Stellar Atmospheres: Lecture 1, 2020.04.01

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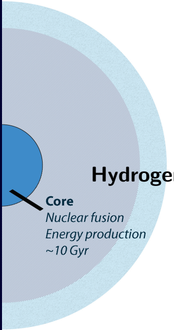
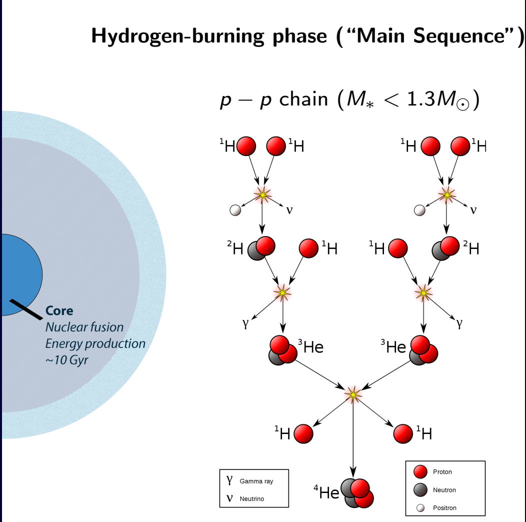
IRyA/UNAM

Stellar structure



Hydrogen-burning phase ("Main Sequence"):

Stellar structure



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Stellar structure

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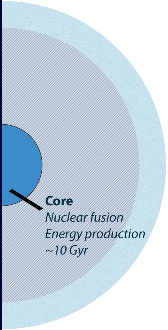
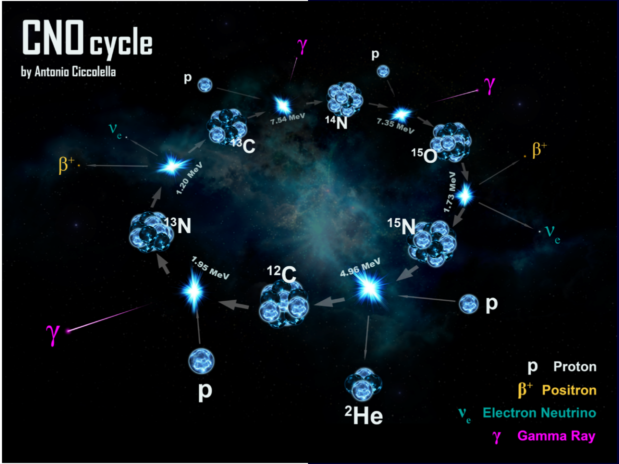
CNO cycle ($M_* > 1.3 M_\odot$)





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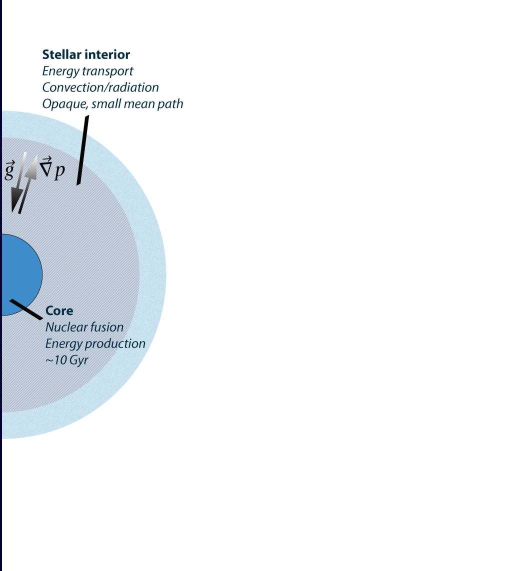

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Fusion energy transported outward by either radiation or convection, depending on which one dominates. In evolved giants, convection also transports products of fusion ("dredge-up" processes).

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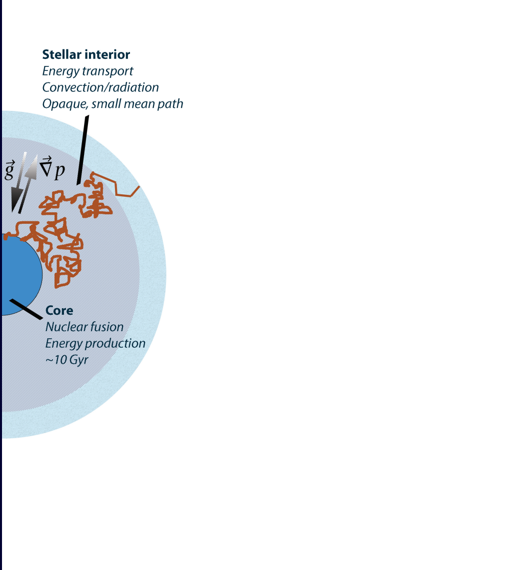

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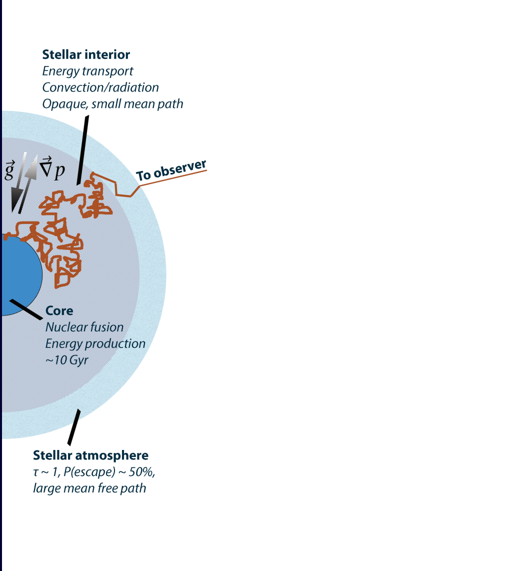
but opaque interior means photon mean free path (typical distance between simultaneous interactions) is small. **Photons can spend $\sim$ Myr in the interior before they reach the surface, if at all.**

What is a stellar atmosphere?



Stellar atmosphere:
"[T]ransition from stellar interior to the interstellar medium" – Gray
"[L]ayers of the star from which we get radiation" – E. Böhm-Vitense
"[L]ayers... from which photons escape freely into space, and can be measured by an outside observer" – I. Hubeny & D. Mihalas

Photosphere: defined as the radius at which **optical depth** is approximately unity (transition from opaque to transparent), or where photon escape probability is 0.5.

Mean free path increases drastically. **Last interaction with material** before photons escape.

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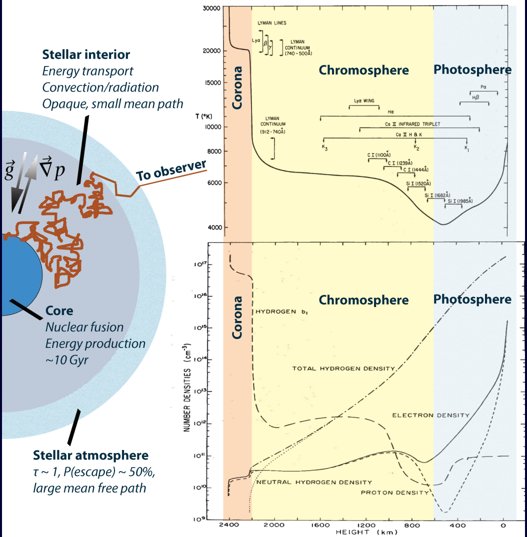

Verazzano et al. (1973)
Model for solar atmosphere

The temperature drops drastically in the photosphere (then rises again).

Knowing the temperature, pressure, density, etc. in the atmosphere, we can identify the regions from which we expect various species of material to emit/absorb.

We can also study the variation of chemical composition over the atmosphere, as well as the distribution of ions of a given species.

Why study stellar atmospheres?

$R_\odot = 7 \times 10^8$ m. Solar photosphere ~ 100 km thick ($\approx 0.02\%$). Density also very low.

> *"Why... would anyone want to study stellar atmospheres? They contain only about 10^{-10} of the mass of a star. Surely such a negligible fraction of its mass cannot affect its overall structure and evolution!"*
>
> *– E. Salpeter*

Why study stellar atmospheres?

- Radiation major source of information in astronomy!! The atmosphere is the only region of a star from which we observe photons. Indirect information about interior. Stars are typically point objects!

For more discussion, see Hubeny & Mihalas pages 16-19.

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Before analysing stellar atmospheres, let's review some basic concepts...

Review: flux density

The power output per unit area per unit frequency (or wavelength) interval is called the flux density. Confusingly, it is often abbreviated as "flux".

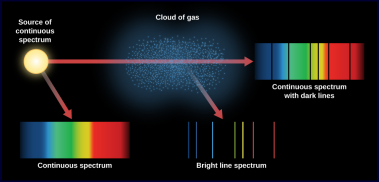
Depending on whether we are computing it per unit frequency or wavelength, it is represented by F_ν or F_λ respectively.
Relation between them (due to relation between ν and λ): $\nu F_\nu = \lambda F_\lambda$.

The SI unit for F_ν is W m^{-2} Hz^{-1}. A derived unit convenient to describe the observed stellar flux densities is the Jansky (Jy): 1 Jy $= 10^{-26}$ W m^{-2} Hz^{-1}.

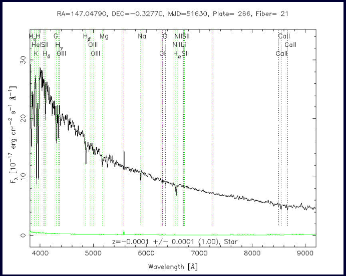
The **integrated flux** is the total amount of energy per unit area per unit time obtained over the entire range of frequencies (or wavelengths) from a given source: $F = \int\limits_0^\infty F_\nu d\nu = \int\limits_0^\infty F_\lambda d\lambda$

Review: spectra

Energy content (e.g., brightness, flux density) as a function of either frequency or wavelength.



Credit: Fraknoi, Morrison, Wolff/OpenStax CNX, CC BY 4.0



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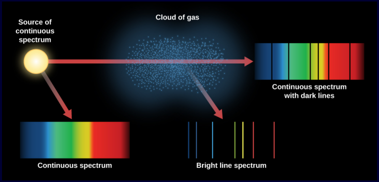

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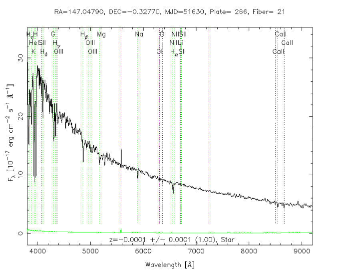

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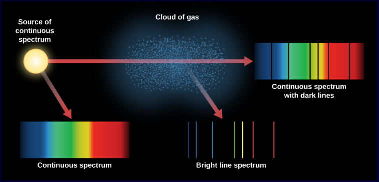

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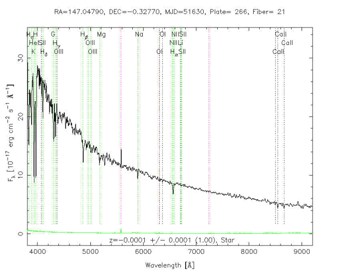

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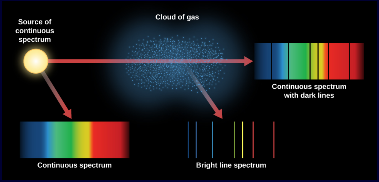
$R(\lambda) \sim 10^4 - 10^5$ for high-resolution optical spectra (e.g., CRIRES on the VLT).
Decreases in general with increasing λ (depends on instrumentation).



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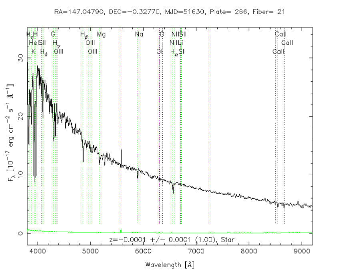

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Review: the blackbody spectrum

The spectrum for a blackbody at temperature T is specified by its intensity (power emitted per unit area per unit frequency per unit solid angle):

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left[\frac{h\nu}{kT}\right]-1} = \frac{2hc}{\lambda^3}\frac{1}{\exp\left[\frac{hc}{\lambda kT}\right]-1}, \text{ and } B_\lambda = \nu B_\nu/\lambda = \frac{2hc}{\lambda^5}\frac{1}{\exp\left[\frac{hc}{\lambda kT}\right]-1}$$

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Wien's Displacement Law: $\lambda_{\rm peak} = b/T$
$\lambda_{\rm peak}$ depends only on T (hotter = bluer).
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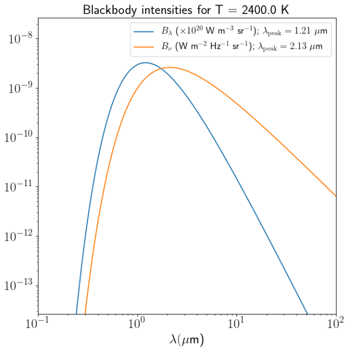

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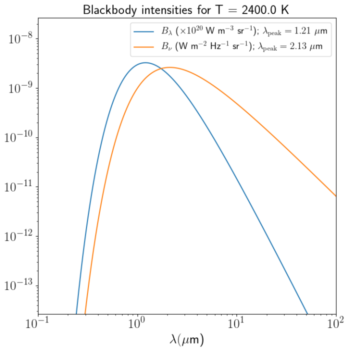

Stefan-Boltzmann Law

Integrated intensity (**radiance**) $= \int_0^\infty d\nu B_\nu(\nu) = \frac{\sigma}{\pi}T^4$,

($\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant).

Integrated power for radius R : $4\pi R^2 \sigma T^4$ (depends only on R and T).

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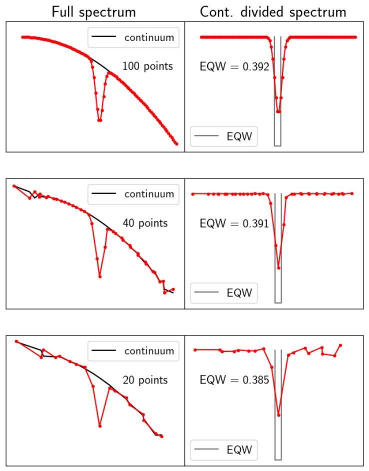

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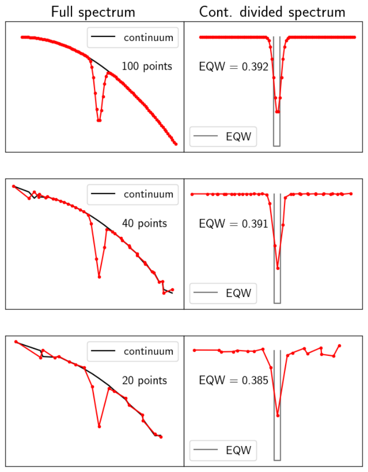
$$EQW = \int d\lambda \left(\frac{F_{\rm cont} - F_\lambda}{F_{\rm cont}} \right) = \int d\lambda \left(1 - \frac{F_\lambda}{F_{\rm cont}} \right)$$

This is the equivalent width – the width that the line would have if it removed all the flux from the continuum. (What about emission?)



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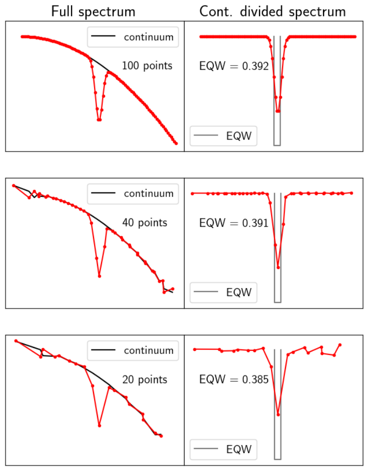

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When you have terrible resolution, use the equivalent width.

Note: determining the continuum is not always easy. Wrong guess for continuum $\Rightarrow$ wrong estimate of line $\Rightarrow$ wrong guess for physical parameters!

Review: photometry

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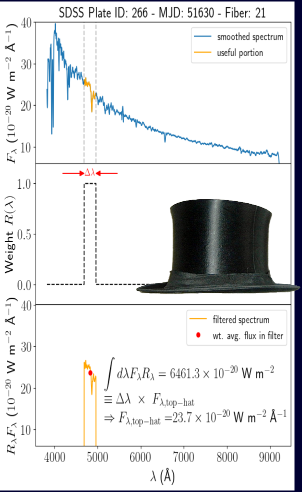

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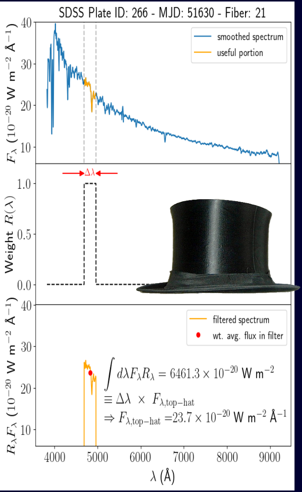

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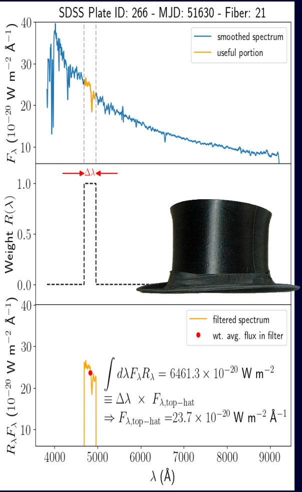

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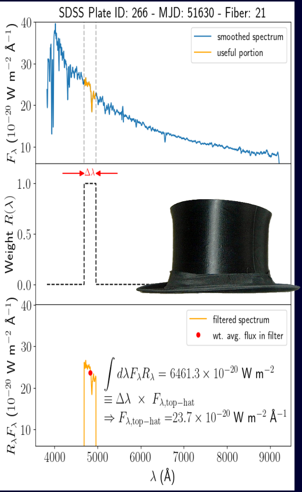
We have just performed photometry! – we collected light over a range of wavelengths and computed a weighted-average flux density for that range.



Review: photometry (contd.)

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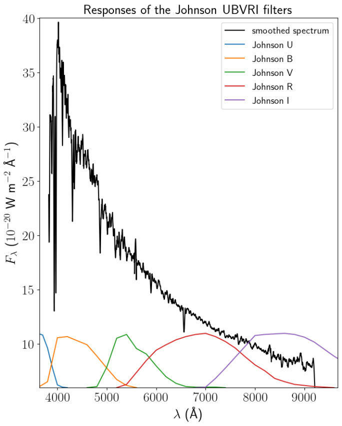

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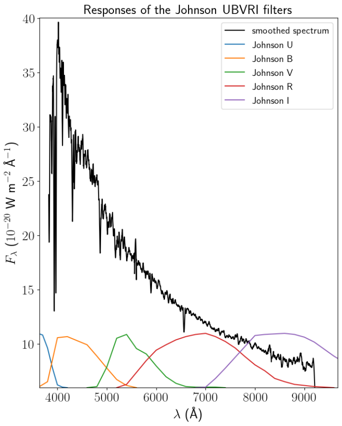

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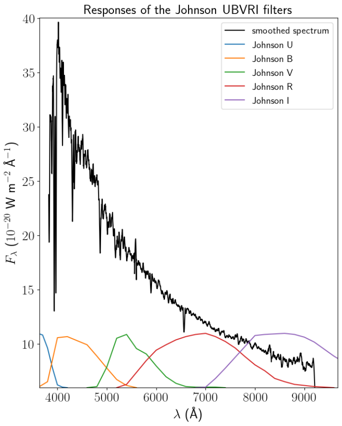
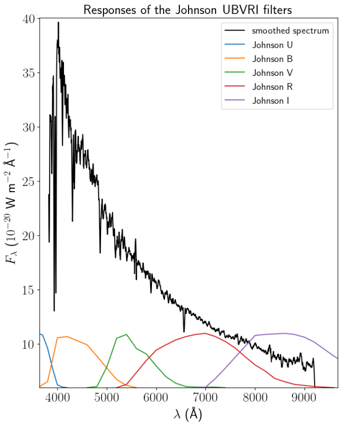
The response per photon R_N can be easily converted to response per unit energy R_E: $R_E = R_N/E$, where $E = hc/\lambda = h\nu$.



Review: photometry (contd.)

The general formula for the broadband flux in a filter A is then given by

$$F_\lambda^{(A)} = \frac{\int d\lambda\ R_E^{(A)}\ F_\lambda}{\int d\lambda\ R_E^{(A)}},$$ with $R_E^{(A)}$ a function of λ.



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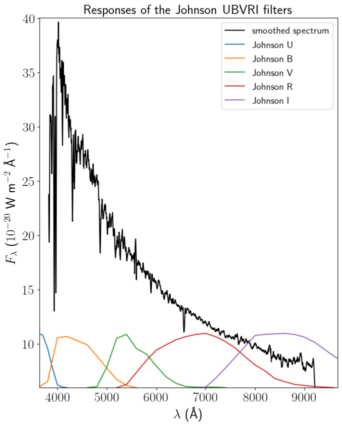

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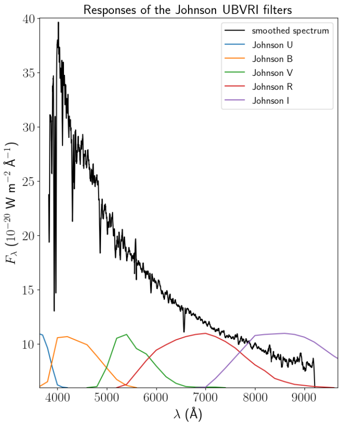

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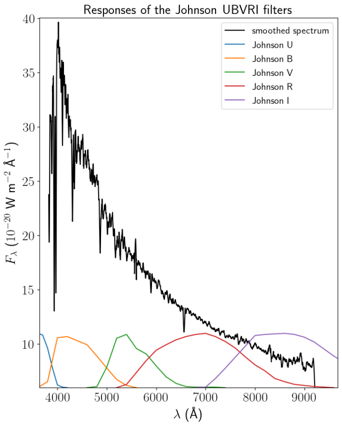
Usually, we don't know the source spectrum and only have access to photometry! The filtering process reduces information. However, photometry in a large number of filters spectral energy distribution (SED), a *very* low resolution spectrum.



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In the Vega magnitude system, originally $F_{\rm ref}$ was set to the flux from Vega (α Lyr) in that filter. The modern definition uses the average flux from a large number of nearby Vega-like stars. Two other popular magnitude systems are the AB and STMAG systems.

For more information, refer to Section 3 in this document by Prof. Jane Arthur and to this document.

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$m^{(A)} = M^{(A)} + \mu$, where μ is the distance modulus.

$M^{(A)}$ depends only on the source properties, and μ depends only on its distance.