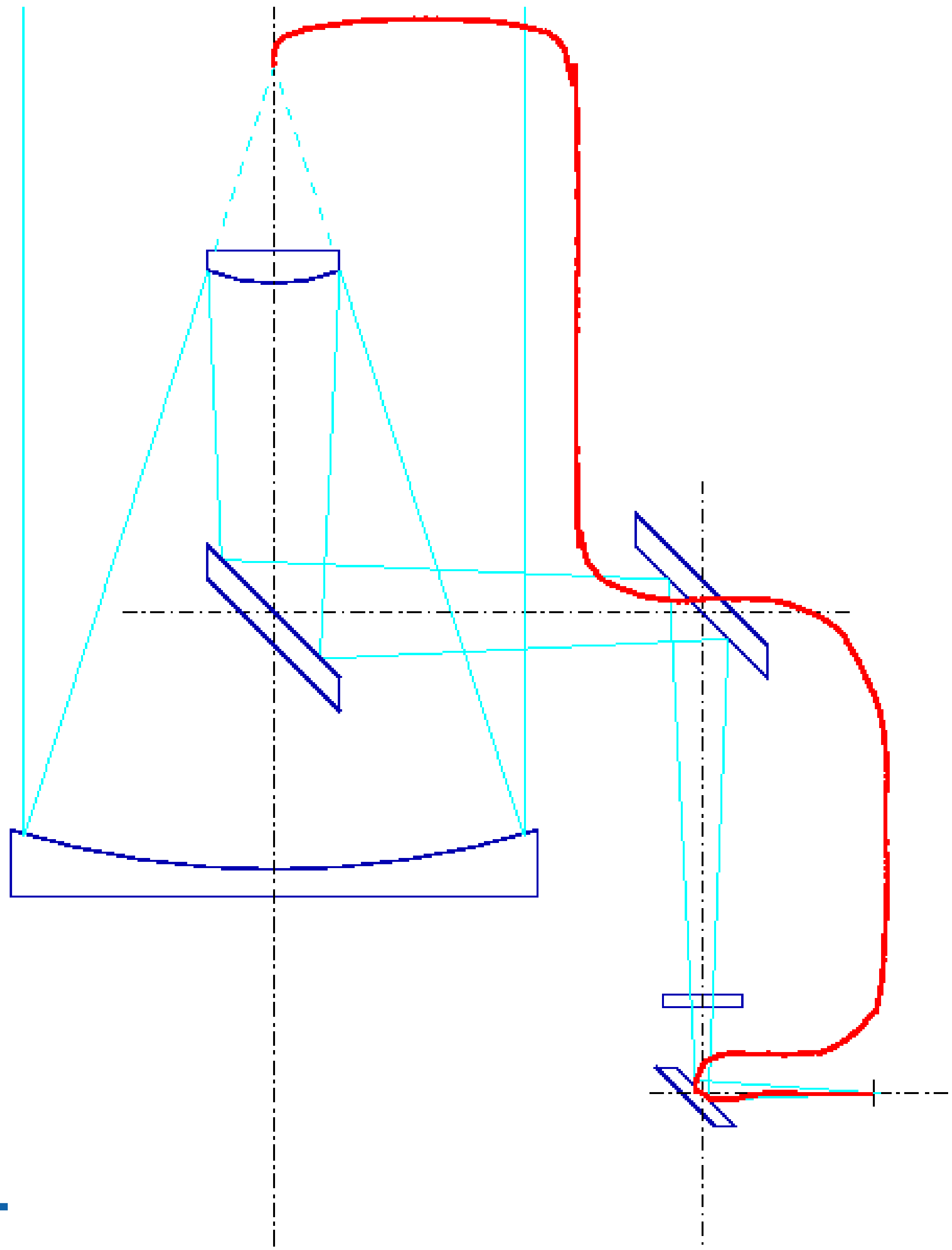
Room: 2.118

Universität Potsdam

Perek 2-m telescope



Perek 2-m telescope

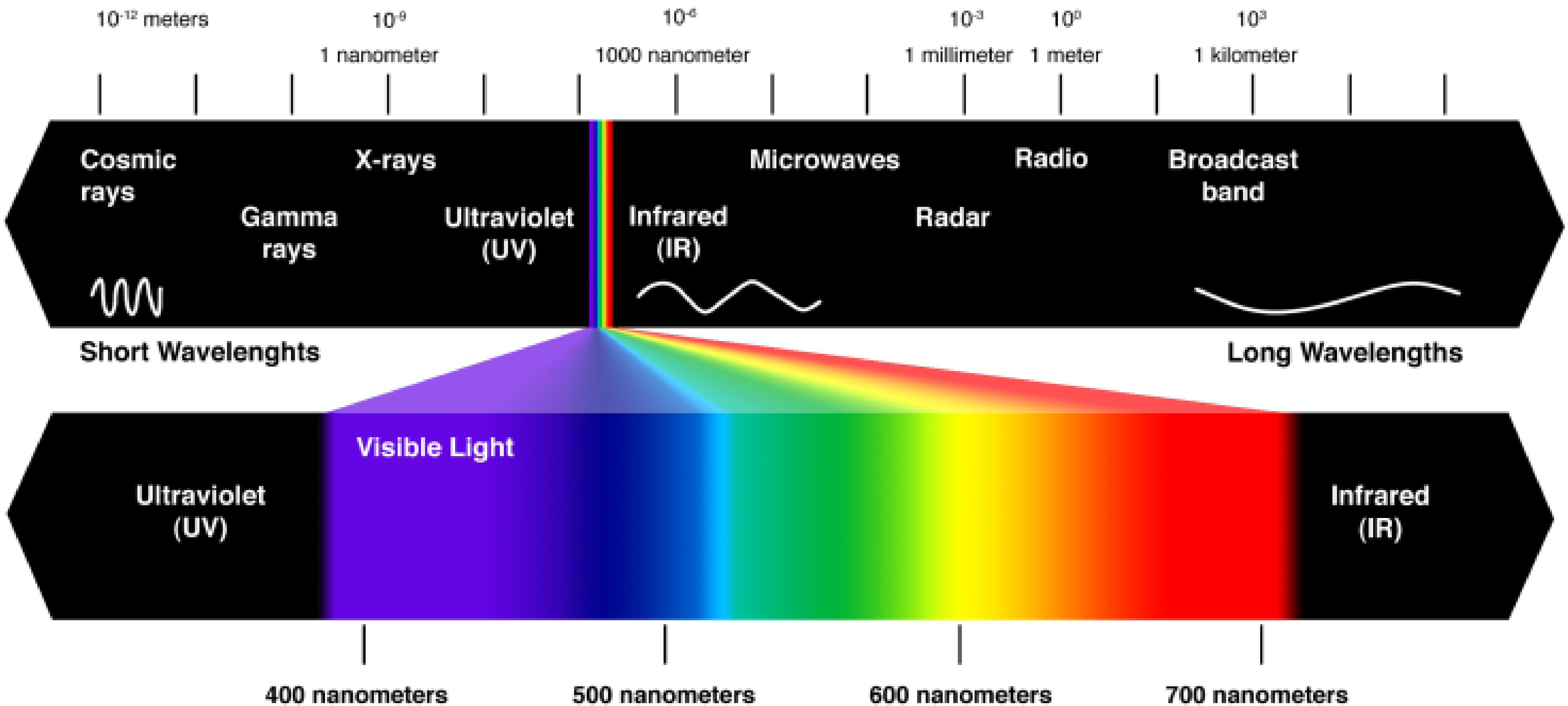


- Manufacturer: Carl Zeiss Jena
- Type of mount: Equatorial
- Primary parabolic mirror D=2 m, thickness 0.3 m, weight 2340 kg
- Original optical setting: primary, Cassegrain, coudé focus
- Current optical setting: optical fiber from primary to coudé focus
- Effective focal length: F=63.5 m
- Effective focal rati: f/4.5 in primary and f/32 in coudé.
- Instruments:
  - single order spectrograph
  - echelle spectrograph
  - photometric camera

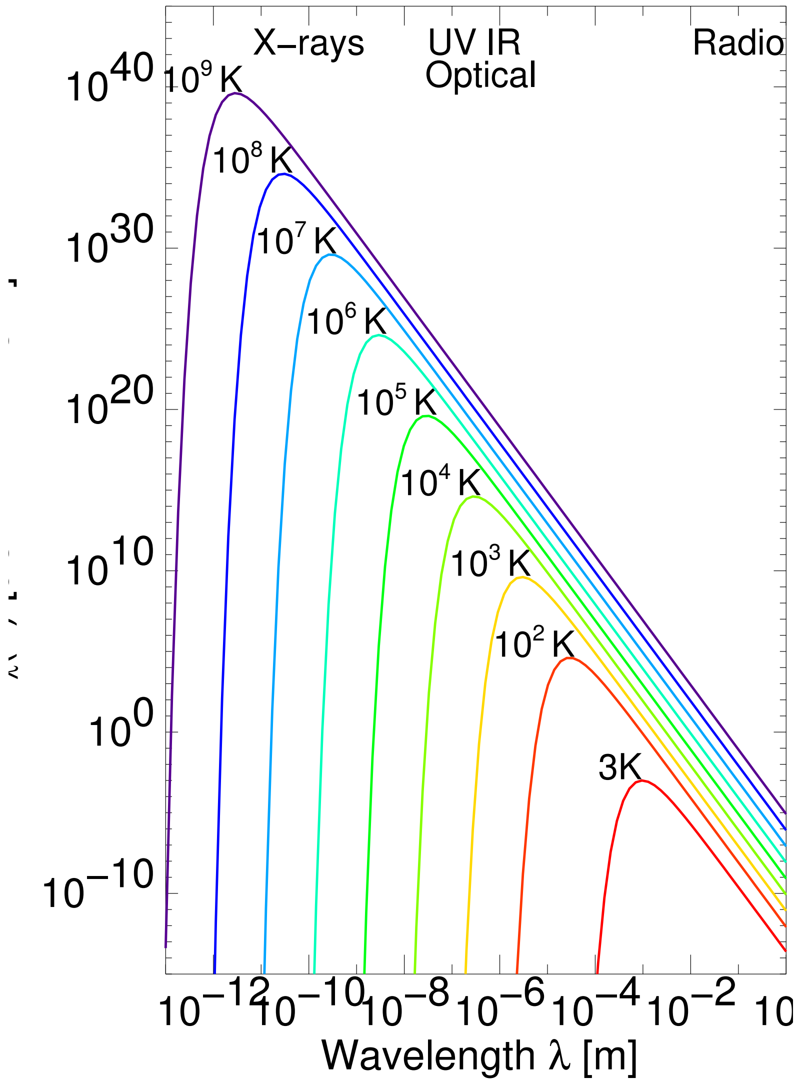
Photometry

What is Photometry?

from Greek photo- ("light") and -metry ("measure") aims at measuring the flux or intensity of electromagnetic radiation emitted by astronomical objects



Planck's Radiation Law



Stefan-Boltzmann law: Flux (power emitted per square-meter surface) of a blackbody:

$$F = B = \int_0^\infty B_\lambda(\lambda)\,\mathrm{d}\lambda = \sigma T^4$$

where $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$

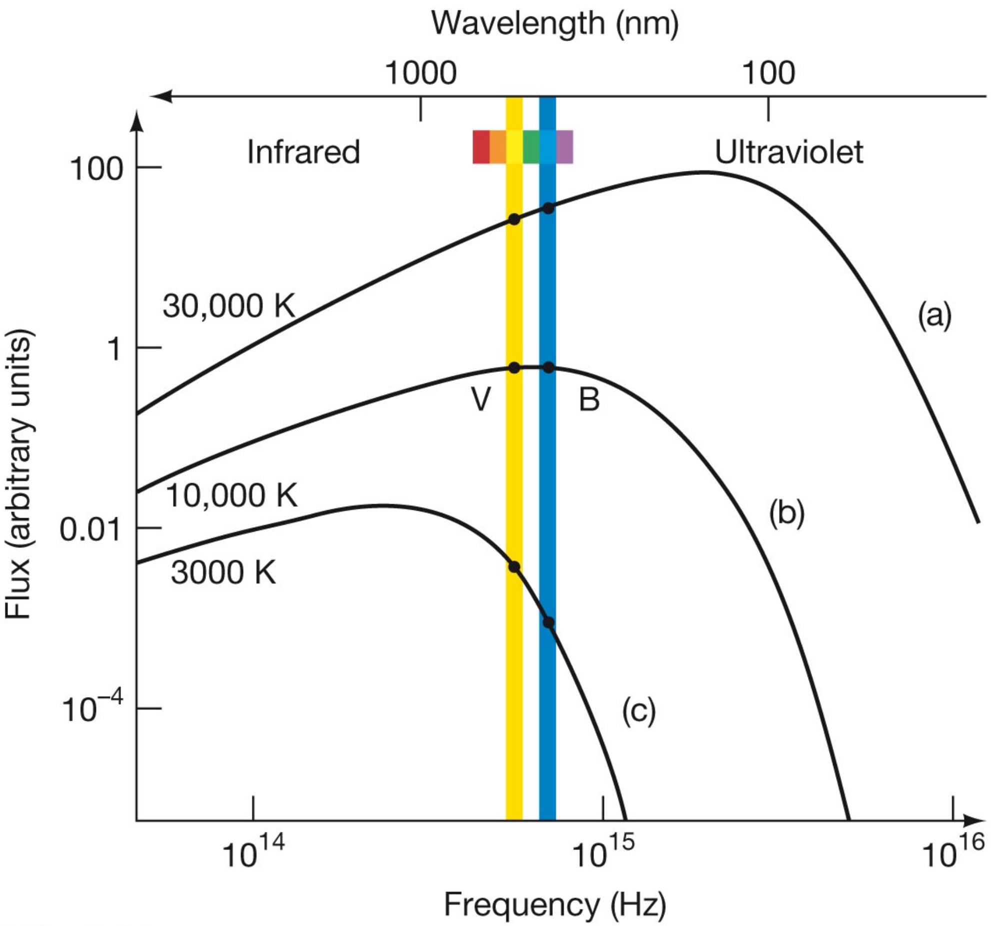
"hotter bodies have a much higher luminosity"

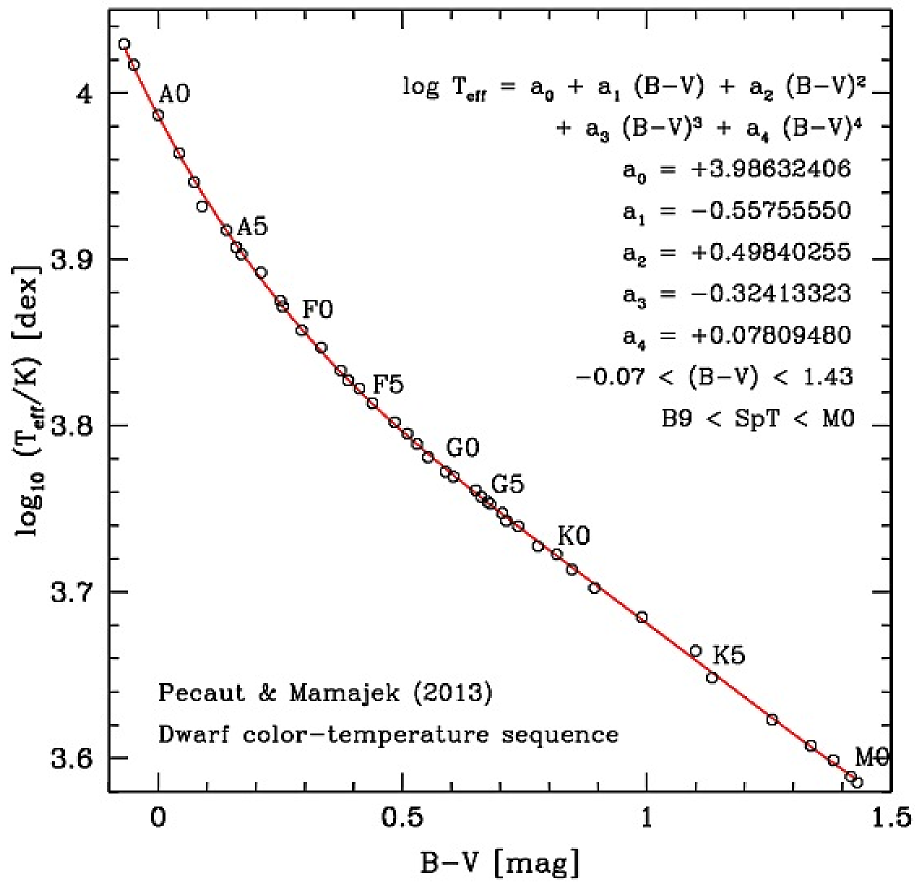
Wien's displacement law: Wavelength of maximum blackbody emission:

$$\lambda_{\max} = 2898/T\ \mu\mathrm{m}$$

"hotter bodies radiate at higher energies"

Color-temperature relation





Photometric filters

Photometric system

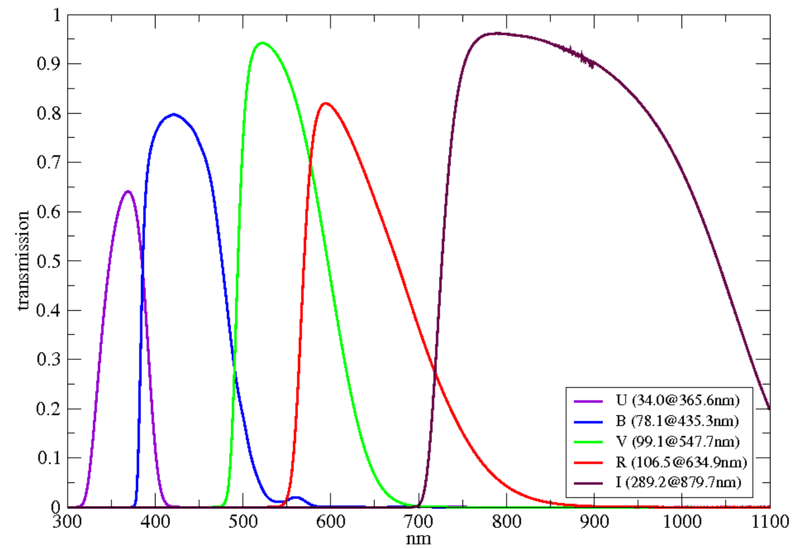
- set of well-defined passbands (or filters)
- standard stars for each photometric system
- observations of lightcurves usually in one or several filters

Bolometric correction

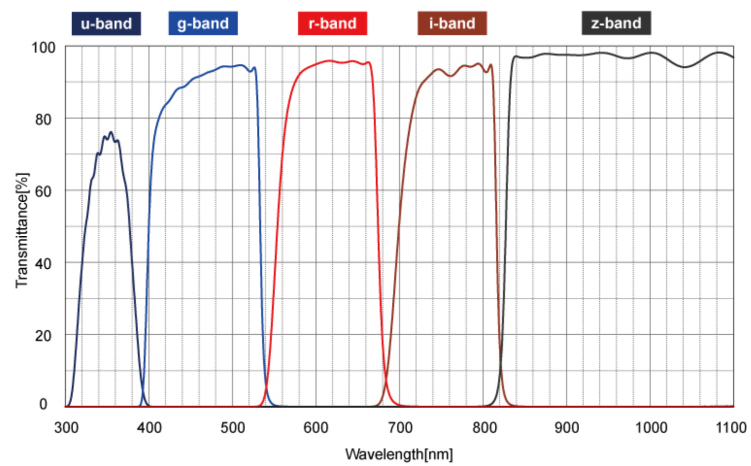
- converts observed magnitude in a certain filter to its bolometric magnitude (dependent on spectral type)

$$BC_V = M_{\mathrm{bol}} - M_V \tag{2.1}$$

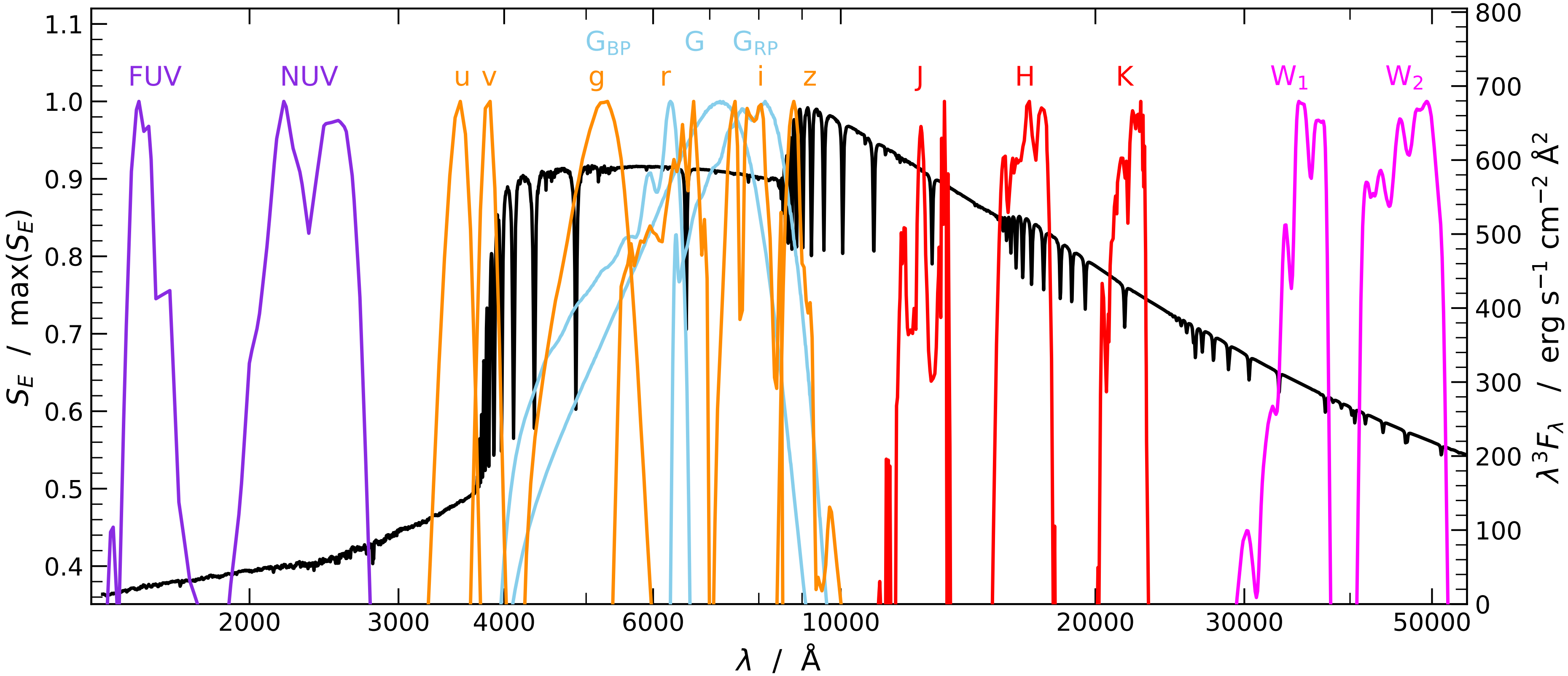
Johnson filters



SDSS filters

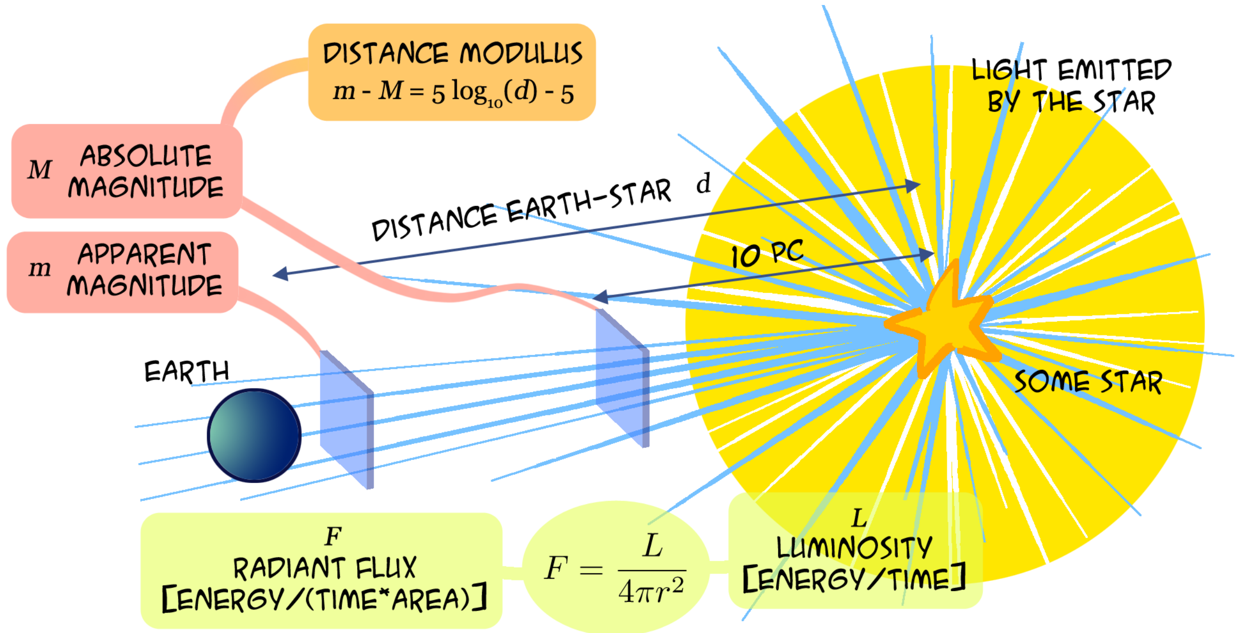


Photometric filters



A historic and current photometric reference: Vega!

Bolometric magnitudes



- apparent magnitude m_x in filter x

$$m_x - m_{x,\mathrm{ref}} = -2.5 \log(F_x / F_{x,\mathrm{ref}}) \tag{2.2}$$

- absolute magnitude M_x in filter x

$$m_x - M_x = 5 \log(d) - 5 \tag{2.3}$$

Extinction correction and BC → bolometric absolute magnitude

Interstellar reddening

Extinction A_V

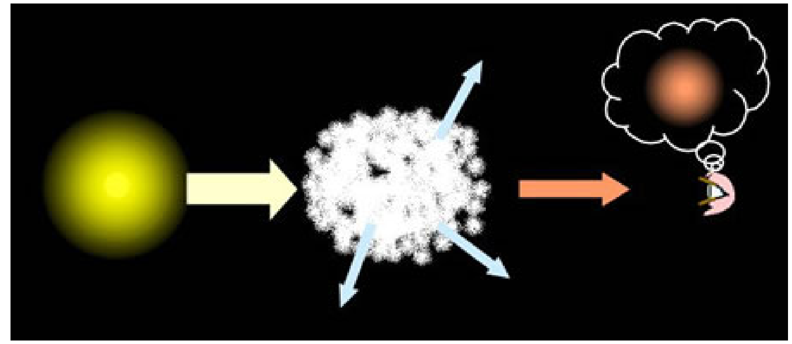
- absorption and scattering of electromagnetic radiation by dust and gas between an emitting astronomical object and the observer
- shorter wavelengths (blue) are more heavily reddened than longer (red) wavelengths
- colour index $B - V$, colour excess E_{B-V}

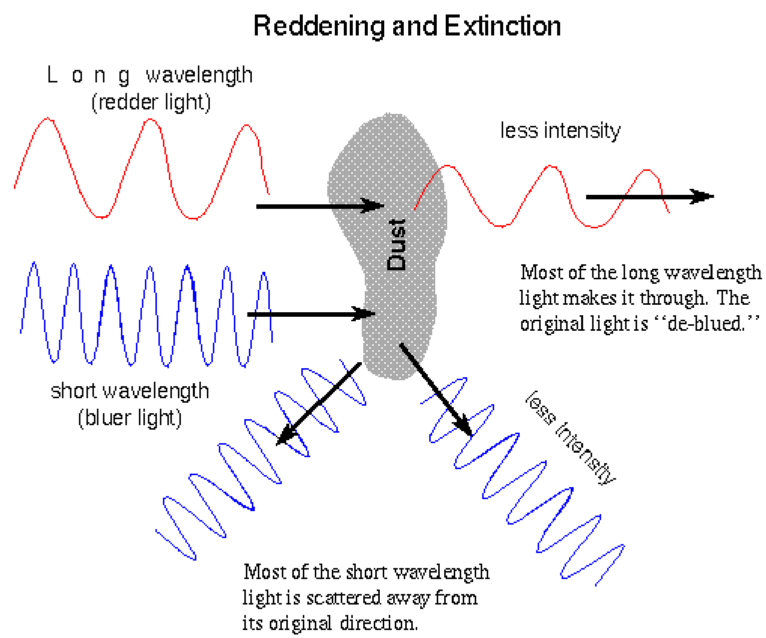
$$E_{B-V} = (B - V) - (B - V)_0 \qquad (2.4)$$

$$A_V = R_V E_{B-V}, \; R_V \approx 3.1 \text{ (Milky Way)} \qquad (2.5)$$

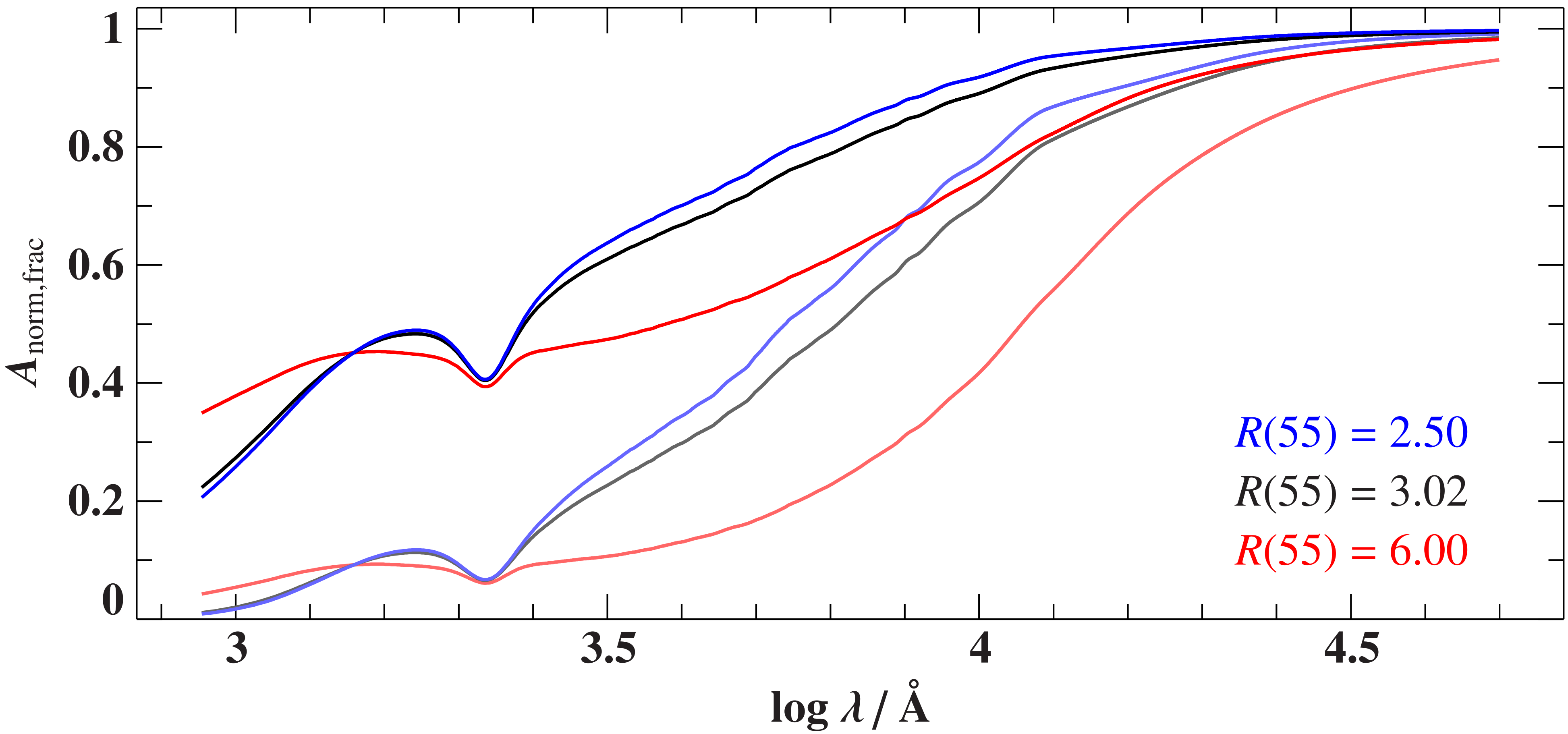
- true distance

$$d = 10^{0.2(m-M+5-A_V)} \qquad (2.6)$$



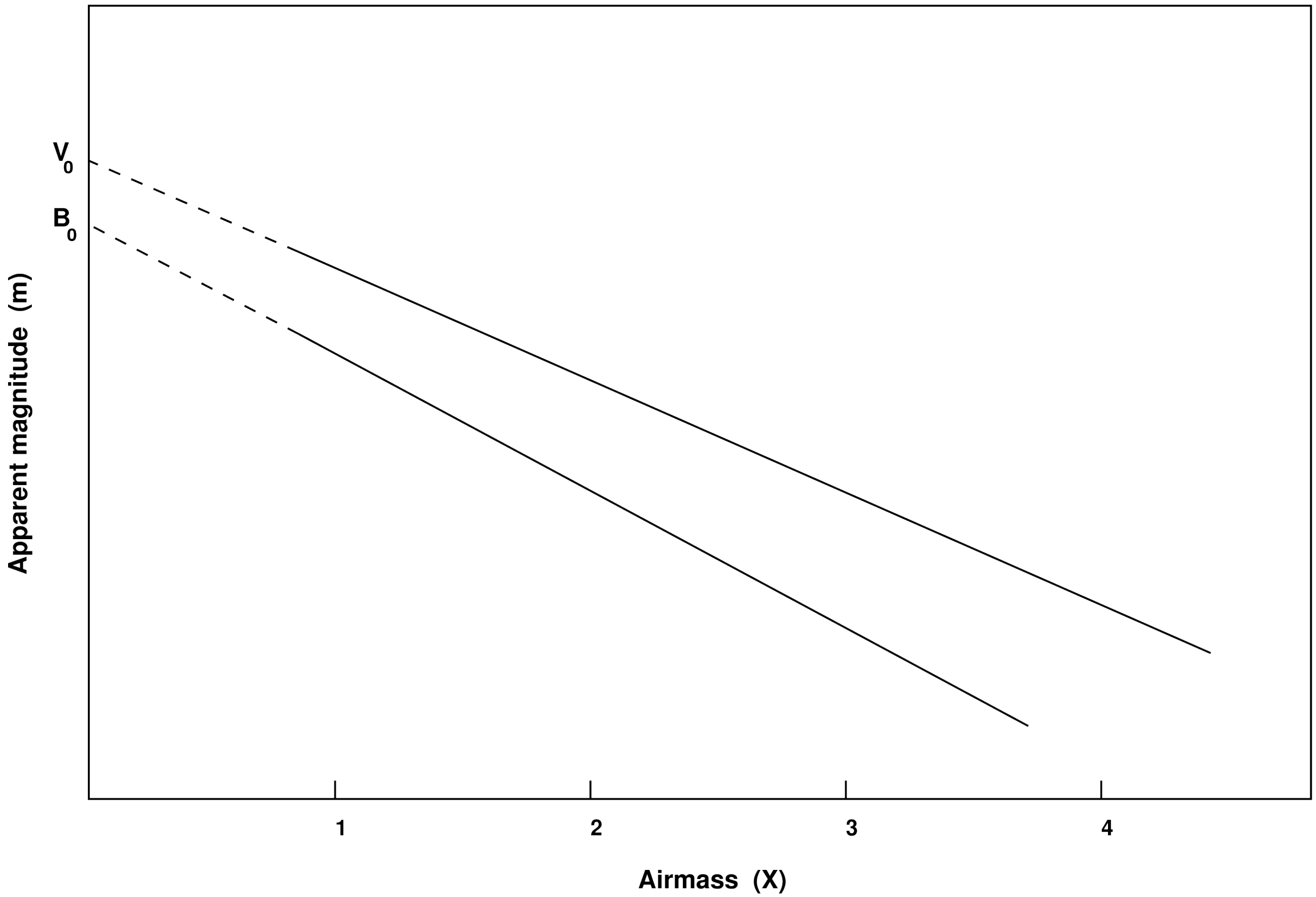


Interstellar reddening



The darker curves are for a colour excess $E(44-55) = 0.1$ mag while the lighter curves are for 0.3 mag.

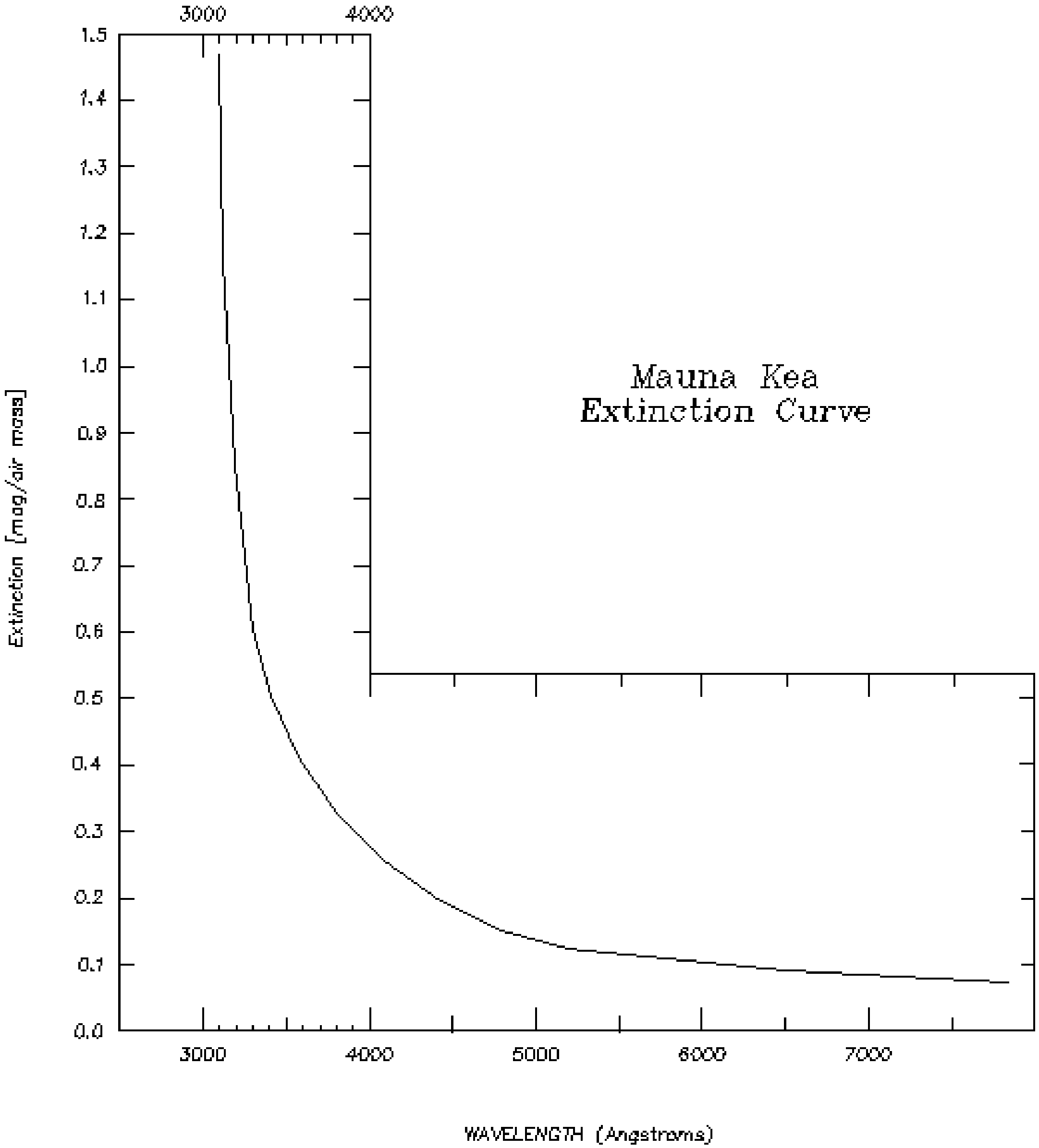
Atmospheric extinction



- $V = V_0 + \kappa(\lambda)X(z)$
  $\kappa(\lambda)$ is the extinction coefficient
  z is the zenith distance
  X is the air mass
  $X(z) \approx \cos^{-1} z$
- extinction greater for blue than for red

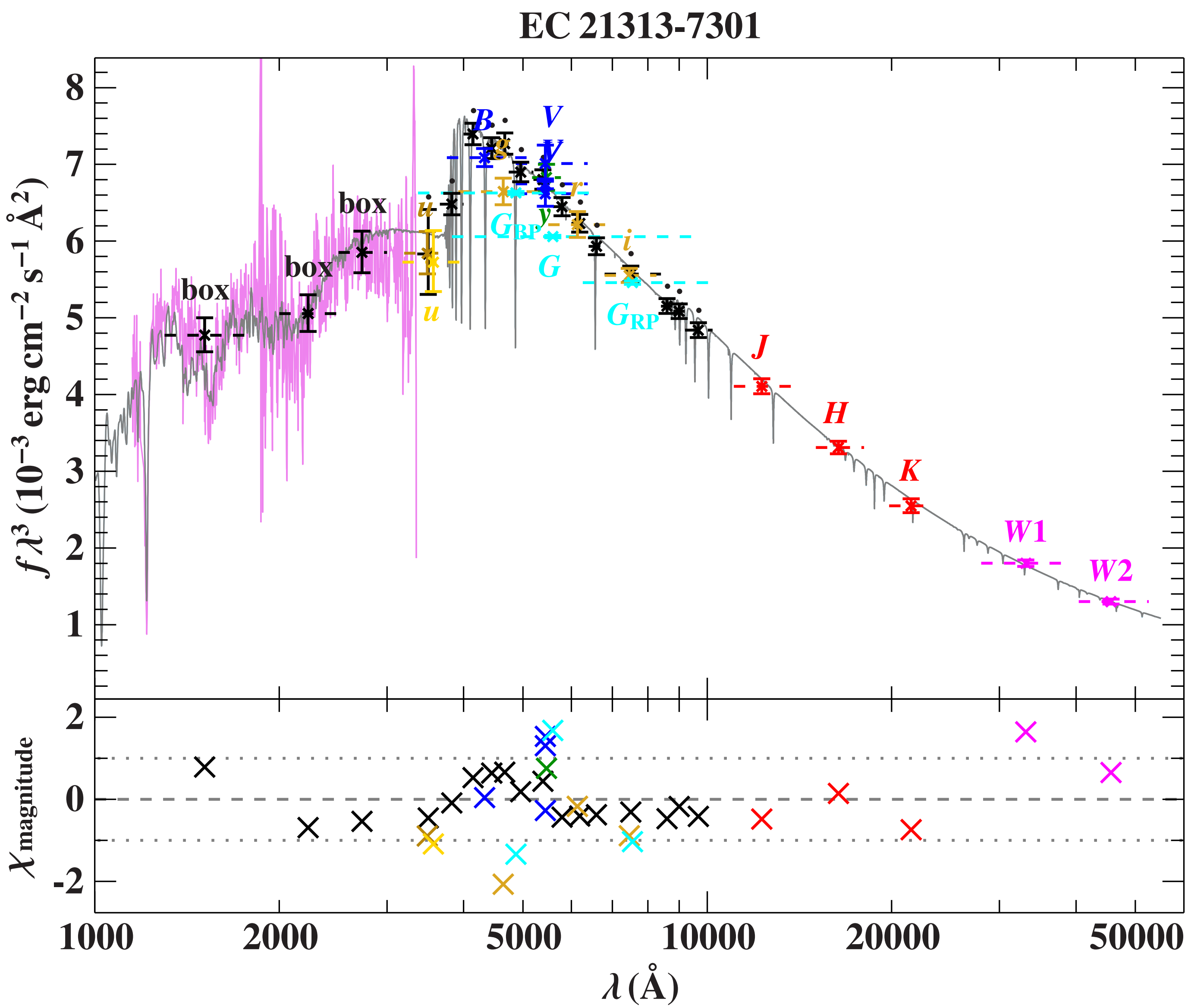
Standard stars to correct for atmospheric extinction and calibrate the sensitivity of the instrument

Atmospheric extinction

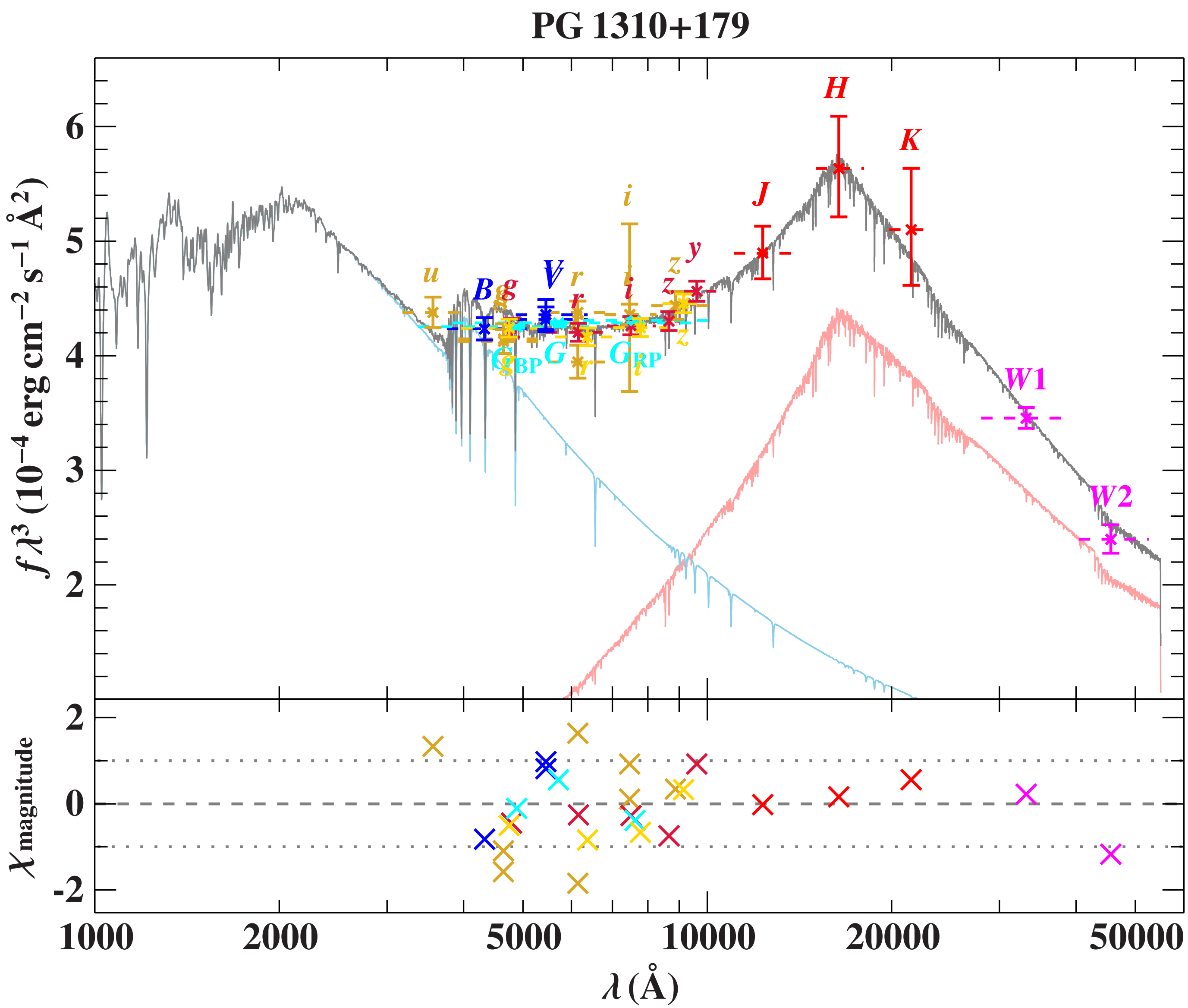


- $V = V_0 + \kappa(\lambda)X(z)$ $\kappa(\lambda)$ is the extinction coefficient
  z is the zenith distance
  X is the air mass
  $X(z) \approx \cos^{-1} z$
- extinction wavelength-dependent
- blue stars are getting weaker compared to red stars

Spectral energy distribution (SED) fitting



Spectral energy distribution (SED) fitting



Absolute vs. differential photometry

Absolute photometry – SEDs

Absolute photometry refers to photometric measurements reported in a standard photometric system by means of a calibration process. This procedure permits to obtain the absolute flux of a given source.

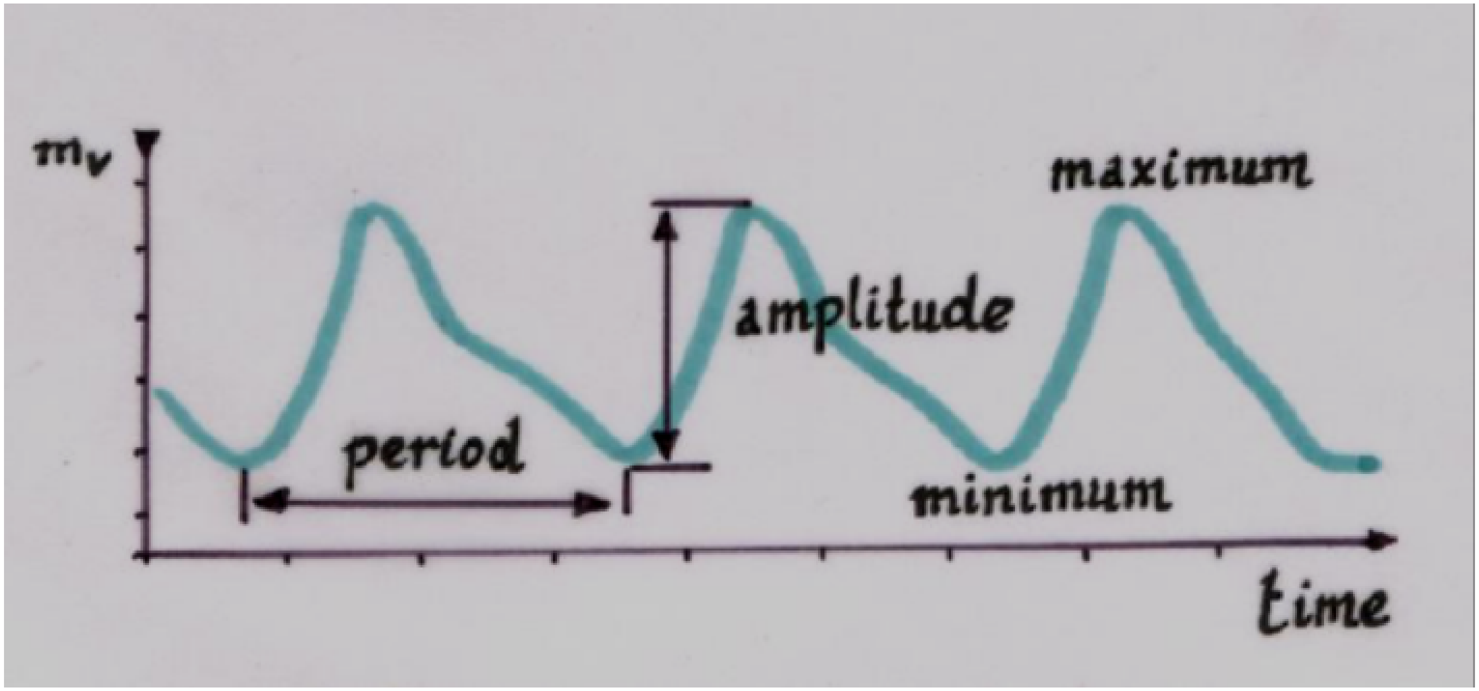
$\Rightarrow$ spectral type, gravity, reddening, age, distance

Differential photometry – lightcurves

Differential photometry refers to photometric measurements of a given source with respect to one or more comparison sources which absolute flux is not necessarily known.

$\Rightarrow$ relative flux variations, lightcurves

Lightcurves



Lightcurve = brightness versus time

- time-series observations
- period P: time between successive minima / maxima, for binaries equal orbital period
- Amplitude A: difference between magnitude at minimum and maximum

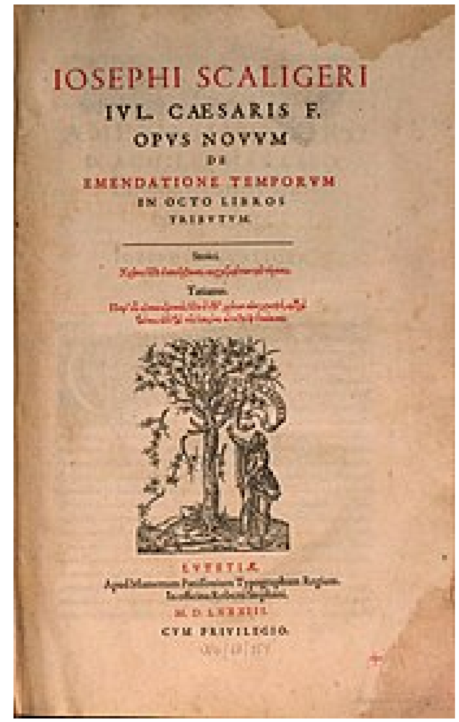
Julian Date

Julian Date JD

- time in days and fractions of a day since:

  1. January -4712 BC, 12:00 UT

  21. May 2019, 04:47:30.62 UT $\equiv$ 2458624.69966



Modified Julian Date MJD

- MJD = JD - 2400000.5

Heliocentric Julian Date HJD

- corrected for differences in the Earth's position with respect to the Sun (maximum correction ± 8.3 min)

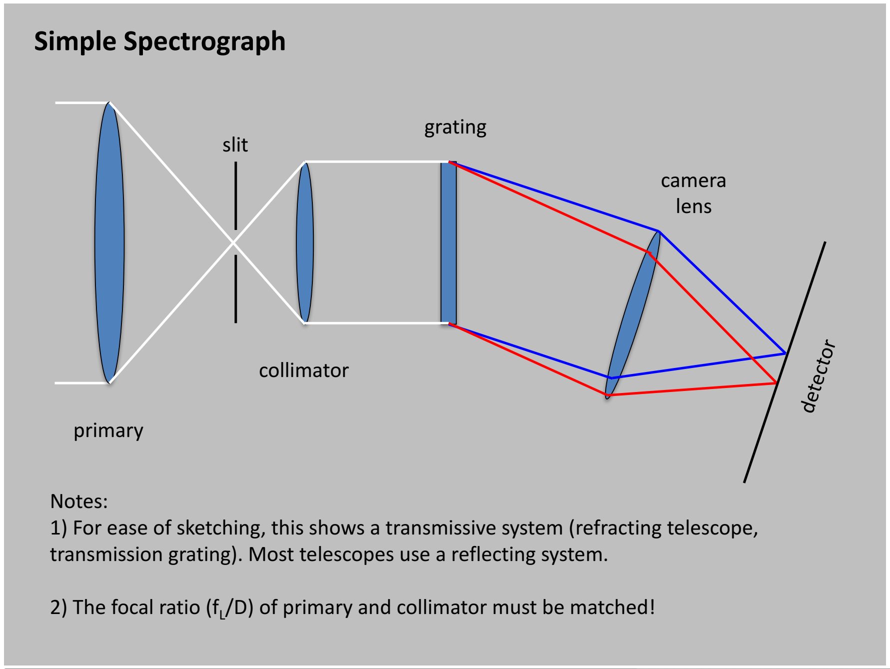
Barycentric Julian Date BJD

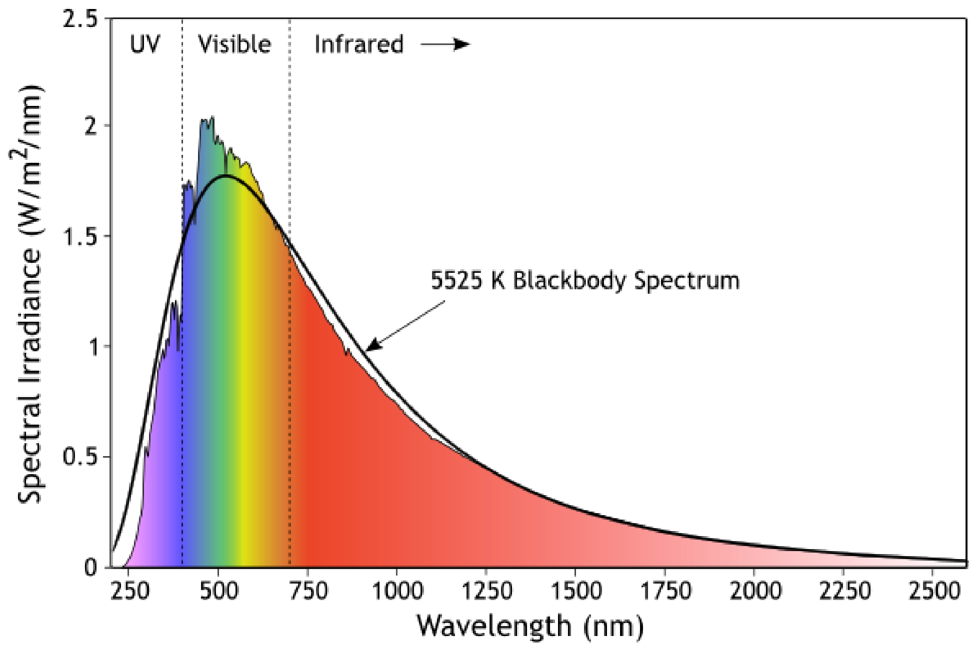
- corrected for differences in the Earth's position with respect to the barycentre of the Solar System
- difference between HJD and BJD is up to ± 4 s

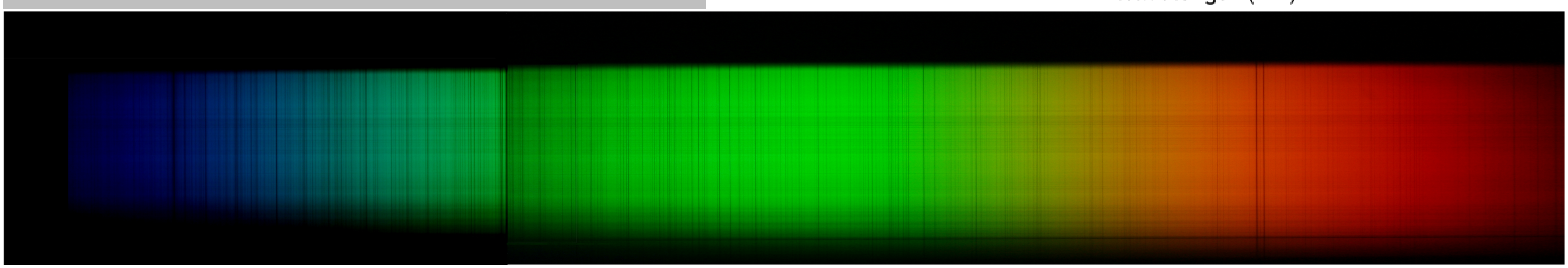
Spectroscopy

What is spectroscopy?

technique of splitting light (or more precisely electromagnetic radiation) into its constituent wavelengths (a spectrum)





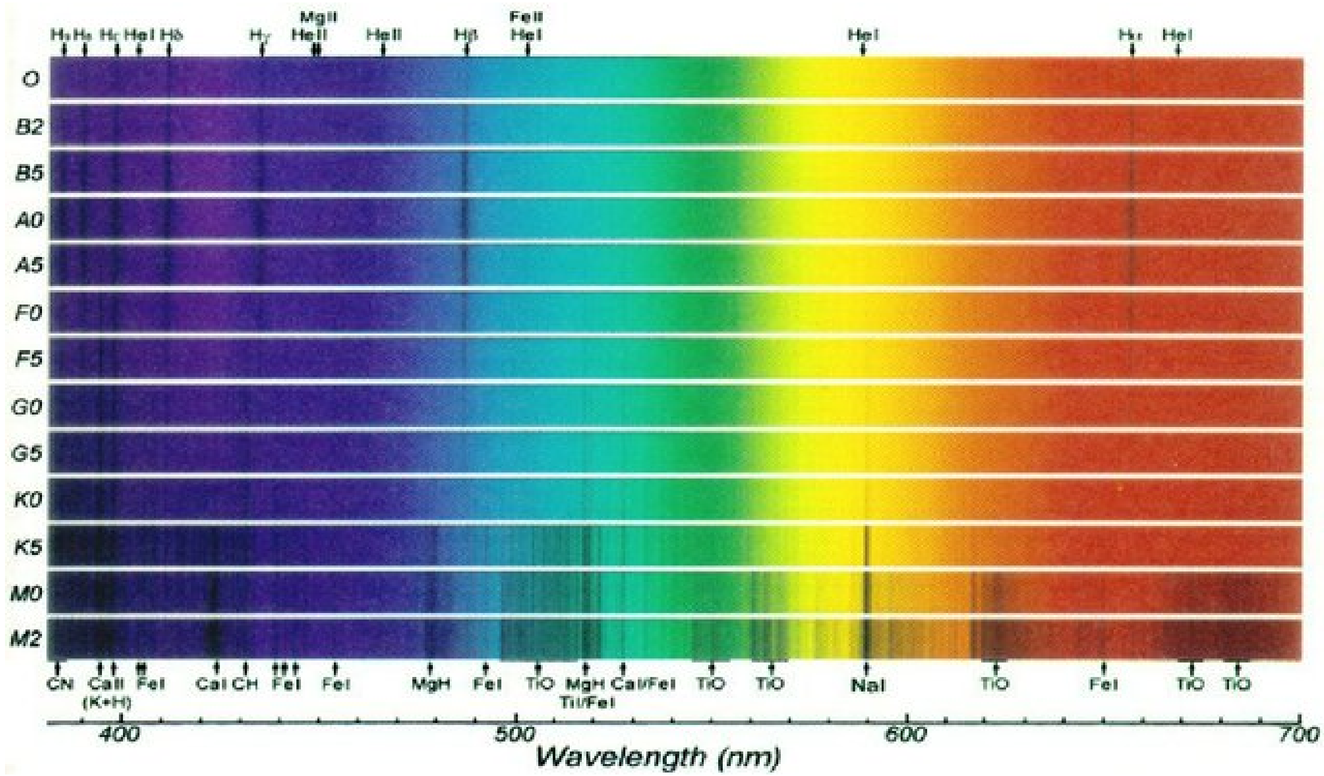


Joseph von Fraunhofer saw 1814 almost 600 lines in the spectrum of the sun

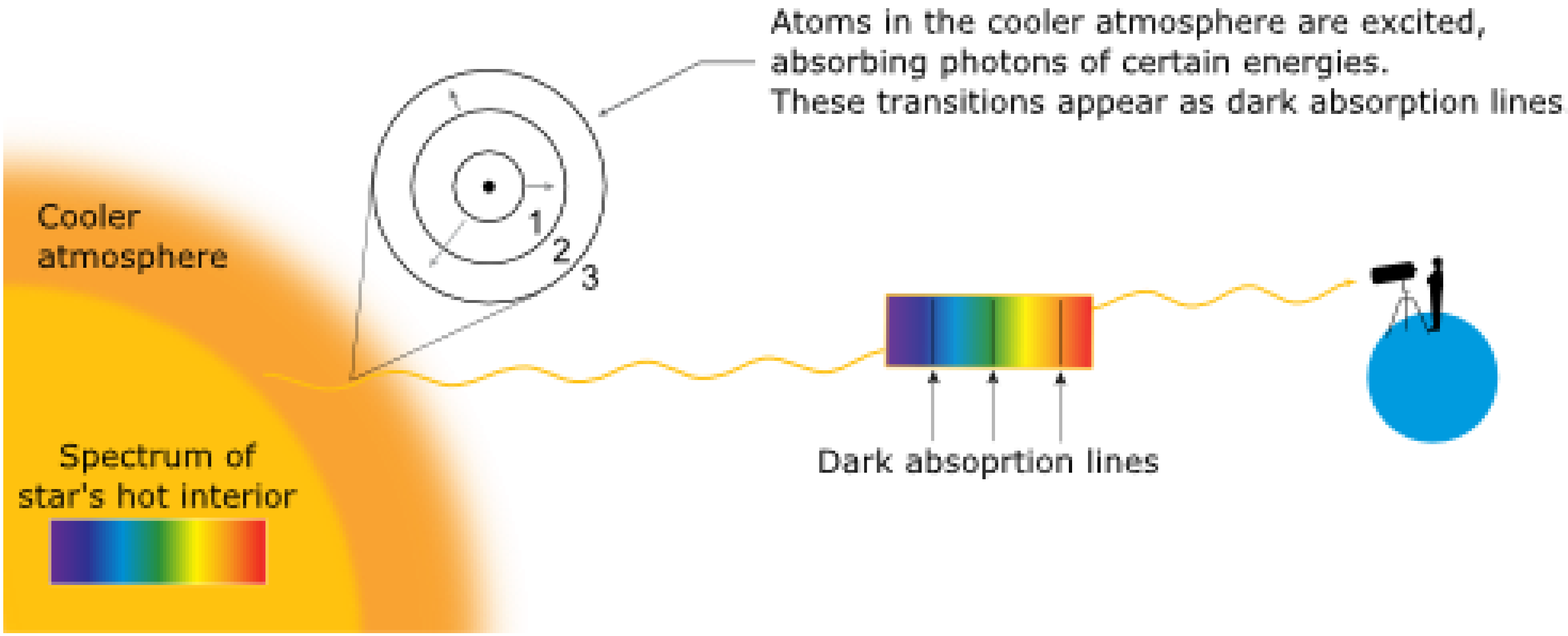
What can we learn from stellar spectra?

Spectra provide a lot of information about an astronomical object:

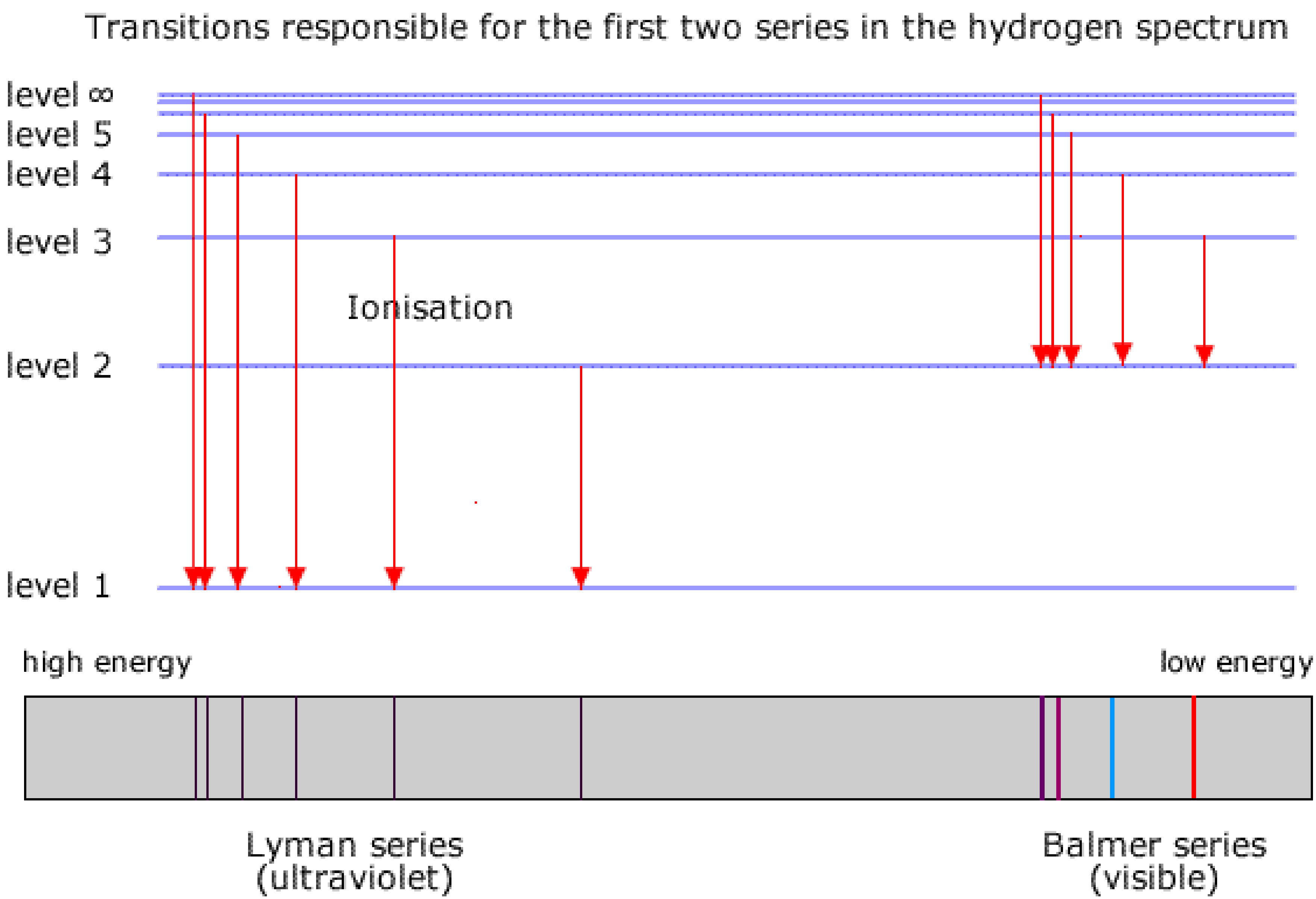
- temperature
- surface gravity
- chemical composition
- stellar winds
- magnetic fields
- projected rotation
- radial velocity:
  Doppler effect $\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$



Formation of stellar spectra



Hydrogen spectrum



Energy level population and ionization stage

Line strength: # of absorbers x line absorption cross-section σ_{ij}

$$\sigma_{ij} = \frac{\pi e^2}{mc} f_{ij} \Phi_\nu \quad (3.1)$$

f_{ij} is the oscillator strength, which is related to the transition probability, Φ_ν the absorption profile

Boltzmann-equation: population of the energy levels within an atom depends in a detailed way upon the mechanisms for populating and de-populating them: radiative, collisional & spontaneous

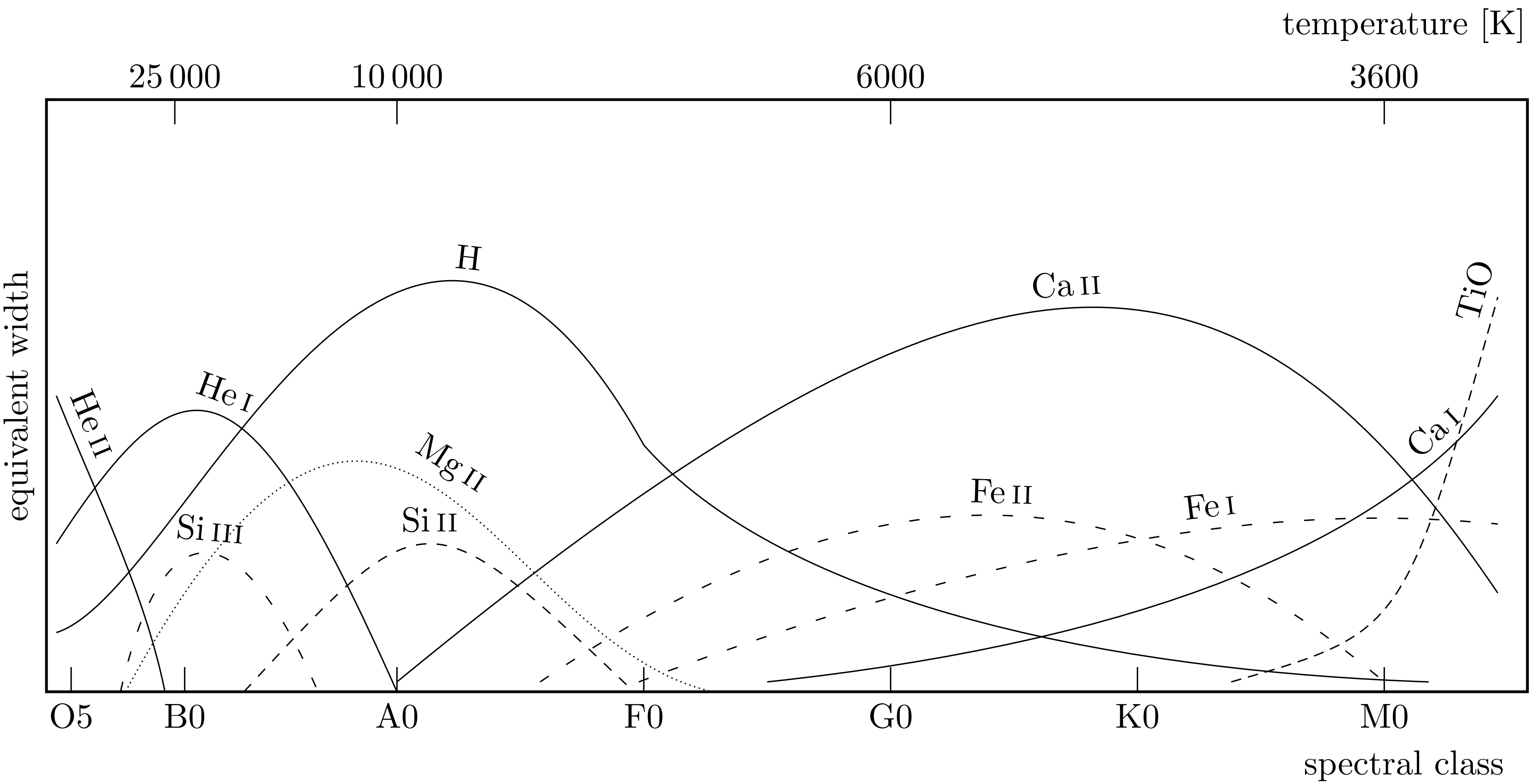
$$\frac{N_j}{N_i} = \frac{g_j}{g_i} e^{-\frac{E_j - E_i}{kT}} \quad (3.2)$$

g_i/g_j are statistical weights that take into account degeneracy of energy states

Saha equation: number of atoms in a given ionization stage

$$\frac{N(X_{r+1})}{N(X_r)} = \frac{2kTg_{r+1}}{P_e g_r} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-\chi_i/kT} \quad (3.3)$$

Line strength vs temperature



Fundamental Astronomy: Karttunen et al.

Line broadening

Natural line broadening: from the uncertainty principle due to finite life time

$$\Phi_\nu^{\mathrm{rad}} = \frac{\gamma_{\mathrm{rad}}/4\pi^2}{(\nu-\nu_{ij})^2 + (\gamma_{\mathrm{rad}}/4\pi)^2},\ \gamma_{\mathrm{rad}} = \frac{1}{\tau_{\mathrm{low}}} + \frac{1}{\tau_{\mathrm{up}}} \qquad \text{(Lorentzian)} \tag{3.4}$$

Pressure broadening: due to collisions with other atoms, or charged particles in the plasma; linear Stark effect for Hydrogen lines, quadratic Stark effect for non-hydrogenic atoms and ions, Van der Waals broadening: non-hydrogenic atoms with neutral hydrogen

Thermal broadening: Doppler shift due to thermal movement of the atoms

$$\Phi_\nu^{\mathrm{Doppler}} = \frac{1}{\sqrt{\pi}\Delta\nu_{\mathrm{D}}} \exp(-(\nu-\nu_0)/\Delta\nu_D)^2,\ \Delta\nu_D = \frac{\nu_0}{c}\sqrt{\frac{2kT}{m}} \qquad \text{(Gaussian)} \tag{3.5}$$

Line broadening

Rotational broadening: Doppler shift due to stellar rotation, we can observe the projection of the rotational velocity in line-of-sight

Instrumental profile: additional broadening depending from the spectral resolving power $R = \lambda/\Delta\lambda$

$$\mathrm{FWHM} = c/2\sqrt{\ln 2}R \qquad \text{(Gaussian)} \tag{3.6}$$

Total line Profile

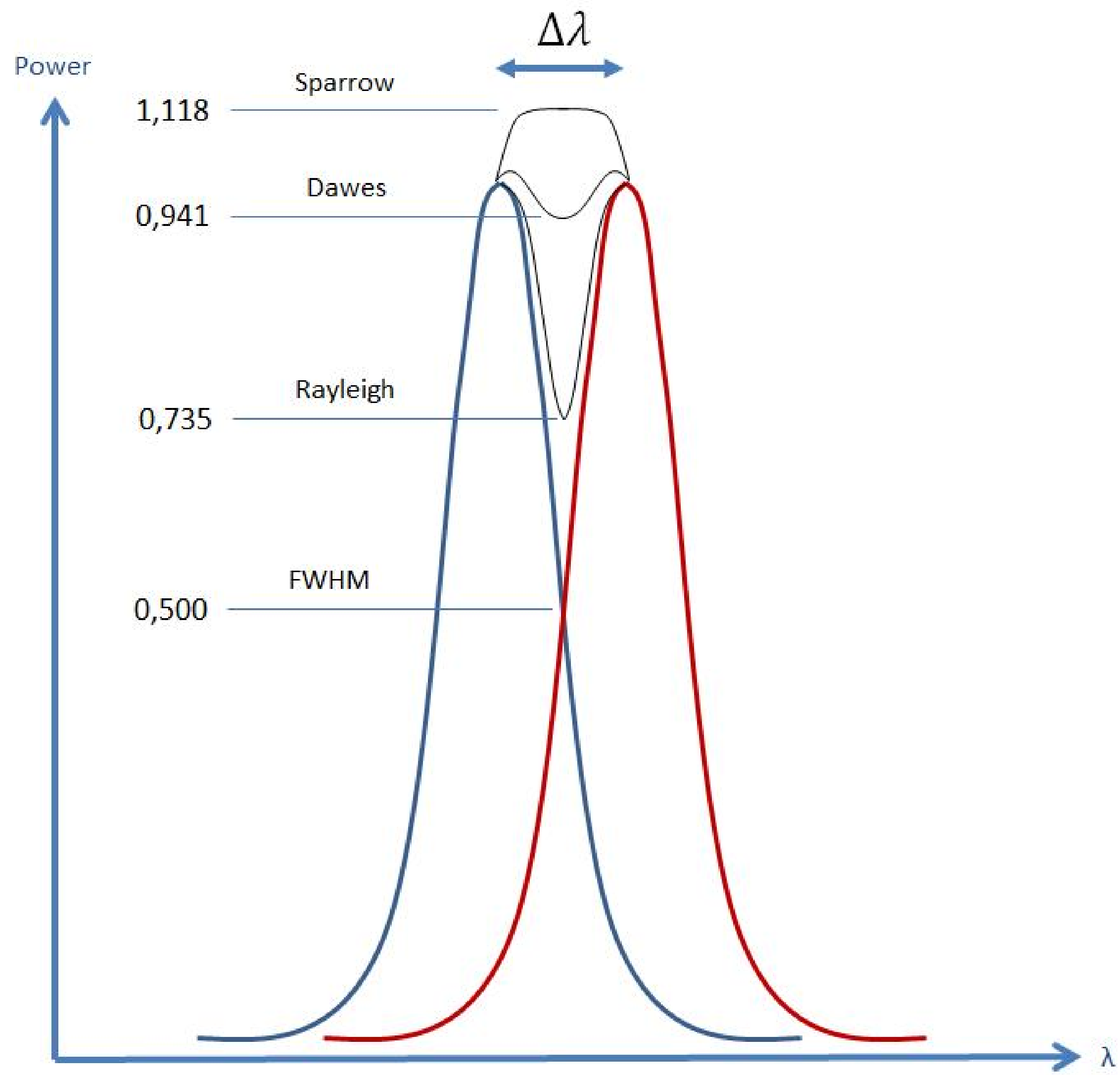
$$\Phi_\nu = \Phi_\nu^{\mathrm{Gaussian}} \star \Phi_\nu^{\mathrm{Lorentz}} \equiv \Phi_\nu^{\mathrm{Voigt}} \tag{3.7}$$

Other effects: Zeeman Splitting, stellar winds

Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

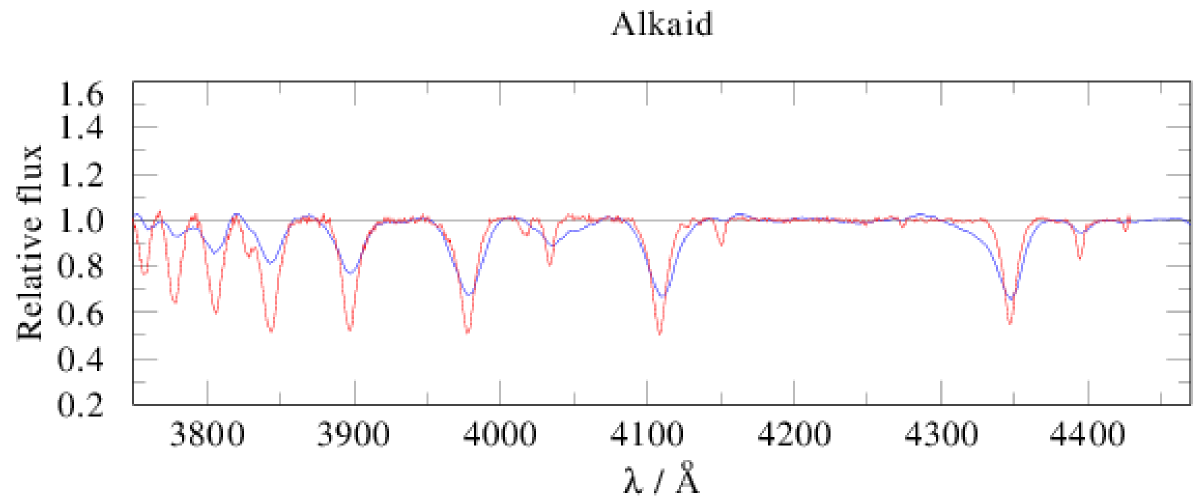


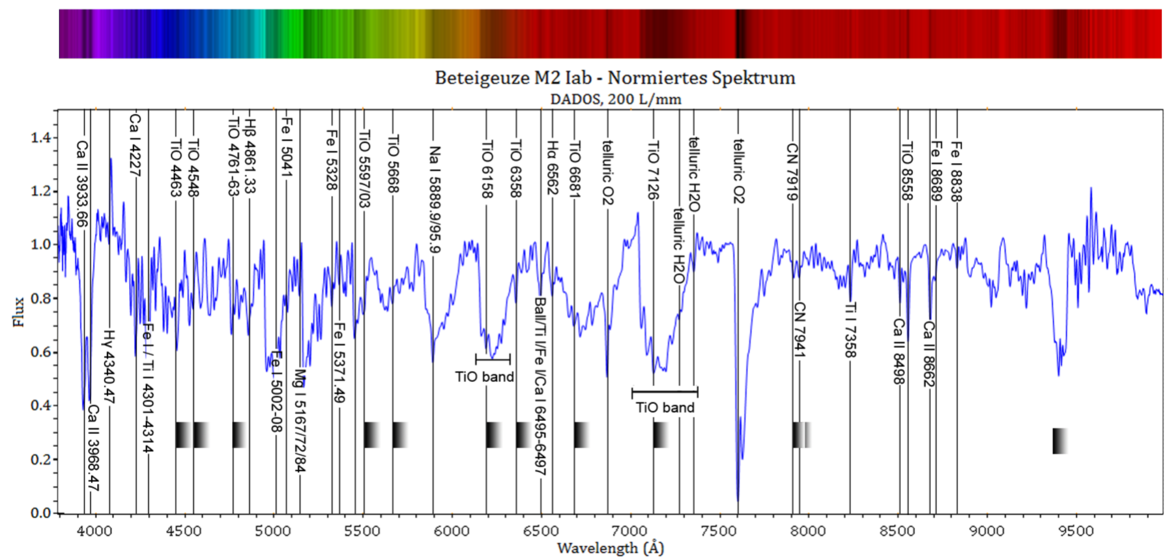
Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range



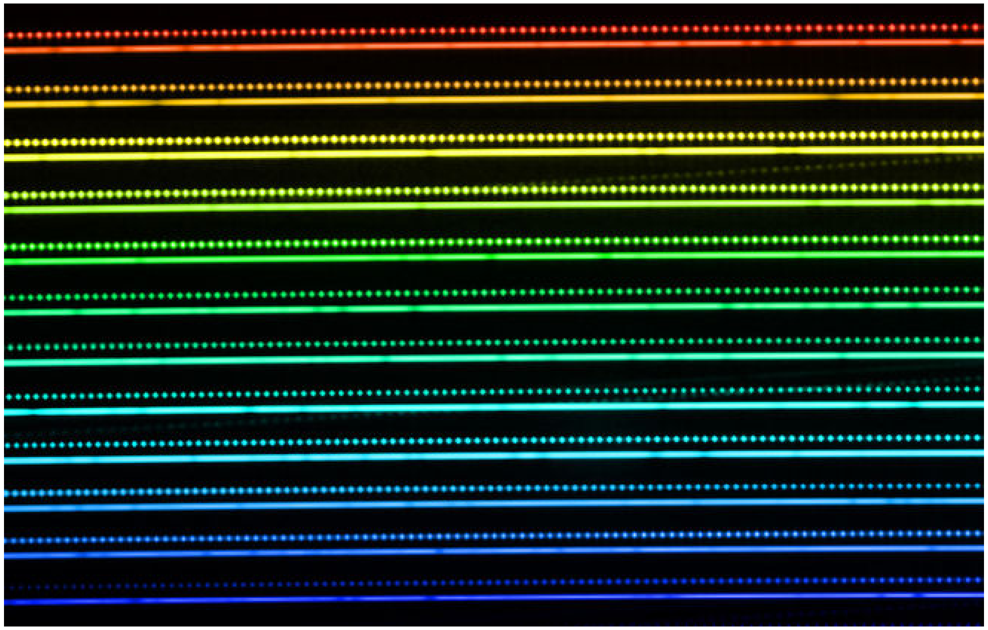


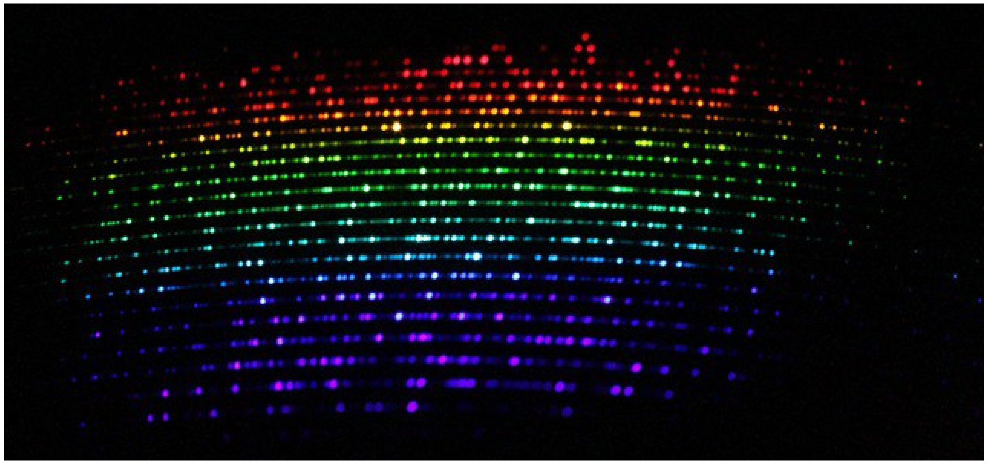
Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range
- wavelength calibration and stability





Properties of Spectrographs

- Spectral resolution

$$R = \frac{\lambda}{\Delta\lambda}$$

- wavelength range
- wavelength calibration and stability
- throughput for best efficiency
- efficiency in the blue/red
- limiting magnitude