OBSERVATIONAL ASTRONOMY

AUTUMN 2023

Lecture 9

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Photometry

The technique that measures the relative amounts of light in different wavelength ranges.

Stellar magnitudes

- **Magnitudes:**
  - Apparent magnitudes $m_1 - m_2 = -2.5 \log \frac{E_1}{E_2}$
  - Absolute magnitudes

$$M - m = -2.5 \log \left(\frac{D}{10}\right)^2$$

D is the object's distance in parsecs

$$M = m + 5 - 5 \log D$$
$$M = m + 5 - 5 \log D \ - \mathrm{A} \cdot \mathrm{D}$$

A is the interstellar absorption in magnitudes per parsec. Within the galactic plane A is ~0.002 mag pc^{-1}.

- Sometimes M may be estimated by some independent method. Then:

$$D = 10^{[(m-M+5)/5]} \text{ pc}$$

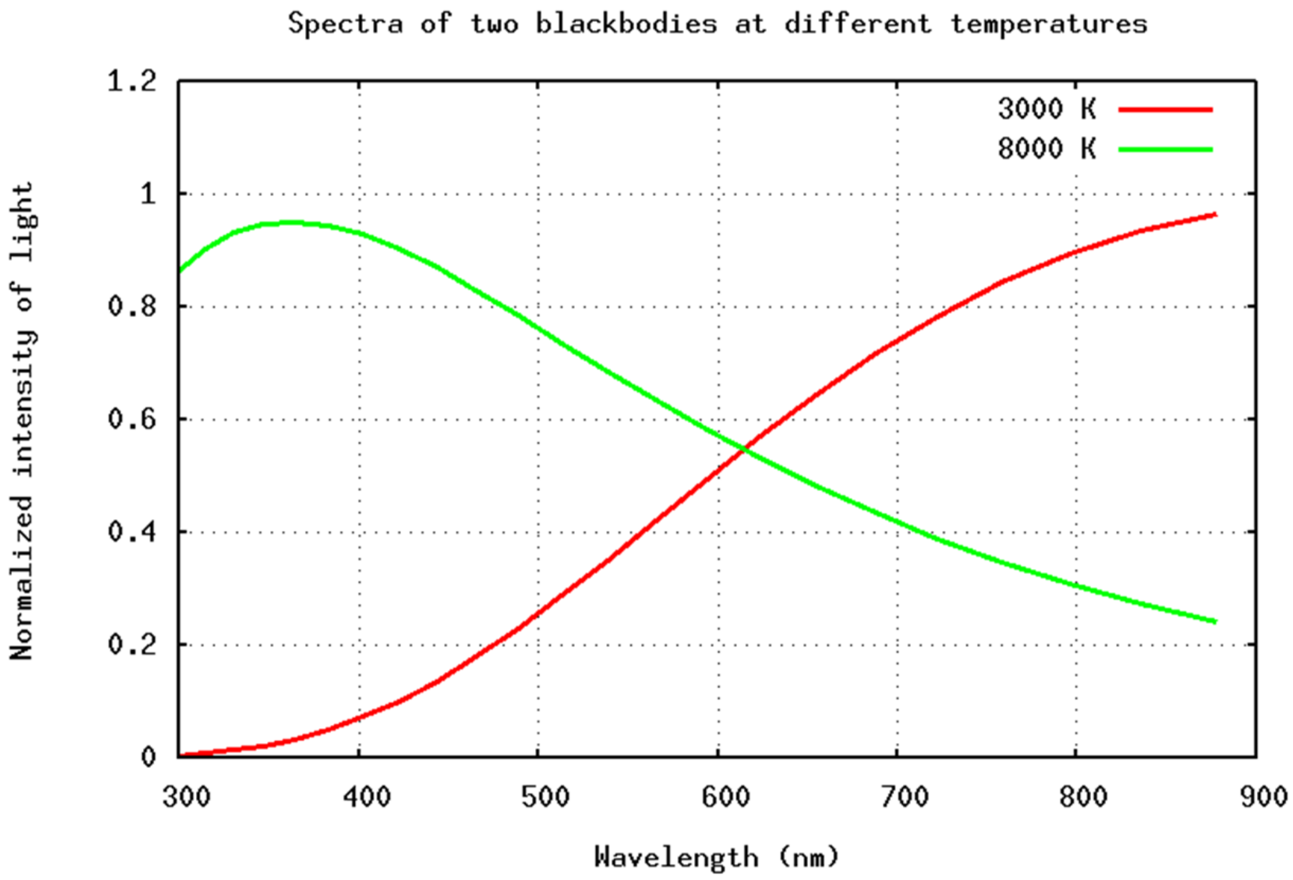
Filters and photometric systems

- Filter (photometric) systems:
  - Filters are used to restrict the wavelengths of electromagnetic radiation that hit the detector.
- Why may we want to do that?
  - Because stars have different colours that means they have different temperatures.

Observing through filters (1)

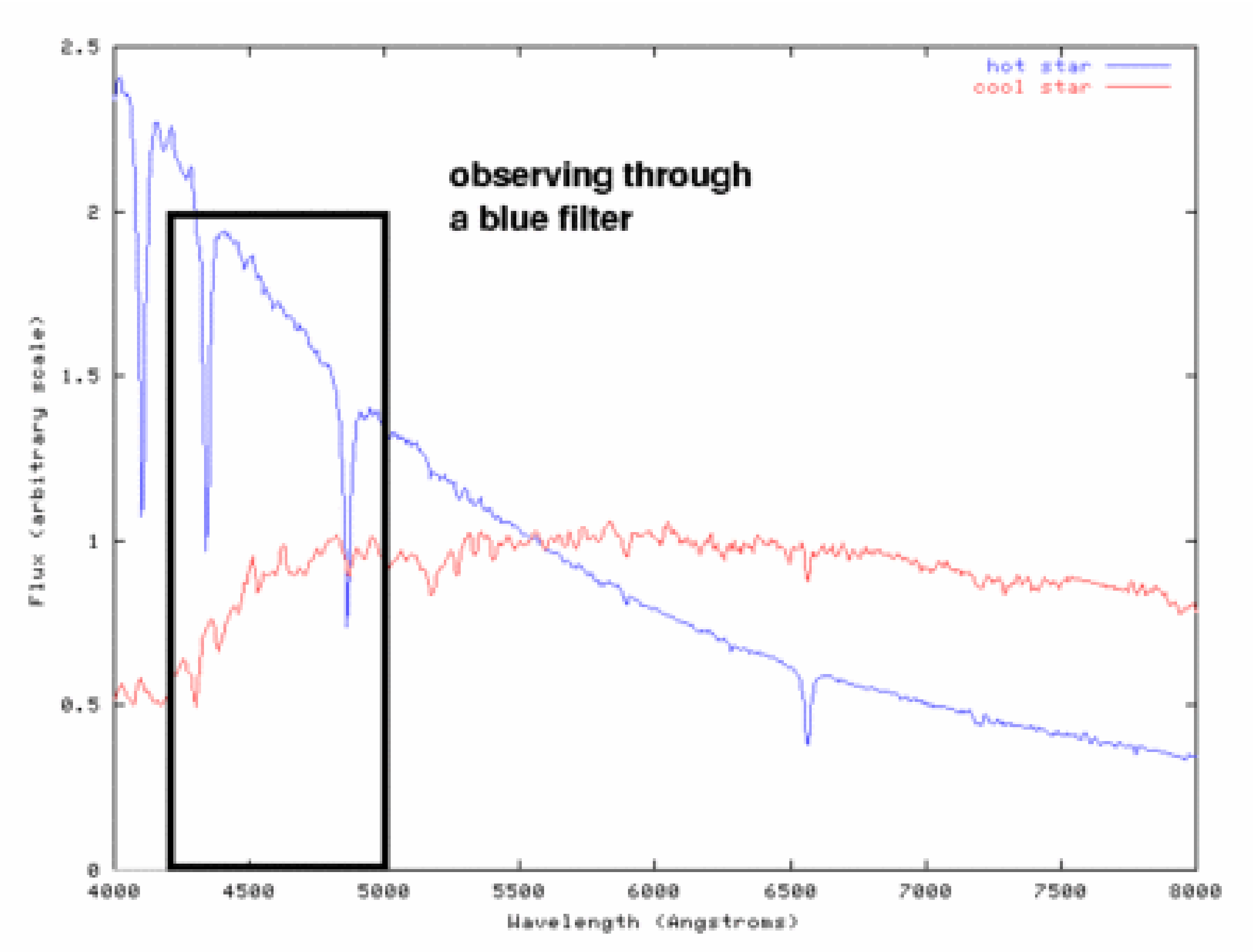
Hot objects emit most of their light at short wavelengths

Cool objects emit most of their light at long wavelengths



Observing through filters (2)

Observing through filters allows us to estimate temperatures.



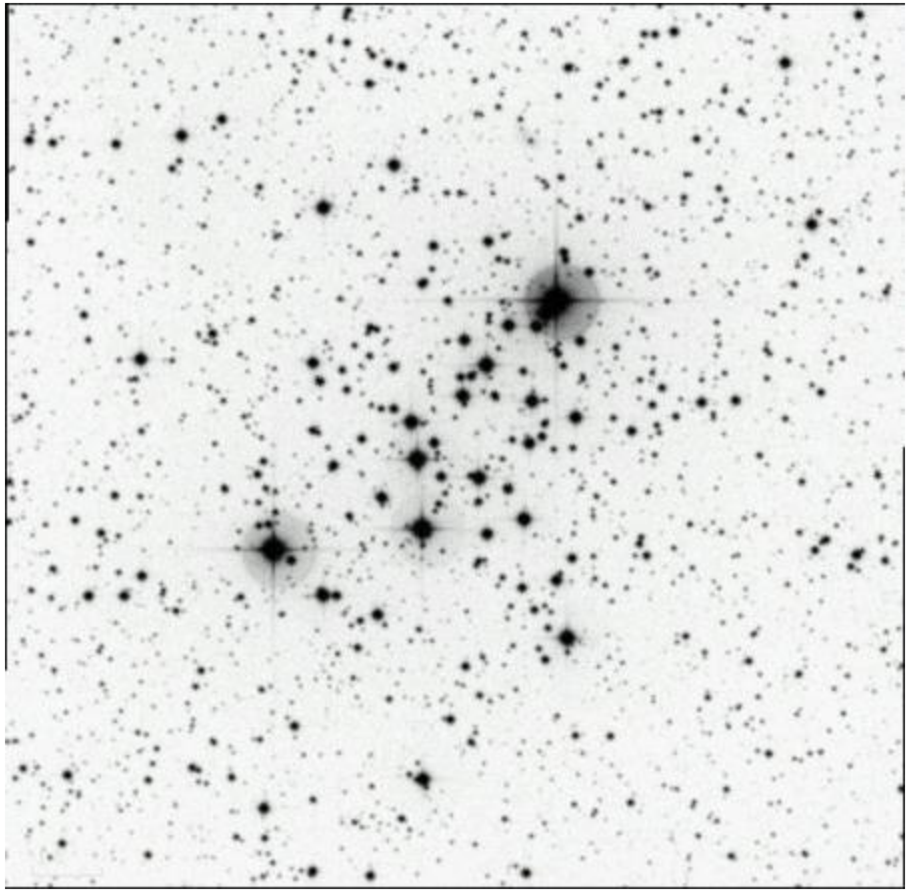
Observing through filters (3)

Which are the three brightest stars?

Observing through filters (4)

Which are the brightest stars?

It depends on
the bandpass through which
one observes them.



Photometric systems

- There is a number of different **photometric systems**, each one based on a particular passband (i.e. a particular combination of filter and detector and telescope).
- They may be grouped into wide, intermediate, and narrowband systems according to the bandwidth of their transmission curves. In the visible region:
  - Wide (broadband) filters have bandwidths of ~1000 Å
  - Intermediate: 100-500 Å
  - Narrowband filters range from 0.5 to 100 Å.
- One should always remember to specify the system when quoting the magnitude of a star.

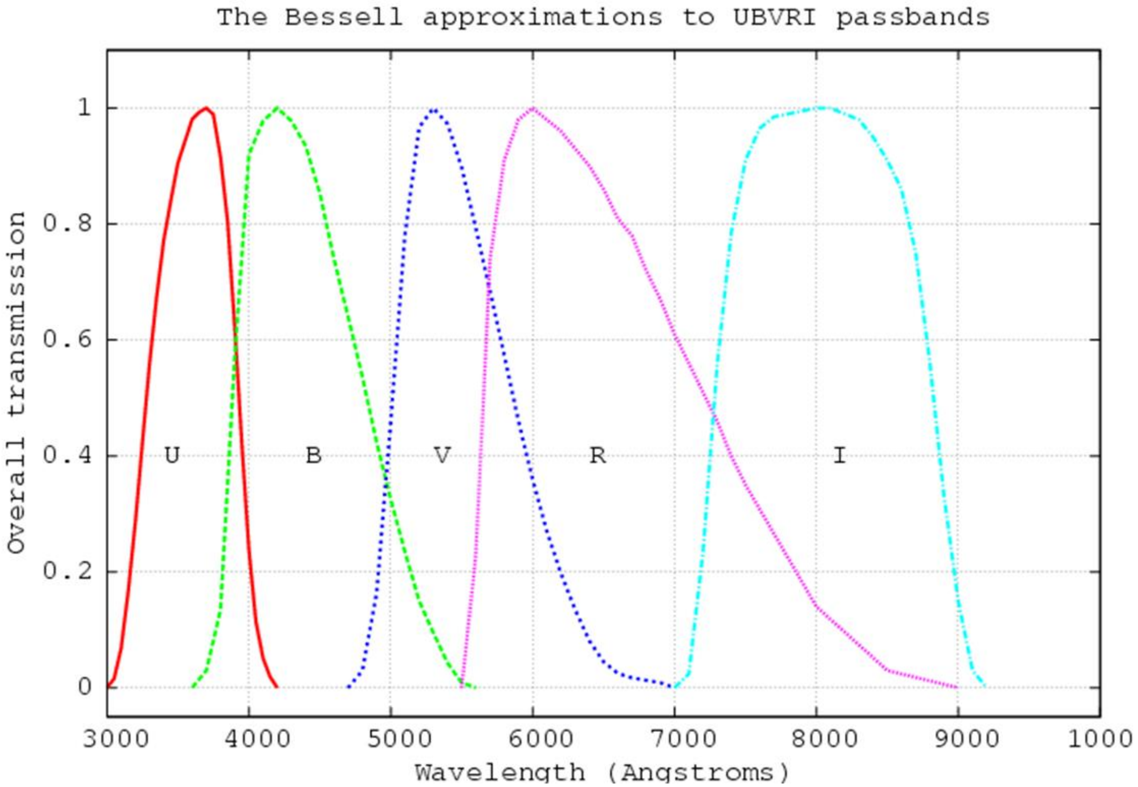
Johnson-Cousins photometric system (UBVRI)

- Most astronomers working in the optical use the Johnson-Cousins **UBVRI** photometric systems:
  - Johnson and Morgan defines the **UBV** system with stars visible in the northern hemisphere
  - Cousins defines the redder **R** and **I** passbands.

- The systems are defined by particular combinations of glass filters and photomultiplier tubes (they were created many years ago before CCDs existed). Since photomultipliers and CCDs have very different spectral sensitivities, it is difficult to make the effective passband of a CCD-based instrument match that of a photomultiplier-based instrument.
- In 1990, Michael Bessell came up with a recipe for making filters out of common colored glasses which would reproduce pretty closely the official Johnson-Cousins **UBVRI** passbands → Bessell filters.

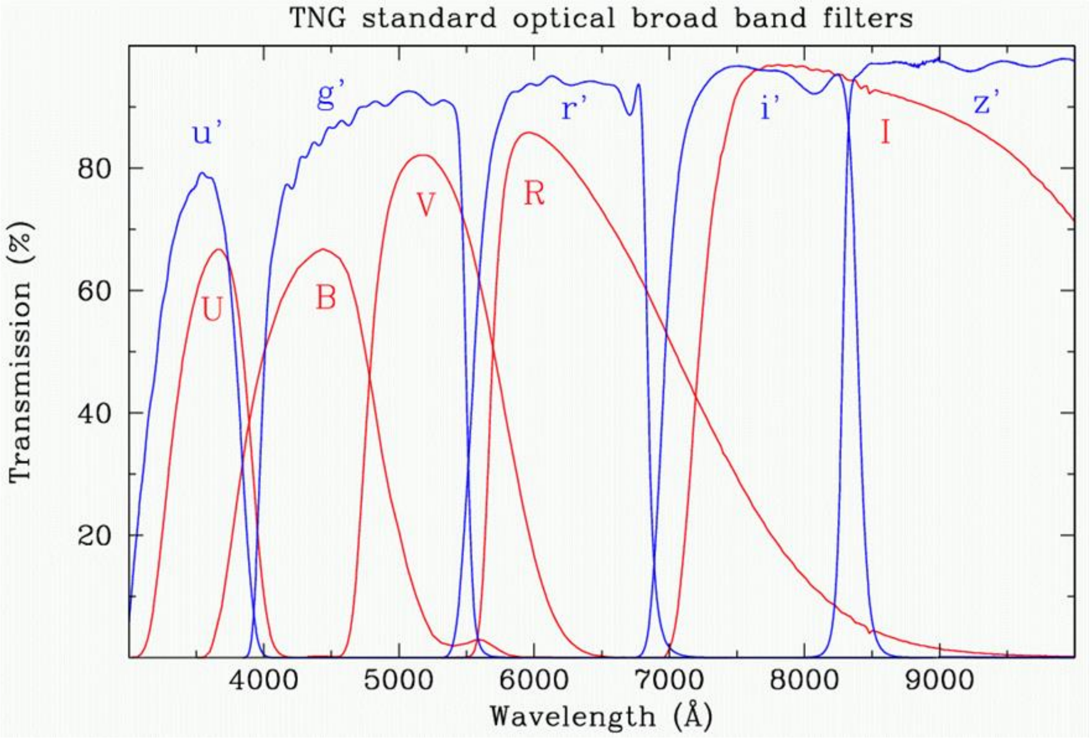
Johnson-Cousins photometric system

- ☐ The spectral resolution of the broadband UBVRI passbands is small: $R = \lambda/\Delta\lambda \approx 5$



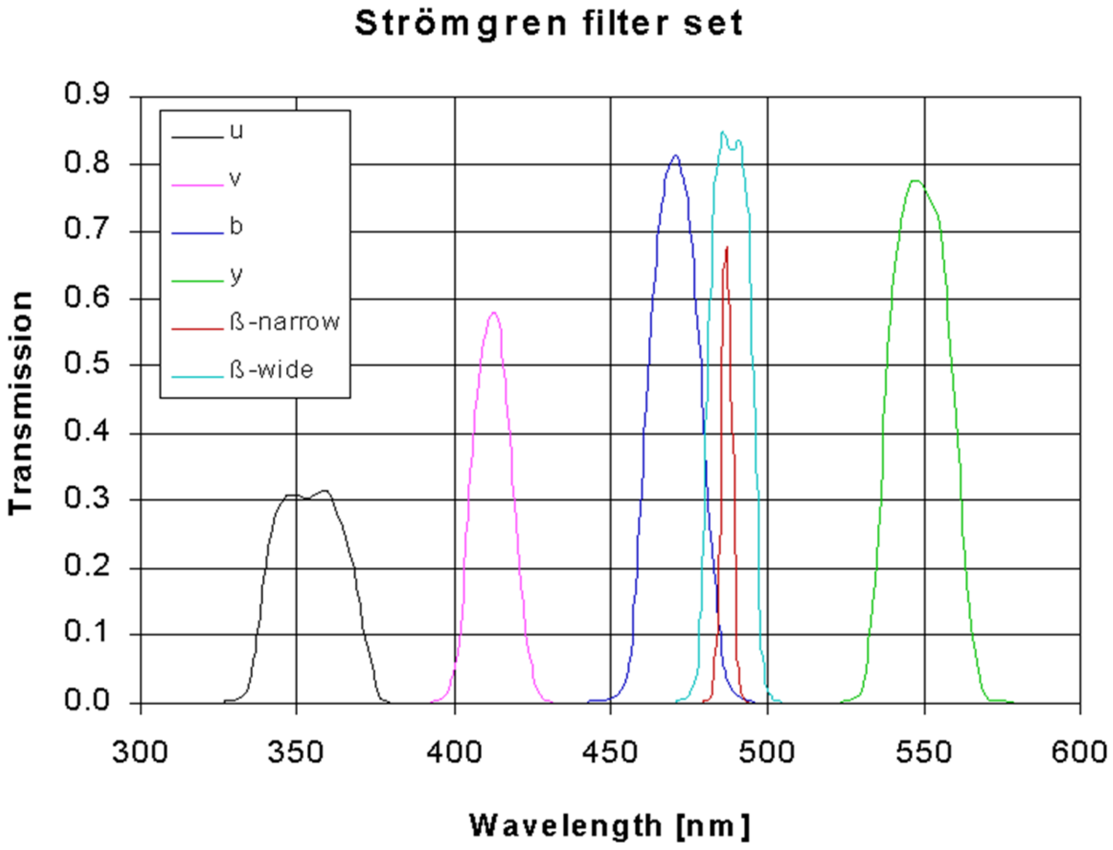
SDSS (ugriz) photometric system

- Although **UBVRI** is the best known optical system, there are a number of others. Some were specifically designed to solve a particular astrophysical problem, others to mesh with particular detectors. One important system is the **u’g’r’i’z’** that is being used by the Sloan Digital Sky Survey (**SDSS**) and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). It has become very popular recently.



Strömgren photometric system

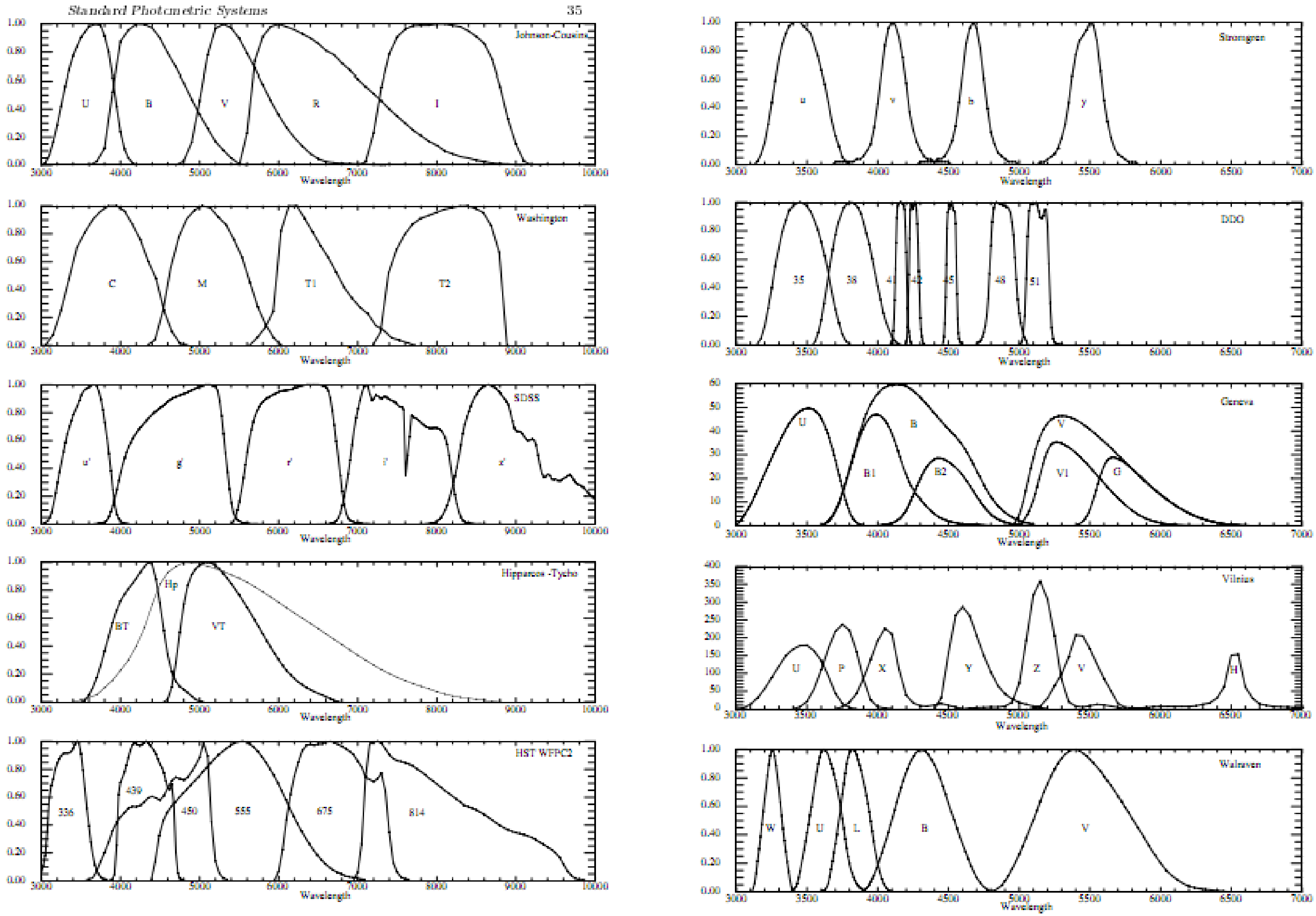
- **Strömgren photometric system** (uvby) is four-colour intermediate-band photometric system (plus Hβ filters) for stellar classification. It was pioneered by the Danish astronomer Bengt Strömgren in 1956.



Narrowband photometric systems

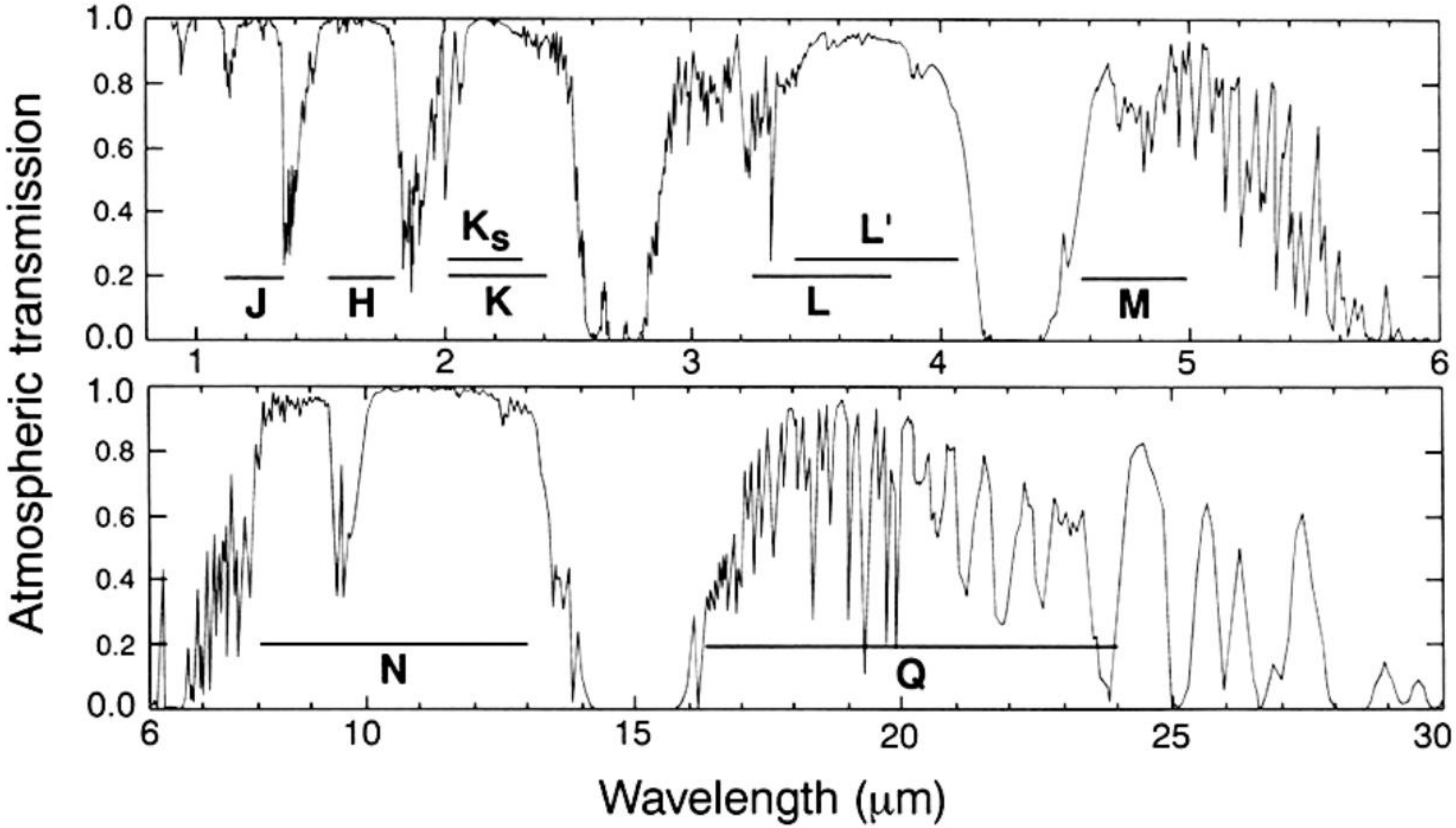
- For some applications, astronomers use narrowband filters; a common filter used to measure light emitted by hydrogen atoms is centered at 6563 Angstroms and roughly 20 Angstroms wide: $R = \lambda/\Delta\lambda \approx 330$
- A narrowband filter like this requires much longer exposure times to build up the same signal as a broadband filter. Since telescope time is so precious, astronomers tend to use broadband systems.
  That's one reason for the popularity of the UBVRI or SDSS systems.

Photometric systems (optical)



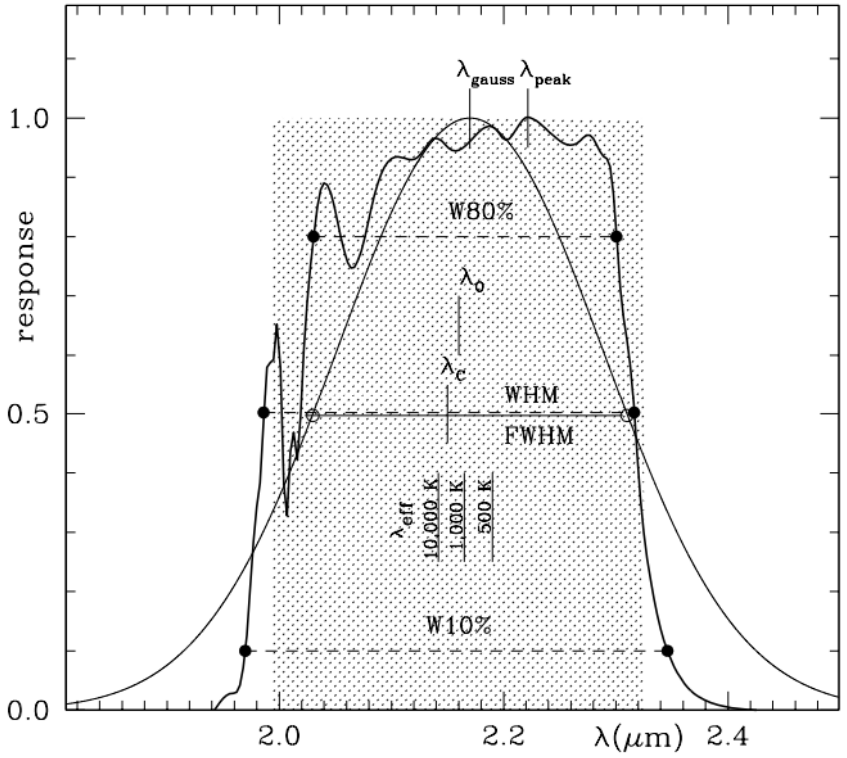
The Infrared Photometric Bands: JHK+others

… where the atmospheric transmission windows are



Filter transmission curves (1)

- Typical broad-band transmission curves are **not** rectangular, and even **not** symmetric.
- Different quantities can be used to describe a filter, e.g.:
  - λ_c is the wavelength halfway between the points, where the band transmission profile reaches half of the maximum value.
  - WHM is the the full wavelength span between the points, where the band transmission profile reaches half of the maximum value.
  - λ_{peak} is the wavelength at which the band transmission profile reaches its maximum.



From Fiorucci and Munari, 2003, A&A, 401, 781

Filter transmission curves (2)

- Some important parameters depend on the source spectrum. For example,
  - λ_0 is the mean wavelength of the band, the property of just a band:

$$\lambda_\circ = \frac{\int \lambda\, F(\lambda)\, \mathrm{d}\lambda}{\int F(\lambda)\, \mathrm{d}\lambda}.$$

  - whereas the effective wavelength λ_{eff} is

$$\lambda_{\text{eff}} = \frac{\int \lambda\, F(\lambda)\, S(\lambda)\, \mathrm{d}\lambda}{\int F(\lambda)\, S(\lambda)\, \mathrm{d}\lambda}.$$

where

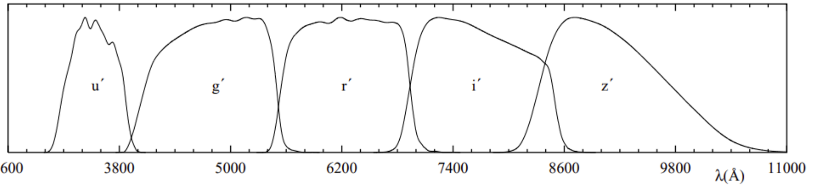
$F(\lambda)$ is the transmission profile of the band, and

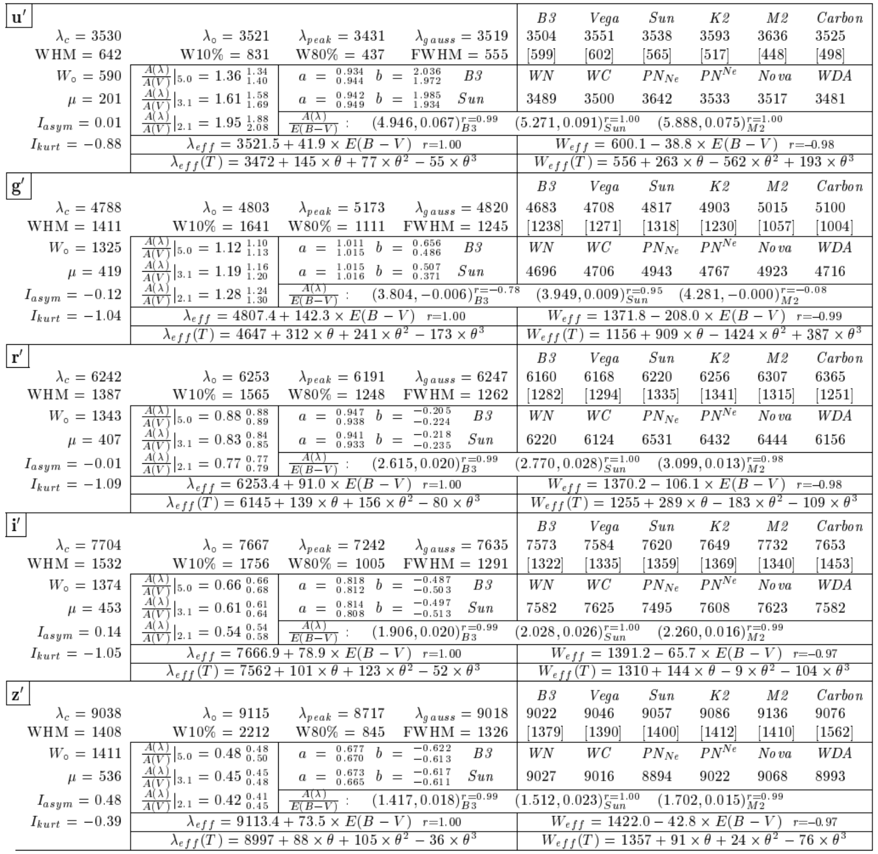
$S(\lambda)$ the energy distribution of a source spectrum.

Filter transmission curves (3)

Good sources of info:

- *The Asiago Database on Photometric Systems* (218 systems; checked on 2023-09-20)
  - http://ulisse.pd.astro.it/Astro/ADPS
  - Fiorucci and Munari, 2003, A&A, 401, 781
- *Filter Profile Service* (10625 filters available on 2023-09-20)
  - http://svo2.cab.inta-csic.es/theory/fps/





u′

$\lambda_c = 3530$ $\lambda_\circ = 3521$ $\lambda_{peak} = 3431$ $\lambda_{gauss} = 3519$

$\mathrm{WHM} = 642$ $\mathrm{W10\%} = 831$ $\mathrm{W80\%} = 437$ $\mathrm{FWHM} = 555$

B3	Vega	Sun	K2	M2	Carbon
3504	3551	3538	3593	3636	3525
[599]	[602]	[565]	[517]	[448]	[498]
WN	WC	PN_{Ne}	PN^{Ne}	Nova	WDA
3489	3500	3642	3533	3517	3481

$W_\circ = 590$ $\frac{A(\lambda)}{A(V)}\Big|_{5.0} = 1.36\,{}^{1.34}_{1.40}$ $a = {}^{0.934}_{0.944}$ $b = {}^{2.036}_{1.972}$ B3

$\mu = 201$ $\frac{A(\lambda)}{A(V)}\Big|_{3.1} = 1.61\,{}^{1.58}_{1.69}$ $a = {}^{0.942}_{0.949}$ $b = {}^{1.985}_{1.934}$ Sun

$I_{asym} = 0.01$ $\frac{A(\lambda)}{A(V)}\Big|_{2.1} = 1.95\,{}^{1.88}_{2.08}$ $\frac{A(\lambda)}{E(B-V)}:$ $(4.946, 0.067)^{r=0.99}_{B3}$ $(5.271, 0.091)^{r=1.00}_{Sun}$ $(5.888, 0.075)^{r=1.00}_{M2}$

$I_{kurt} = -0.88$ $\lambda_{eff} = 3521.5 + 41.9 \times E(B-V)$ r=1.00 $W_{eff} = 600.1 - 38.8 \times E(B-V)$ r=–0.98

$\lambda_{eff}(T) = 3472 + 145 \times \theta + 77 \times \theta^2 - 55 \times \theta^3$ $W_{eff}(T) = 556 + 263 \times \theta - 562 \times \theta^2 + 193 \times \theta^3$

g′

$\lambda_c = 4788$ $\lambda_\circ = 4803$ $\lambda_{peak} = 5173$ $\lambda_{gauss} = 4820$

$\mathrm{WHM} = 1411$ $\mathrm{W10\%} = 1641$ $\mathrm{W80\%} = 1111$ $\mathrm{FWHM} = 1245$

B3	Vega	Sun	K2	M2	Carbon
4683	4708	4817	4903	5015	5100
[1238]	[1271]	[1318]	[1230]	[1057]	[1004]
WN	WC	PN_{Ne}	PN^{Ne}	Nova	WDA
4696	4706	4943	4767	4923	4716

$W_\circ = 1325$ $\frac{A(\lambda)}{A(V)}\Big|_{5.0} = 1.12\,{}^{1.10}_{1.13}$ $a = {}^{1.011}_{1.015}$ $b = {}^{0.656}_{0.486}$ B3

$\mu = 419$ $\frac{A(\lambda)}{A(V)}\Big|_{3.1} = 1.19\,{}^{1.16}_{1.20}$ $a = {}^{1.015}_{1.016}$ $b = {}^{0.507}_{0.371}$ Sun

$I_{asym} = -0.12$ $\frac{A(\lambda)}{A(V)}\Big|_{2.1} = 1.28\,{}^{1.24}_{1.30}$ $\frac{A(\lambda)}{E(B-V)}:$ $(3.804, -0.006)^{r=-0.78}_{B3}$ $(3.949, 0.009)^{r=0.95}_{Sun}$ $(4.281, -0.000)^{r=-0.08}_{M2}$

$I_{kurt} = -1.04$ $\lambda_{eff} = 4807.4 + 142.3 \times E(B-V)$ r=1.00 $W_{eff} = 1371.8 - 208.0 \times E(B-V)$ r=–0.99

$\lambda_{eff}(T) = 4647 + 312 \times \theta + 241 \times \theta^2 - 173 \times \theta^3$ $W_{eff}(T) = 1156 + 909 \times \theta - 1424 \times \theta^2 + 387 \times \theta^3$

r′

$\lambda_c = 6242$ $\lambda_\circ = 6253$ $\lambda_{peak} = 6191$ $\lambda_{gauss} = 6247$

$\mathrm{WHM} = 1387$ $\mathrm{W10\%} = 1565$ $\mathrm{W80\%} = 1248$ $\mathrm{FWHM} = 1262$

B3	Vega	Sun	K2	M2	Carbon
6160	6168	6220	6256	6307	6365
[1282]	[1294]	[1335]	[1341]	[1315]	[1251]
WN	WC	PN_{Ne}	PN^{Ne}	Nova	WDA
6220	6124	6531	6432	6444	6156

$W_\circ = 1343$ $\frac{A(\lambda)}{A(V)}\Big|_{5.0} = 0.88\,{}^{0.88}_{0.89}$ $a = {}^{0.947}_{0.938}$ $b = {}^{-0.205}_{-0.224}$ B3

$\mu = 407$ $\frac{A(\lambda)}{A(V)}\Big|_{3.1} = 0.83\,{}^{0.84}_{0.85}$ $a = {}^{0.941}_{0.933}$ $b = {}^{-0.218}_{-0.235}$ Sun

$I_{asym} = -0.01$ $\frac{A(\lambda)}{A(V)}\Big|_{2.1} = 0.77\,{}^{0.77}_{0.79}$ $\frac{A(\lambda)}{E(B-V)}:$ $(2.615, 0.020)^{r=0.99}_{B3}$ $(2.770, 0.028)^{r=1.00}_{Sun}$ $(3.099, 0.013)^{r=0.98}_{M2}$

$I_{kurt} = -1.09$ $\lambda_{eff} = 6253.4 + 91.0 \times E(B-V)$ r=1.00 $W_{eff} = 1370.2 - 106.1 \times E(B-V)$ r=–0.98

$\lambda_{eff}(T) = 6145 + 139 \times \theta + 156 \times \theta^2 - 80 \times \theta^3$ $W_{eff}(T) = 1255 + 289 \times \theta - 183 \times \theta^2 - 109 \times \theta^3$

i′

$\lambda_c = 7704$ $\lambda_\circ = 7667$ $\lambda_{peak} = 7242$ $\lambda_{gauss} = 7635$

$\mathrm{WHM} = 1532$ $\mathrm{W10\%} = 1756$ $\mathrm{W80\%} = 1005$ $\mathrm{FWHM} = 1291$

B3	Vega	Sun	K2	M2	Carbon
7573	7584	7620	7649	7732	7653
[1322]	[1335]	[1359]	[1369]	[1340]	[1453]
WN	WC	PN_{Ne}	PN^{Ne}	Nova	WDA
7582	7625	7495	7608	7623	7582

$W_\circ = 1374$ $\frac{A(\lambda)}{A(V)}\Big|_{5.0} = 0.66\,{}^{0.66}_{0.68}$ $a = {}^{0.818}_{0.812}$ $b = {}^{-0.487}_{-0.503}$ B3

$\mu = 453$ $\frac{A(\lambda)}{A(V)}\Big|_{3.1} = 0.61\,{}^{0.61}_{0.64}$ $a = {}^{0.814}_{0.808}$ $b = {}^{-0.497}_{-0.513}$ Sun

$I_{asym} = 0.14$ $\frac{A(\lambda)}{A(V)}\Big|_{2.1} = 0.54\,{}^{0.54}_{0.58}$ $\frac{A(\lambda)}{E(B-V)}:$ $(1.906, 0.020)^{r=0.99}_{B3}$ $(2.028, 0.026)^{r=1.00}_{Sun}$ $(2.260, 0.016)^{r=0.99}_{M2}$

$I_{kurt} = -1.05$ $\lambda_{eff} = 7666.9 + 78.9 \times E(B-V)$ r=1.00 $W_{eff} = 1391.2 - 65.7 \times E(B-V)$ r=–0.97

$\lambda_{eff}(T) = 7562 + 101 \times \theta + 123 \times \theta^2 - 52 \times \theta^3$ $W_{eff}(T) = 1310 + 144 \times \theta - 9 \times \theta^2 - 104 \times \theta^3$

z′

$\lambda_c = 9038$ $\lambda_\circ = 9115$ $\lambda_{peak} = 8717$ $\lambda_{gauss} = 9018$

$\mathrm{WHM} = 1408$ $\mathrm{W10\%} = 2212$ $\mathrm{W80\%} = 845$ $\mathrm{FWHM} = 1326$

B3	Vega	Sun	K2	M2	Carbon
9022	9046	9057	9086	9136	9076
[1379]	[1390]	[1400]	[1412]	[1410]	[1562]
WN	WC	PN_{Ne}	PN^{Ne}	Nova	WDA
9027	9016	8894	9022	9068	8993

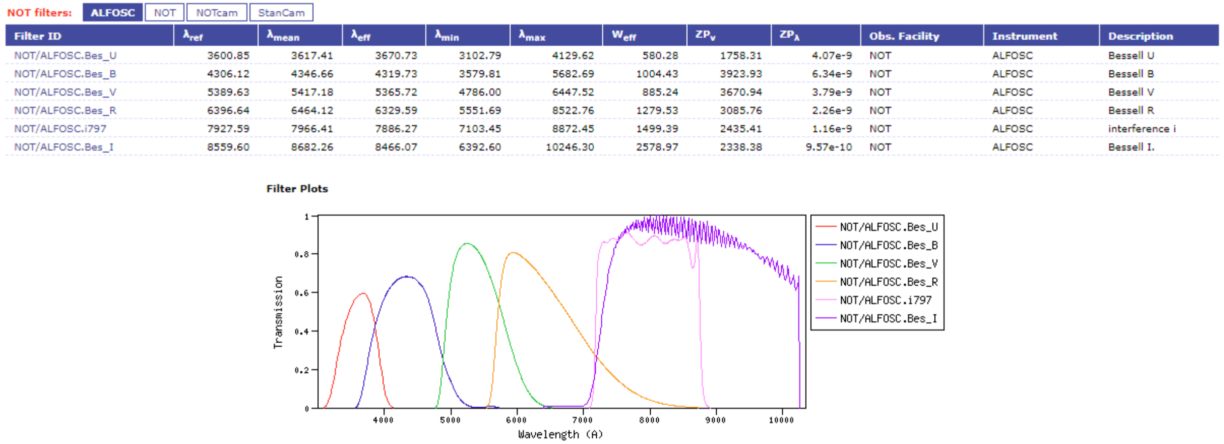
$W_\circ = 1411$ $\frac{A(\lambda)}{A(V)}\Big|_{5.0} = 0.48\,{}^{0.48}_{0.50}$ $a = {}^{0.677}_{0.670}$ $b = {}^{-0.622}_{-0.613}$ B3

$\mu = 536$ $\frac{A(\lambda)}{A(V)}\Big|_{3.1} = 0.45\,{}^{0.45}_{0.48}$ $a = {}^{0.673}_{0.665}$ $b = {}^{-0.617}_{-0.611}$ Sun

$I_{asym} = 0.48$ $\frac{A(\lambda)}{A(V)}\Big|_{2.1} = 0.42\,{}^{0.41}_{0.45}$ $\frac{A(\lambda)}{E(B-V)}:$ $(1.417, 0.018)^{r=0.99}_{B3}$ $(1.512, 0.023)^{r=1.00}_{Sun}$ $(1.702, 0.015)^{r=0.99}_{M2}$

$I_{kurt} = -0.39$ $\lambda_{eff} = 9113.4 + 73.5 \times E(B-V)$ r=1.00 $W_{eff} = 1422.0 - 42.8 \times E(B-V)$ r=–0.97

$\lambda_{eff}(T) = 8997 + 88 \times \theta + 105 \times \theta^2 - 36 \times \theta^3$ $W_{eff}(T) = 1357 + 91 \times \theta + 24 \times \theta^2 - 76 \times \theta^3$



Filter ID	λ_{ref}	λ_{mean}	λ_{eff}	λ_{min}	λ_{max}	W_{eff}	ZP_ν	ZP_λ	Obs. Facility	Instrument	Description
NOT/ALFOSC.Bes_U	3600.85	3617.41	3670.73	3102.79	4129.62	580.28	1758.31	4.07e-9	NOT	ALFOSC	Bessell U
NOT/ALFOSC.Bes_B	4306.12	4346.66	4319.73	3579.81	5682.69	1004.43	3923.93	6.34e-9	NOT	ALFOSC	Bessell B
NOT/ALFOSC.Bes_V	5389.63	5417.18	5365.72	4786.00	6447.52	885.24	3670.94	3.79e-9	NOT	ALFOSC	Bessell V
NOT/ALFOSC.Bes_R	6396.64	6464.12	6329.59	5551.69	8522.76	1279.53	3085.76	2.26e-9	NOT	ALFOSC	Bessell R
NOT/ALFOSC.i797	7927.59	7966.41	7886.27	7103.45	8872.45	1499.39	2435.41	1.16e-9	NOT	ALFOSC	interference i
NOT/ALFOSC.Bes_I	8559.60	8682.26	8466.07	6392.60	10246.30	2578.97	2338.38	9.57e-10	NOT	ALFOSC	Bessell I.

Filter Plots

Magnitudes & Photometric systems

- When writing the magnitude of a star, astronomers use an abbreviation to denote the photometric system of the measurement:
  - V = 1.03 (or 1.03V) means “magnitude of this star in the V system is 1.03”
  - B = 0.46 (or 0.46B) means “magnitude of this star in the B system is 0.46”

But a magnitude system can be different!

Magnitude systems

$$m_1 - m_2 = -2.5\, log \frac{F}{F_0}$$

- The flux F_0 defines the reference or **zeropoint** of the magnitude scale. The choice is arbitrary.
- Standardizing magnitudes (magnitude systems):
  - Vega system
  - AB system
  - ST Magnitudes

A magnitude system is **not** a photometric (filter) system
(you can use a filter in any system)

Photometry: Vega system

- Astronomers have chosen to use the bright star Vega (α Lyr) as their starting point.
- In the UBVRI systems, the star Vega is **defined** to have a magnitude of zero in all bands (actually, this is not quite true):

$$U = 0.0;\ B = 0.0;\ V = 0.0;\ R = 0.0;\ I = 0.0$$

- This means also that all the colours of Vega are zero.
- The zero-point of this system depends on the flux of Vega (outside the atmosphere) and is different in different bands.

Photometry: AB system

- In the **AB system**, which is not based on Vega, it is assumed that the flux constant F_0 is the **same** for all wavelengths and passbands.
- That constant is per definition such that in the V filter: $m_V^{Vega} = m_V^{AB} = 0$
(or more accurately: $F_\lambda\ d\nu \equiv F_\lambda\ d\lambda$ when averaged over the V filter, or at the effective wavelength of the V filter, $\lambda_{eff} = 5480$ Å. Based on the work of Oke (1974), then

$$m_\nu = -2.5\, log\, F_\nu - (48.585 \pm 0.005)$$

where $F_\nu(\lambda)$ is the spectral flux density per unit frequency of a source at the top of the Earth's atmosphere in units of erg $s^{-1} cm^{-2} Hz^{-1}$.

- Note that the AB magnitude system is expressed in c rather than F_λ!

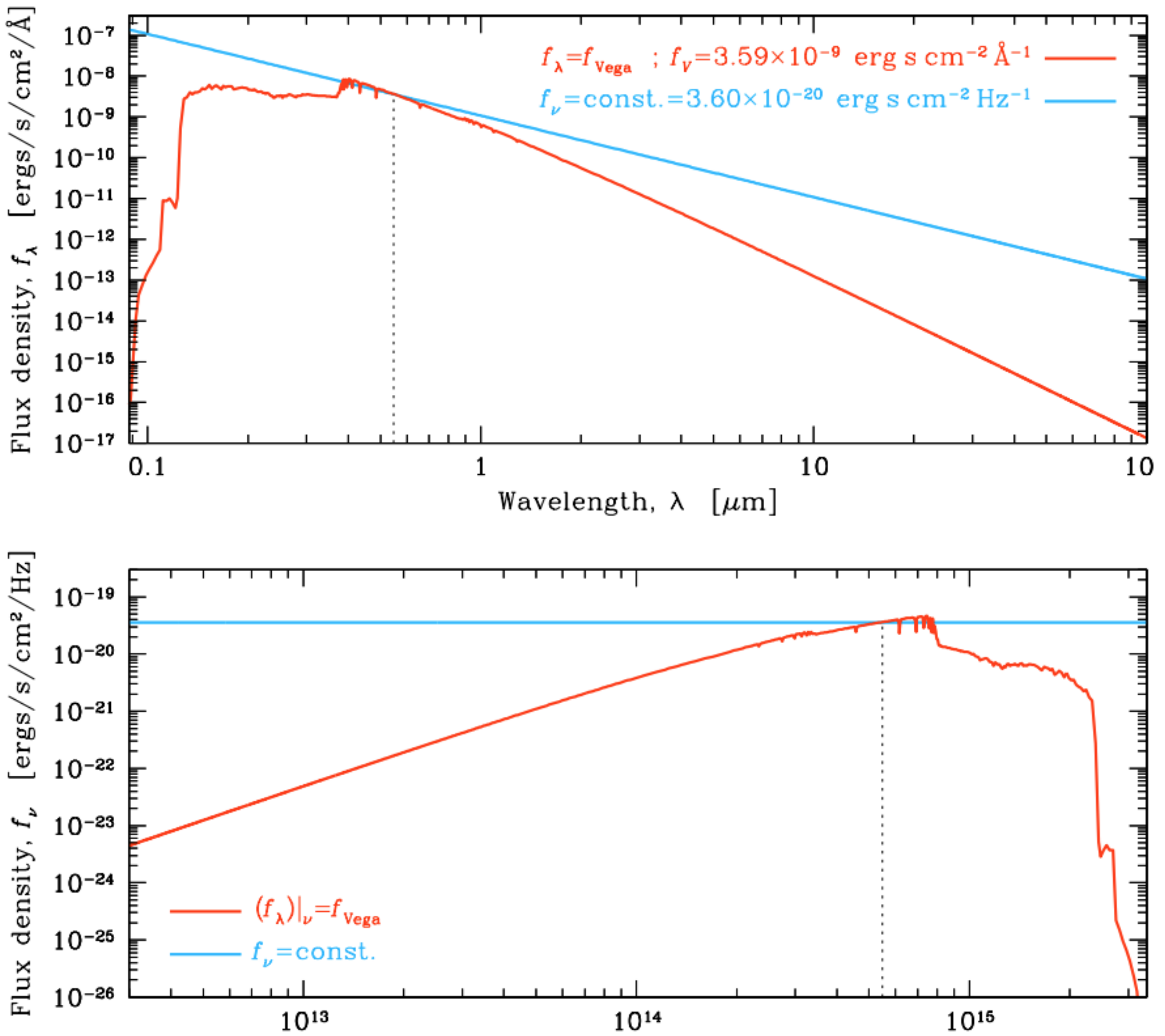
The flux density in F_ν is related to the flux density in F_λ by:

$$F_\nu\,[\text{ergs s}^{-1}\ \text{cm}^{-2}\ \text{Hz}^{-1}] = 10^{-8}\,\frac{\lambda[\text{Å}]^2}{c[\text{cm s}^{-1}]}\,F_\lambda\,[\text{ergs s}^{-1}\ \text{cm}^{-2}\ \text{Å}^{-1}]$$

- One can easily convert between AB magnitudes and Janskys:
In AB magnitudes, mag 0 has a flux of 3631 Jy.

AB and VEGA systems compared

- The difference between AB and VEGA magnitudes becomes very large at redder wavelengths!
- The spectrum of Vega is very complicated at IR wavelengths and often model atmospheres are used adding to uncertainties



Photometry: ST Magnitudes

The ST magnitude system is defined such that an object with constant flux F_λ=3.63×10^{-9} ergs s^{-1} cm^{-2} Å^{-1} will have magnitude ST = 0 in every filter. In general,

$$ST_{mag} = -2.5\,log\,F_\lambda - 21.1$$

We will not discuss this system anymore.

Bolometric magnitudes

- **Bolometric magnitudes:** this gives a magnitude corresponding to the total flux integrated over all wavelengths
- The calculations are expressed as the difference between the bolometric magnitude and observed magnitude. The difference is then known as the bolometric correction: $BC = m_{bol} - V$
- The XXIXth IAU General Assembly in Honolulu recommended zero points for the absolute and apparent bolometric magnitude scales:
  - Resolution B2 defines the zero point of the absolute bolometric magnitude scale such that a radiation source with $M_{Bol}=0$ has luminosity $L_0=3.0128\times10^{28}$ W.
  - The zero point of the apparent bolometric magnitude scale ($m_{bol}=0$) corresponds to irradiance $F_{Bol} = 2.518 \times 10^{-8}$ W m^{-2}. The zero points were chosen so that the nominal solar luminosity (3.828×10^{26} W) corresponds to $M_{Bol}(\text{Sun}) = 4.74$.
  - The nominal total solar irradiance (1361 W m^{-2}) corresponds approximately to apparent bolometric magnitude $m_{bol}(\text{Sun}) = -26.832$.

Standard Stars for Photometry (1)

- The primary standards for the UBV system are a set of 10 bright, naked eye stars of magnitude 2 to 5, known as the North Pole sequence – comprise stars within 2° of the North pole star. The magnitudes of these stars define the UBV colour system.
- Instead of using the primary standards directly, we use a series of secondary standard stars, or just standard stars, whose magnitudes have been carefully measured relative to the primary stars.
- For broadband optical work (UBVRI filter system) the standard stars used most frequently today are from the work of the astronomer Arlo Landolt. Landolt has devoted many years to measuring a set of standard star magnitudes.

Standard Stars for Photometry (2)

- What makes a good standard star?
  - A standard star must not be variable!
  - Standard stars must be of a brightness that will not overwhelm the detector and telescope in use, but must be bright enough to give a good S/N in a short exposure. For very large telescopes, many of the Landolt stars are too bright.
  - Ideally, a set of stars very close together in the sky will cover a wide range of colours.
  - Standard stars should be located across the sky so that they span a wide range of airmass.

Colour indices (1)

- **Colour indices**: this is the difference between magnitudes at two separate wavelengths:

$$C_{BV} = B - V;\ C_{VR} = V - R,\ \text{and so on.}$$

- International colour index (outdated, but can be found in the literature) based upon photographic and photovisual magnitudes:

$$m_p - m_{pv} = C = B - V - 0.11$$

Colour indices (2)

- The B – V colour index is closely related to the spectral type with an almost linear relationship for main sequence stars.
- For most stars, the B and V regions are located on the long wavelength side of the maximum spectral intensity.
- If we assume that the effective wavelengths of the B and V filters are 4400 and 5500 Å, then using the Planck equation:

$$L_\lambda(T) = \frac{2\,h\,c_0^2}{\lambda^5}\left[\exp\left(\frac{h\,c_0}{\lambda\,k_\mathrm{B}T}\right) - 1\right]^{-1}$$

we obtain:

$$B - V \approx -2.5\log\left[3.05\,\frac{\exp(2.617\times10^4/T)}{\exp(3.27\times10^4/T)}\right]$$

Colour indices (3)

- For $T < 10000$ K this is approximately

$$B - V \approx -2.5 \log \left[3.05 \frac{\exp(2.617 \times 10^4/T)}{\exp(3.27 \times 10^4/T)} \right] = -1.21 + \frac{7090}{T}$$

The magnitude scale is an arbitrary one.
For T = 9600 K (Vega temperature), $B–V = 0.0$,
but we have obtained ~0.5. Using this correction, we get:

$$T = \frac{7090}{(B - V) + 0.74} \; K$$

Colour excess and Interstellar absorption

- More distant stars are affected by interstellar absorption, and since this is strongly inversely dependent upon wavelength.
- The colour excess measure the degree to which the spectrum is reddened:

$$E_{U-B}=(U-B)-(U-B)_0$$

$$E_{B-V}=(B-V)-(B-V)_0$$

where the subscript 0 denotes unreddened quantities – intrinsic colour indices.

- In the optical spectrum, interstellar absorption varies with both wavelength and the distance like this semi-empirical relationship:

$$A_\lambda=6.5\times10^{-10}/\lambda-2.0\times10^{-4}\ \text{mag pc}^{-1}$$

where λ is in nanometers

Photometry

- Simple UBV photometry for hot stars results in determinations of temperature, Balmer discontinuity, spectral type, and reddening. From the latter we can estimate distance.
- Thus, we have a very high return of information for a small amount of observational effort. This is why the relatively crude methods of wideband photometry is so popular.

Photometry

Effective wavelengths (for an A0 star like Vega), absolute fluxes (corresponding to zero magnitude) and zeropoint magnitudes for the UBVRIJHKL Johnson-Cousins system

Bessell et al.
(1998, A&A, 333, 231)

Band	λc (Å)	$f_{\nu 0}$	$f_{\lambda 0}$	$zp(f_\lambda)$	$zp(f_\nu)$
U	3660	1.790	417.5	-0.152	0.770
B	4380	4.063	632.0	-0.602	-0.120
V	5450	3.636	363.1	0.000	0.000
R	6410	3.064	217.7	0.555	0.186
I	7980	2.416	112.6	1.271	0.444
J	12200	1.589	31.47	2.655	0.899
H	16300	1.021	11.38	3.760	1.379
K	21900	0.64	3.961	4.906	1.886
L	34500	0.285	0.708	6.775	2.765

f_λ (10^{-11} erg $s^{-1} cm^{-2}$ $Å^{-1}$)
$mag_\lambda = -2.5 \log (f_\lambda) - 21.100 - zp(f_\lambda)$

f_ν (10^{-20} erg $s^{-1} cm^{-2}$ Hz^{-1} = 1000 Jy)
$mag_\nu = -2.5 \log (f_\nu) - 48.585 - zp(f_\nu)$

Photometry: Fun with Units (1)

- **Why do we continue to use magnitudes?**
  - Historical reasons: astronomers have built up a vast literature of catalogues and measurements in the magnitude system.
  - The magnitude system is logarithmic, which turns the huge range in brightness ratios into a much smaller range in magnitude differences: the difference between the Sun and the faintest star visible to the naked eye is only 32 magnitudes.
  - Simplicity: Astronomers have figured out how to use magnitudes in some practical ways which turn out to be easier to compute than the corresponding brightness ratios.
- However, in general converting between different magnitude and photometric systems is difficult: conversion factors depend on the spectrum of each object.

Photometry: Fun with Units (2)

- Astronomers who study objects outside the optical wavelengths do not have any historical measurements to incorporate into their work.
- In those regimes, measurements are almost always quoted in "more rational" systems: units which are linear with intensity (rather than logarithmic) and which become larger for brighter objects:
  - $\mathrm{erg\ s^{-1}cm^{-2}\ \AA^{-1}}$
  - $\mathrm{erg\ s^{-1}cm^{-2}\ Hz^{-1}}$

  - 1 Jansky [Jy] = $10^{-26}\ \mathrm{W\ m^{-2}\ Hz^{-1}} = 10^{-23}\ \mathrm{erg\ s^{-1}cm^{-2}\ Hz^{-1}}$
    F_ν [Jy]=$3.34\times10^{4}\ \lambda^{2}\ F_\lambda$ [erg $\mathrm{s^{-1}\ cm^{-2}\ \AA^{-1}}$]
    F_λ [erg $\mathrm{s^{-1}\ cm^{-2}\ \AA^{-1}}$]= $3.00\times10^{-5}\ \lambda^{-2}\ F_\nu$ [Jy]

Photometry: Fun with Units (3)

- Fluxes for a V = 0 star of spectral type A0 V at 5450 Å:
  - $f^0_\lambda = 3.63 \times 10^{-9}$ erg $s^{-1} cm^{-2}$ Å^{-1}, or
  - $\varphi^0{}_\lambda = f^0_\lambda / h\nu = 996$ photons $s^{-1} cm^{-2}$ Å^{-1}

  - Useful:
    - 1 Jy = $1.51 \times 10^3 / \lambda$ photons $s^{-1} cm^{-2}$ Å^{-1}

    - $\Delta\lambda / \lambda$ = 0.15 (U), 0.22 (B), 0.16 (V), 0.23 (R), 0.19 (I)

Night Sky Brightnesses

Lunar Age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

Signal from the sky background is present in every pixel of the aperture. Because each instrument generally has a different pixel scale, the sky brightness is usually tabulated for a site in units of mag/arcsecond^2.