OBSERVATIONAL ASTRONOMY

FALL 2025

Lecture 10

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Magnitude systems

$$m_1 - m_2 = -2.5\, log\, \frac{F_1}{F_2} \quad \text{or} \quad m = -2.5\, log\, \frac{F}{F_0}$$

where 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 F_ν rather than F_λ!

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

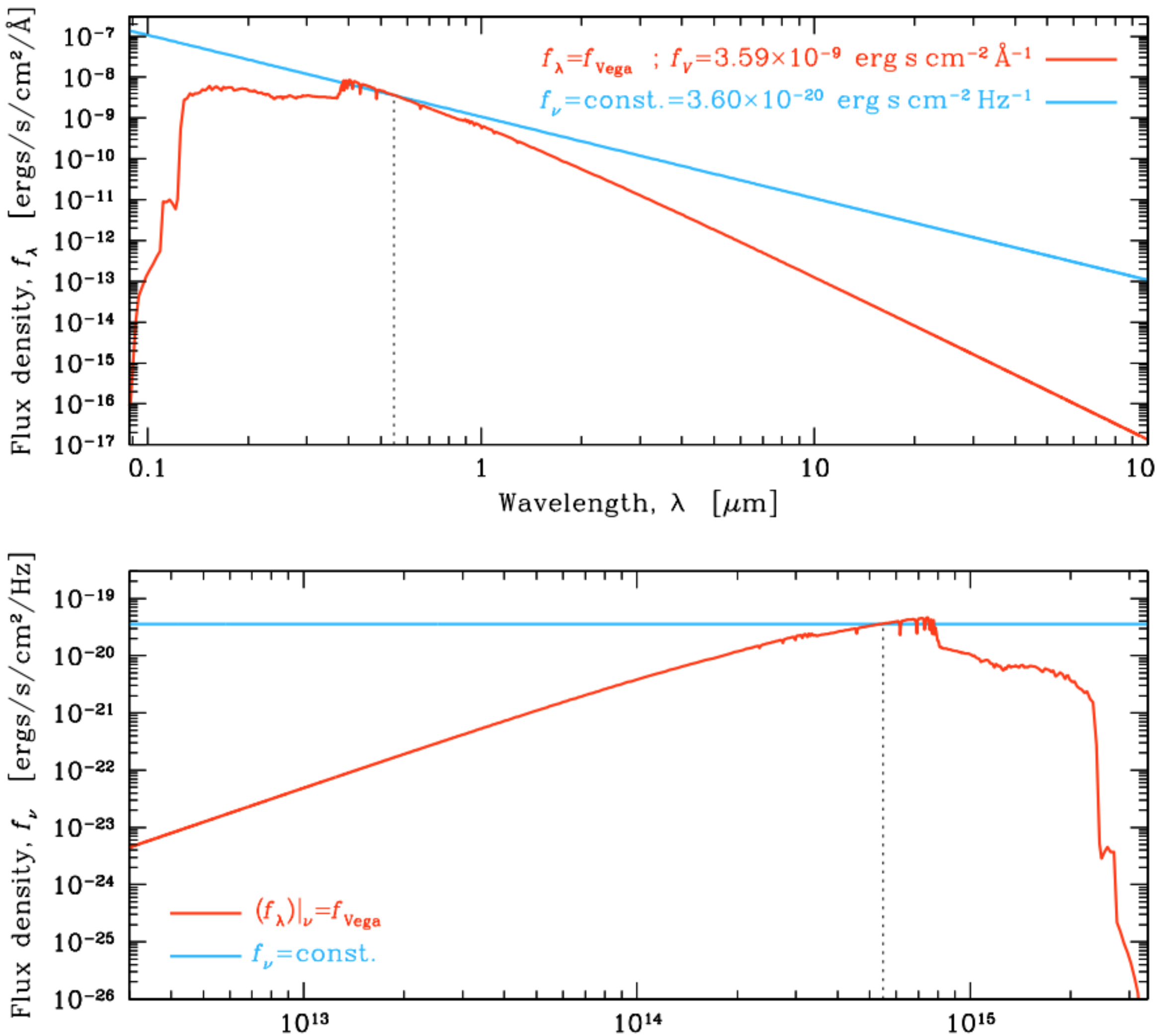
$$F_\nu [\text{ergs s}^{-1}\ \text{cm}^{-2}\ \text{Hz}^{-1}] = 10^{-8} \frac{\lambda[\text{Å}]^2}{c[\text{cm s}^{-1}]} F_\lambda [\text{ergs s}^{-1}\ \text{cm}^{-2}\ \text{Å}^{-1}]$$

- 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 $F_\lambda = 3.63\times10^{-9}$ 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 $M_{Bol}(\mathrm{Sun}) = 4.74$.
  - The nominal total solar irradiance (1361 W m^{-2}) corresponds approximately to apparent bolometric magnitude $m_{bol}(\mathrm{Sun}) = -26.832$.

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:

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

we obtain:

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

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), $B\text{–}V = 0.0$,
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_{λ})	zp(f_{ν})
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}) f_{ν} (10^{-20} erg $s^{-1} cm^{-2}$ Hz^{-1} = 1000 Jy)

$mag_{\lambda} = -2.5 \log (f_{\lambda}) - 21.100 - zp(f_{\lambda})$ $mag_{\nu} = -2.5 \log (f_{\nu}) - 48.585 - zp(f_{\nu})$

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:

  - erg $s^{-1} cm^{-2}$ $Å^{-1}$
  - erg $s^{-1} cm^{-2}$ Hz^{-1}

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

Photometry: Fun with Units (3)

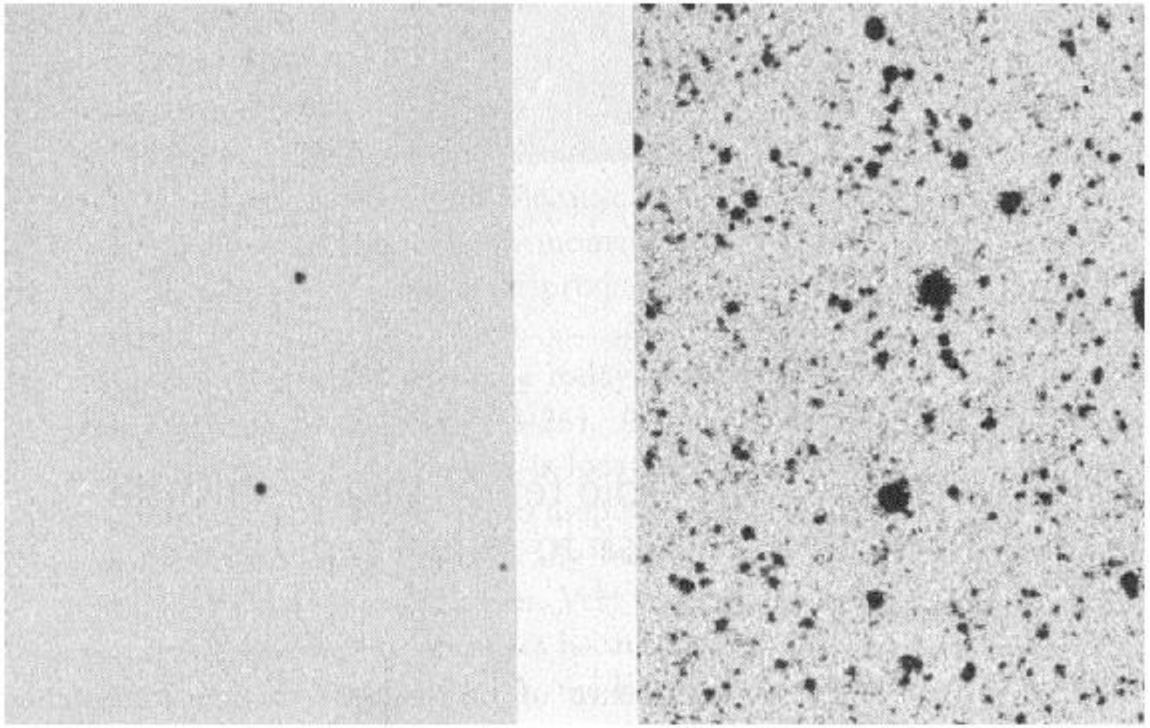
- Fluxes for a V = 0 star of spectral type A0 V at 5450 Å:
  - $f^0_\lambda = 3.63 \times 10^{-9}$ erg $s^{-1} cm^{-2}$ Å^{-1}, or
  - $\varphi^0{}_\lambda = f^0_\lambda / h\nu = 996$ photons $s^{-1} cm^{-2}$ Å^{-1}
  - Useful:
    - 1 Jy = $1.51 \times 10^3 / \lambda$ photons $s^{-1} cm^{-2}$ Å^{-1}
    - $\Delta\lambda / \lambda$ = 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.

Practical Photometry: S/N (2)



Physical limitations on the precision of photometric measurements (1)

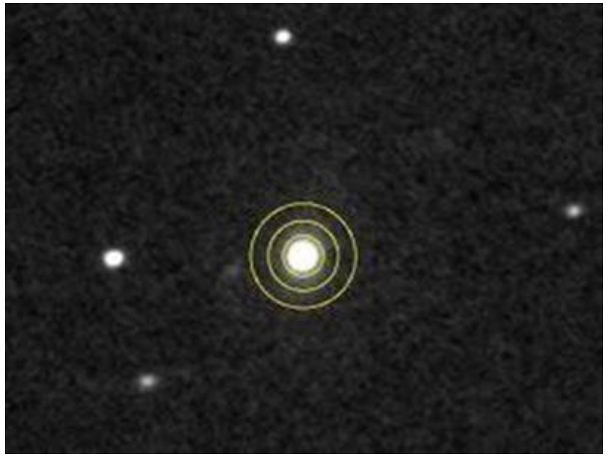
From lecture 9 (slides 353+):

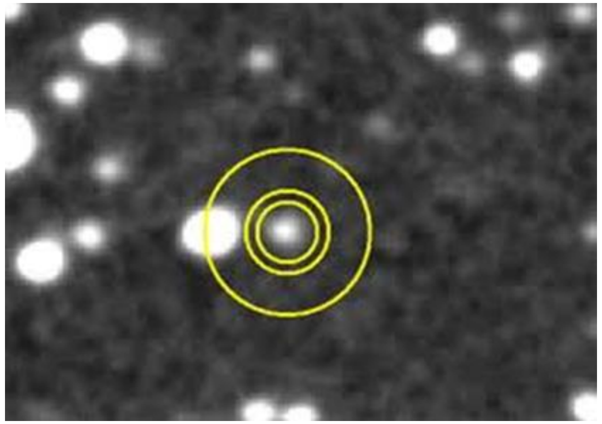
- To calculate the *Output* Signal-To-Noise Ratio of an observation we need to know the signal, and all sources of noise. These are:
  - Photon noise (shot noise) from the signal;
  - Photon noise from the sky background under the signal;
  - Photon noise from the sky background measurement to be subtracted off;
  - Readout noise from all sources;
  - Fixed pattern noise;
  - Bias noise;
  - Dark current noise.

Physical limitations on the precision of photometric measurements (2)

- Detective quantum efficiency= DQE $=[\frac{SNR_{out}}{SNR_{in}}]^2$
- We observe a star on a CCD detector, and process the data in the simplest way possible.
- $Reduced\ Frame = \frac{Object\ Frame - Bias\ Frame}{Flat\ Frame - Bias\ Frame}$

Physical limitations on the precision of photometric measurements (3)





The upper is good, the bottom is bad

- An area centred on the star is defined to be the object area, and is large enough to contain all of the photons from that star.
- An equal area some distance away, which is found to be free of stars, is defined as the sky background area, and the sky background is measured from that.

Aperture photometry (1)

- There are a number of parameters we need to take into account to calculate the signal which reaches the detector:
  - **t** – exposure time
  - **D** – diameter of the telescope
  - S_{sky} [photons / (cm^2 arcsec^2 second)] – brightness of the sky
  - **η** – quantum efficiency of a detector (QE)
  - φ_* [photons / (cm^2 second Å)] – the source flux to be measured
  - Star is observed in a circular aperture of area **β** square arcseconds which covers n_{pix} pixels
  - Sky background is determined from a circular aperture of the same size
  - Readout noise is σ_R electrons
  - We observe a star of magnitude V in the V filter

!

Signal calculation (1)

- We start from the number of photons incident upon the top of the atmosphere of the Earth from this star:

$$N_{*}=\phi_{*}\,\Delta\lambda\,A \text{ photons/second}$$

incident upon the top of the atmosphere in photometric (clear) conditions

$\Delta\lambda$ is the filter passband in Å
φ_{*} is the flux from a star in photons $s^{-1}cm^{-2}$ Å^{-1}
A is the telescope collecting area in centimetres^2

Signal calculation (2)

- That's at the top of the atmosphere. There are a number of efficiency factors we need to multiply by to calculate the signal which reaches the detector:
  - Atmospheric transmission ε_{atm} (~0.88 for a star at the zenith, in the V filter).
  - Telescope reflection efficiency ε_{tel}
    (~0.92 per mirror = 0.846 for a Cassegrain telescope)
  - Filter transmission ε_{filt} (~0.85 for a broadband filter)
  - CCD Responsive Quantum Efficiency η (~0.75)
  - Cryostat entrance window efficiency ε_{win} (~0.95)

Signal calculation (3)

- There is also a geometric efficiency factor as part of the aperture of the telescope is blocked by the secondary mirror.

  For a ***D*** metre aperture telescope with a ***d*** metre secondary mirror:

$$\varepsilon_{\mathrm{geom}} = \frac{\pi D^2 - \pi d^2}{\pi D^2} = \frac{D^2 - d^2}{D^2}$$

For example, if ***D***=2.0m and ***d***=0.6m, then $\varepsilon = 0.91$

Signal calculation (4)

- For a star the number of photons which is detected is given by:

$$N_{star} = \eta\ \varepsilon_{atm}\ \varepsilon_{tel}\ \varepsilon_{filt}\ \varepsilon_{win}\ \varepsilon_{geom}\ \phi_{*}\ \Delta\lambda\ A\ t$$

t is the exposure time in seconds,

$\Delta\lambda$ = 870 Å for the V band.

For example, for a star of magnitude V=23 on a 2 metre telescope with the efficiencies we have quoted:

$$N_{star} = 2.5\ t$$

Signal calculation (5)

- In the absence of sky background and readout noise it would be simple, we would integrate for 1000 seconds, detect 2500 photons, and have a signal to noise ratio of 50. But sky and readout noise are significant.
- Every square arcsecond of sky gives:

$$N_{sky} = \eta\ \varepsilon_{atm}\ \varepsilon_{tel}\ \varepsilon_{filt}\ \varepsilon_{win}\ \varepsilon_{geom}\ \phi_{sky}\ \Delta\lambda\ A\ t$$

φ_{sky} is the flux from the sky in photons $s^{-1}cm^{-2}\,\text{Å}^{-1}arcsec^{-1}$

$\approx$10 t photons from the dark sky ($V\approx21.5$)