



OBSERVATIONAL ASTRONOMY

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Lecture 10

Vitaly Neustroev

Magnitude systems

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

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

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- 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

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- 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: $F_\lambda dv \equiv F_\lambda d\lambda$ when averaged over the **V** filter, or at the effective wavelength of the **V** filter, $\lambda_{\text{eff}} = 5480 \text{ \AA}$. Based on the work of Oke (1974), then

$$m_v = -2.5 \log F_v - (48.585 \pm 0.005)$$

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

Photometry: AB system

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- 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:

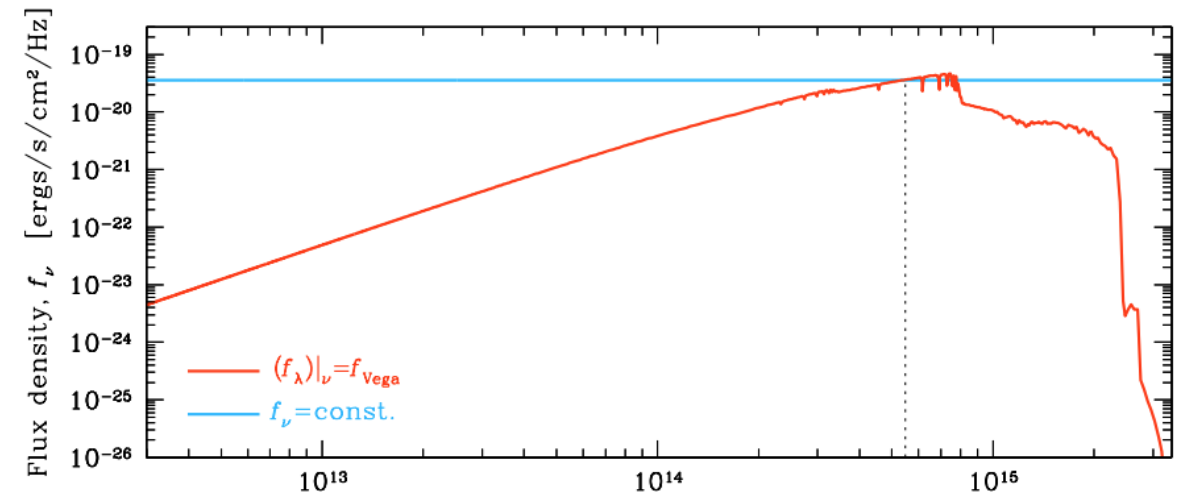
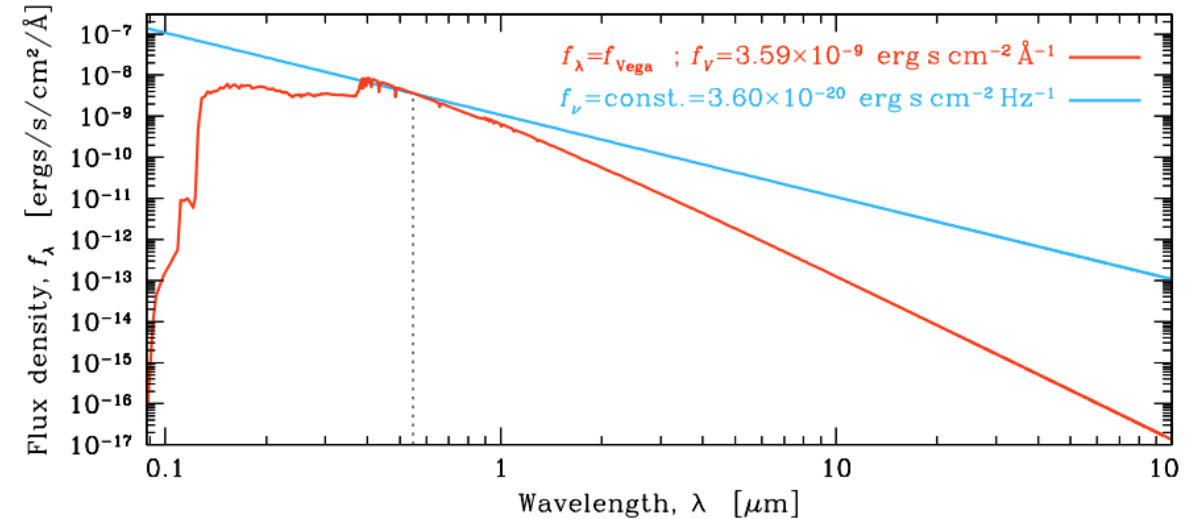
$$F_\nu [\text{ergs s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}] = 10^{-8} \frac{\lambda [\text{\AA}]^2}{c [\text{cm s}^{-1}]} F_\lambda [\text{ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}]$$

- 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

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- 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

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The ST magnitude system is defined such that an object with constant flux $F_\lambda = 3.63 \times 10^{-9} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ 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

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- **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: $BC = m_{\text{bol}} - V$
- 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 $M_{\text{bol}}=0$ has luminosity $L_0=3.0128 \times 10^{28}$ W.
 - ▣ The zero point of the apparent bolometric magnitude scale ($m_{\text{bol}}=0$) corresponds to irradiance $F_{\text{bol}} = 2.518 \times 10^{-8}$ W m⁻². The zero points were chosen so that the nominal **solar** luminosity (3.828×10^{26} W) corresponds to $M_{\text{bol}}(\text{Sun}) = 4.74$.
 - ▣ The nominal total solar irradiance (1361 W m⁻²) corresponds approximately to apparent bolometric magnitude $m_{\text{bol}}(\text{Sun}) = -26.832$.

Standard Stars for Photometry (1)

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- 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)

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- 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)

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- **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)

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- 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)

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- 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:

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

Colour excess and Interstellar absorption

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- 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:

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

where λ is in nanometers

Photometry

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- 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

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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	λ_c (Å)	f_{v0}	$f_{\lambda 0}$	$zp(f_\lambda)$	$zp(f_v)$
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

$$f_\lambda \text{ (} 10^{-11} \text{ erg s}^{-1} \text{cm}^{-2} \text{ Å}^{-1} \text{)}$$

$$\text{mag}_\lambda = -2.5 \log(f_\lambda) - 21.100 - zp(f_\lambda)$$

$$f_v \text{ (} 10^{-20} \text{ erg s}^{-1} \text{cm}^{-2} \text{ Hz}^{-1} = 1000 \text{ Jy)}$$

$$\text{mag}_v = -2.5 \log(f_v) - 48.585 - zp(f_v)$$

Photometry: Fun with Units (1)

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- **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)

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- 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:

- $\text{erg s}^{-1}\text{cm}^{-2} \text{\AA}^{-1}$

- $\text{erg s}^{-1}\text{cm}^{-2} \text{Hz}^{-1}$

- $1 \text{ Jansky [Jy]} = 10^{-26} \text{ W m}^{-2} \text{Hz}^{-1} = 10^{-23} \text{ erg s}^{-1}\text{cm}^{-2} \text{Hz}^{-1}$

$$F_{\nu} [\text{Jy}] = 3.34 \times 10^4 \lambda^2 F_{\lambda} [\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}]$$

$$F_{\lambda} [\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}] = 3.00 \times 10^{-5} \lambda^{-2} F_{\nu} [\text{Jy}]$$

Photometry: Fun with Units (3)

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- Fluxes for a $V = 0$ star of spectral type A0 V at $5450 \text{ \AA}$:
 - $f_{\lambda}^0 = 3.63 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$, or
 - $\varphi_{\lambda}^0 = f_{\lambda}^0 / h\nu = 996 \text{ photons s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$
- Useful:
 - $1 \text{ Jy} = 1.51 \times 10^3 / \lambda \text{ photons s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$
 - $\Delta\lambda / \lambda = 0.15 \text{ (U), } 0.22 \text{ (B), } 0.16 \text{ (V), } 0.23 \text{ (R), } 0.19 \text{ (I)}$

Night Sky Brightnesses

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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/arcsecond².