ASTR 535 : Observational Techniques

Light, magnitudes, and the signal equation

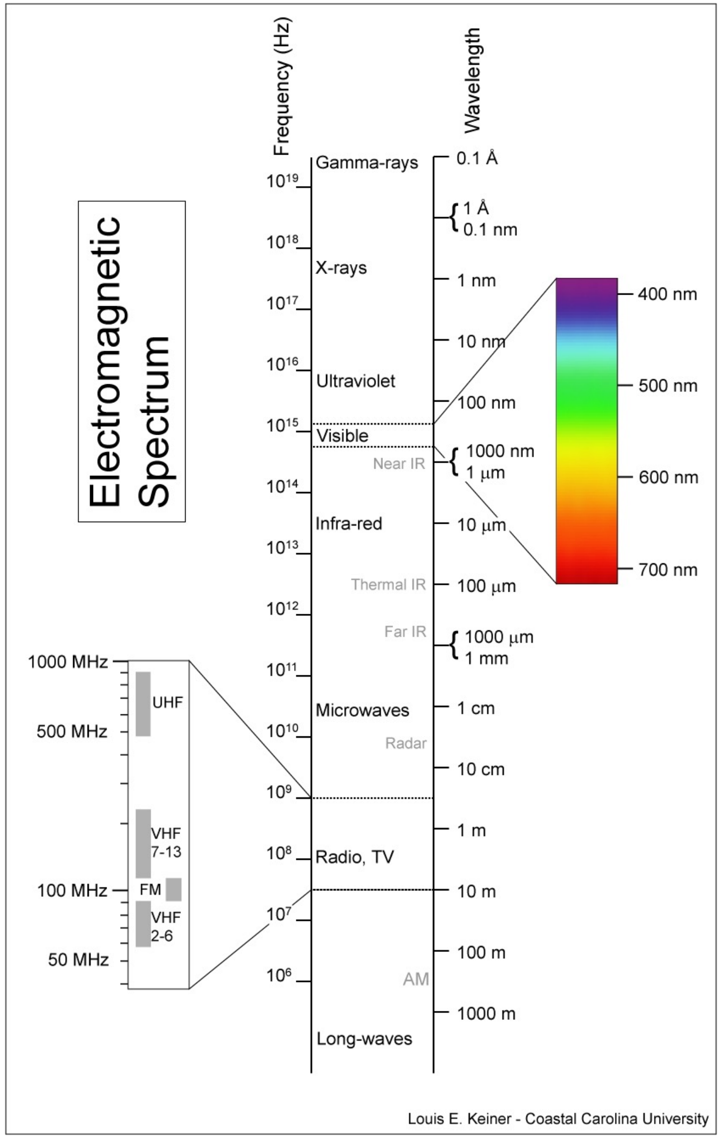
Light and its measured quantities

Learning objectives

- Know the basic characteristics of light: energy, frequency and wavelength, and how they are related. Know the different regimes in the electromagnetic spectrum, the units used to characterize the different regimes, and characteristic wavelengths for each regime.
- Have a complete understanding of the difference between surface brightness, flux, and luminosity and their units.
- Recognize and understand that flux (or surface brightness or luminosity) is generally a function of wavelength/frequency and can be specified per unit wavelength or per unit frequency and how to convert between the two.

Light and the electromagnetic spectrum

- Light is a type of energy: electromagnetic energy
- Comes in packets called photons, which have characteristics of both particles and waves
- Covers a wide range of energies, making up the electromagnetic spectrum
- Different parts of the spectrum have different names: gamma rays, X rays, ultraviolet, optical (VIBGYOR), infrared, microwave, radio



Energy, frequency, wavelength, and speed

The energy of a photon is directly related to its frequency (cycles/s)

$$E = h\nu$$

As with any wave, the frequency, wavelength and speed are related by

$$v = \lambda\nu$$

Light in a vacuum travels at the same speed, c, regardless of energy, so

$$\lambda = c / \nu$$

In a medium, light travels slower, so the wavelength changes

$$\lambda = c / n\nu$$

where n is the index of refraction.

Units

- Light can be characterized by energy, frequency, or wavelength
- At high energies, astronomers often use energy (MeV or keV)
- At lower energies, astronomers often use wavelength, but with different units:

  Angstroms = 10^{-10} m

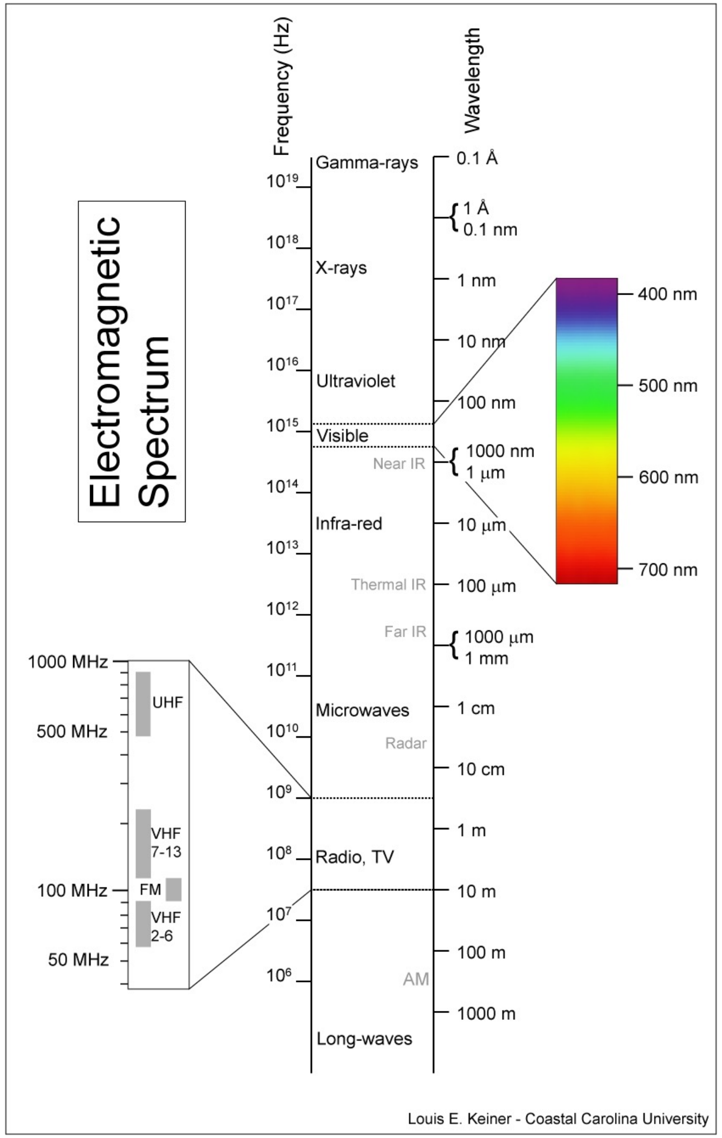
  nanometer = 10^{-9} m

  microns = 10^{-6} m

  millimeters = 10^{-3} m

  centimeters = 10^{-2} m

  - far-UV (0.01 - 0.1μ, 10-100 nm, 100-1000 Å)
  - near-UV (.1 - 0.35μ, 100-350 nm, 1000-3500 Å)
  - optical (0.35 - 1μ, 350-1000 nm, 3500-10000 Å)
  - near-IR (1000-10000 nm, 10000-100000 Å, 1 - 10μ)
  - mid-IR (10 - 100μ)
  - far-IR (100 - 1000μ)
- In the radio, astronomers may use cm or m, or frequency (MHz)



Measuring light

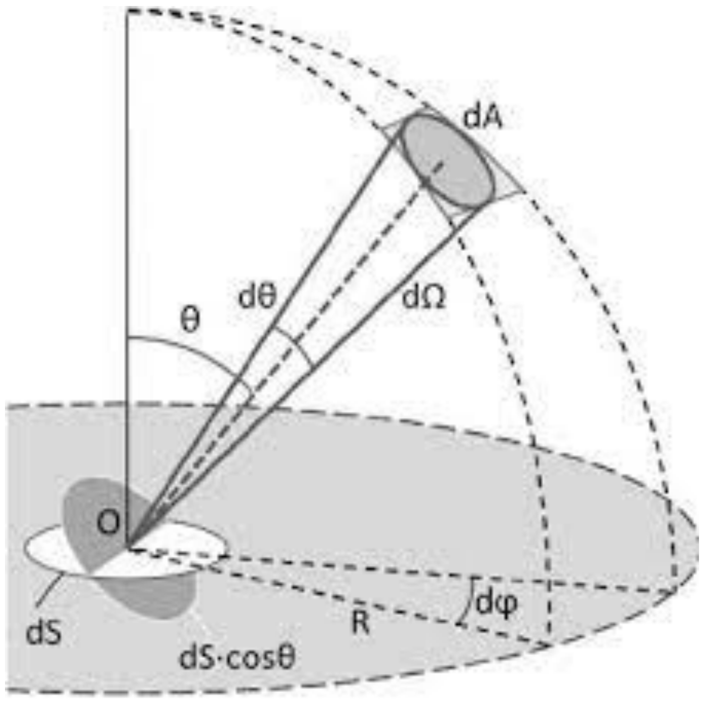
- Three fundamental quantities:

    intensity or surface brightness (radiance)

    flux (irradiance)

    luminosity (radiant flux)

Surface brightness



- the amount of energy received in a unit surface element per unit time from a unit solid angle in the direction (ϑ, φ), where ϑ is the angle away from the normal to the detector surface element, and φ the azimuthal angle.
- The solid angle is related to the physical size of an object and its distance: $\Omega = A/d^2$. Note units often used for solid angle:
  - sterradian : 4π in a sphere
  - square degree : $4\pi\ (180/\pi)^2 \approx 41253$ square degrees in a sphere
  - square arcsec

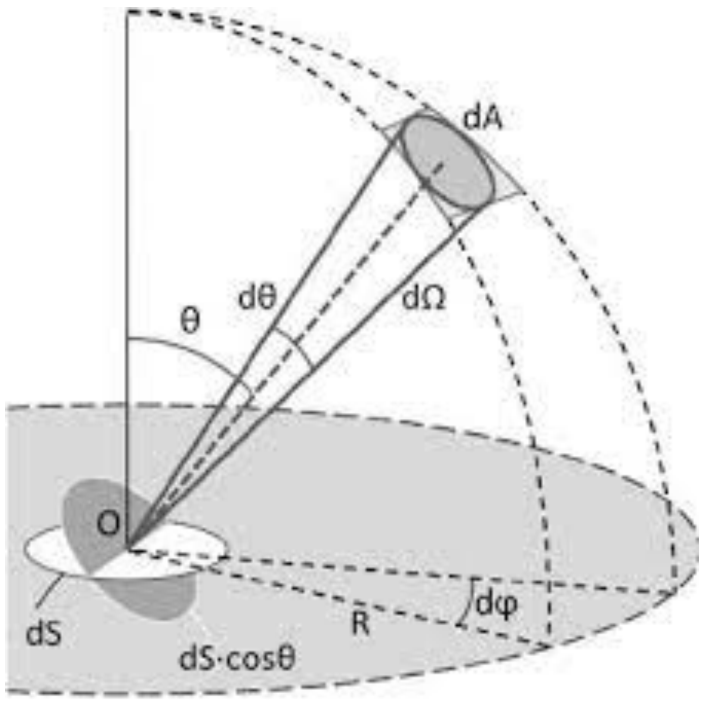
Flux

- The flux is the amount of energy passing through a unit surface element in all directions, defined by

$$F_\nu = \int I_\nu \cos\vartheta \, d\Omega$$

where $d\Omega$ is the solid angle element, and the integration is over the entire solid angle subtended by the object

In astronomical applications, we usually point our telescope in the direction of the object, so $\vartheta=0$, and the area we integrate over is small, so $\cos\vartheta$ is well approximated by unity



Luminosity

- The luminosity is the *intrinsic* energy emitted by the source per second. For an isotropically emitting source:

$$L = 4\pi d^2 F$$

where *d* is the distance to the source

- For a isotropic, constant source, this leads to the inverse square law:

$$F = L / 4\pi d^2$$

What do we observe?

- Many objects in astronomy are very far away, so they subtend relatively small areas on the sky
- Resolved sources are those for which we can distinguish one location in the source from another.
  - Our ability to distinguish depends on the tool we are using to observe
  - For resolved source, we can observe the surface brightness
- Unresolved sources are those for which we cannot distinguish one location in the source from another: the sources appear “point-like”
  - For unresolved sources, we can only observe the flux
- To determine the luminosity of a source, we must know the distance

Monochromatic flux

The amount of light emitted is generally a function of wavelength (or, alternatively, frequency), so we actually are often interested in estimates of the *monochromatic flux/intensity/luminosity* (sometimes referred to as *flux/intensity/luminosity density*) :

F_{λ} : flux / unit wavelength

or

F_{ν} : flux / unit frequency

Monochromatic fluxes

- Since wavelength and frequency are inversely related, a fixed range in wavelength does not correspond to a fixed range in frequency, and vice versa.
  - Conversion from F_λ to F_ν depends on wavelength
- Integrating over a given range of wavelength and the corresponding range of frequency must give the same flux:

$$\int_{\lambda 1}^{\lambda 2} F_\lambda \, \mathrm{d}\lambda = -\int_{c/\lambda 2}^{c/\lambda 1} F_\nu \, \mathrm{d}\nu$$

where the – sign comes from reversing the limits (wavelength runs in opposite direction from frequency)

This implies

$$F_\lambda = F_\nu \frac{d\nu}{d\lambda} = \frac{c}{\lambda^2} F_\nu = \frac{\nu^2}{c} F_\nu$$

and

$$\lambda \, F_\lambda = \nu \, F_\nu$$

Units

- Most astronomers work in cgs units
- Sometimes F_{λ}, sometimes F_{ν}
  - Sometimes F_{ν} as a function of λ
- You may also run into the Jansky, which is a unit of monochromatic flux per unit frequency:

$$1 \text{ Jansky (Jy)} = 10^{-26} W/m^2/Hz$$

Photon flux

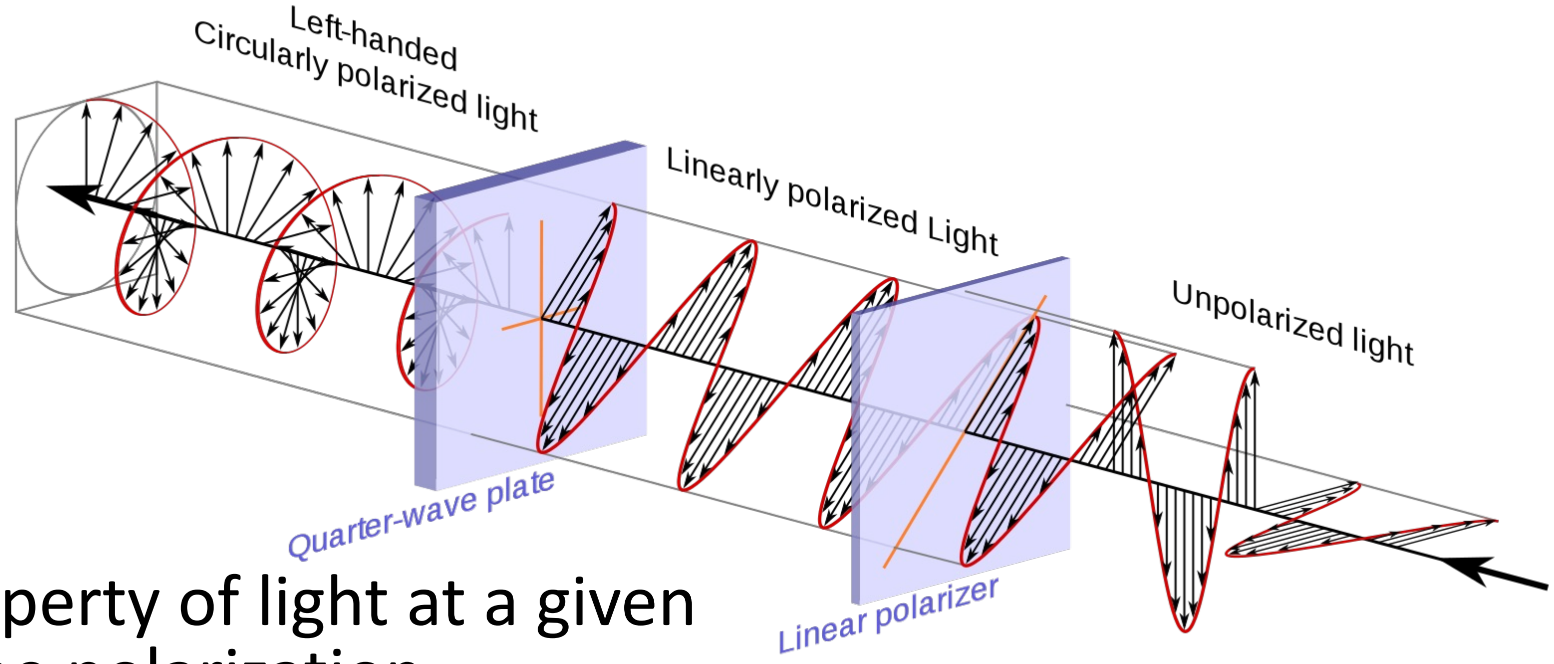
- most modern detectors count photons not energy, so we observe **photon fluxes,** which are related to energy flux by

  photon flux = energy flux / energy per photon

  $$= \int F_\lambda \frac{\lambda}{hc} \mathrm{d}\lambda$$

- Bolometers register energy, rather than photons

Polarization



- There is an additional property of light at a given wavelength/frequency: the polarization
- Light can be linearly and/or circularly polarized
- Polarization is often characterized by the Stokes parameters: I, Q, U, V

which give the intensity, two components of linear polarization, and the circular polarization

- The degree of polarization from astronomical sources is usually small, but polarization can arise from emission that is reflected or scattered light, and emission from regions where magnetic fields are significant

Terminology of astronomical measurements

- Photometry : broad-band flux measurement
- Spectroscopy: relative measurement of fluxes as a function of wavelength
- Spectrophotometry : absolute measurement of flux as a function of wavelength
- Spectropolarimetry : polarization as a function of wavelength
- Astrometry : concerned with positions of observed flux
- Morphology : intensity as a function of position; often, absolute measurements are unimportant

ASTR 535 : Observational Techniques

Light, magnitudes, and the signal equation

Magnitudes

Learning objectives

- Know how magnitudes are defined, be able to work with them very comfortably, and recognize that relative fluxes can be represented as magnitudes independent of the magnitude system.

Magnitudes

- Magnitudes have traditionally been used by astronomers to describe the amount of light from astronomical sources
- They can be used to describe fluxes, surface brightnesses, and luminosities
- Magnitudes are a dimensionless way of representing brightness, defined by:

$$m = -2.5 \log \frac{F}{F_0}$$

or:

$$F = F_0 10^{-0.4\, m}$$

where F is the flux of the object being described, and F_0 is a reference flux that defines a *photometric system*

Magnitudes and relative fluxes

- In many cases, astronomers work with relative fluxes of two objects
- Within a given photometric system, this removes the reference flux

$$m_1 - m_2 = -2.5 \log \frac{F_1}{F_2}$$

$$\frac{F_1}{F_2} = 10^{-0.4\,(m_1 - m_2)}$$

- Since magnitudes are logarithmic, differences in magnitudes correspond to flux ratios
  - Ratios of magnitudes are generally unphysical!
- Note that relative fluxes are generally much easier to measure than absolute ones

Magnitudes and relative fluxes

- Defining equation first presented by Pogson (1856)

$$m_1 - m_2 = -2.5 \log \frac{F_1}{F_2}$$

- Defined such that 5 magnitudes is a factor of 100 in brightness, and runs “backwards” (larger magnitudes are fainter)
  - Every 2.5 magnitudes is a factor of 10 in brightness
  - One magnitude is a factor of $10^{-0.4} \approx 2.512$ in brightness
- These are true within any photometric system, and do not require knowledge of F_0
  - Reference fluxes are only needed to go from magnitude to flux

Luminosities and absolute magnitudes

- Luminosities are represented by giving the magnitude that an object would have if it were located at a distance of 10 parsecs
- Using the inverse square law, this leads to the distance modulus:

$$m_0 – M = 5 \log d – 5$$

where d is the distance in parsecs and m_0 is the magnitude corrected for interstellar extinction

$$m_0 = m - A$$

Monochromatic magnitudes

- Monochromatic fluxes can also be represented in magnitudes:

$$F_\lambda = F_0(\lambda)10^{-0.4m_\lambda}$$

Note that this explicitly shows that the reference flux, $F_0(\lambda)$, may be a function of wavelength!

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Light, magnitudes, and the signal equation

Photometric systems

Photometric systems

- As discussed previously, magnitudes are defined by

$$m = -2.5 \log \frac{F}{F_0}$$

or:

$$F = F_0 10^{-0.4\, m}$$

- If we are comparing brightnesses of two objects within the same system, we don't need to know F_0, but if we want to convert from a flux to a magnitude, or vice versa, we do
- We also recognize that fluxes depend on wavelength, so

$$F_\lambda = F_0(\lambda) 10^{-0.4 m_\lambda}$$

and F_0 could depend on wavelength

Photometric systems

- You may come across three different types of photometric system zeropoints (choices of F_0)
  - STMAG : F_0 is a constant F_λ
  - ABNU : F_0 is a constant F_ν
  - VEGAMAG : F_0 has the spectral shape of an A0V star

STMAG : relative to constant F_λ

- Used by Space Telescope Science Institute
- F_0 = 3.63x10^{-9} ergs / cm^2 / s/ Å

  This is roughly the flux of Vega at 5500 A

$$m_\lambda = -2.5 \log \frac{F_\lambda}{F_0} = -2.5 \log F_\lambda - 21.1$$

(where F_λ is in units of ergs/cm^2/s/Å)

$$F_\lambda = F_0 10^{-0.4\, m_\lambda}$$

- So, Vega will have a magnitude of 0 at 5500 Å, but will deviate from zero at different wavelengths/bandpasses to the extent to which its spectrum deviates from a flat F_λ spectrum

ABNU: relative to a constant F_ν

- Used by many surveys, e.g. SDSS (ugriz), panStarrs, …
- $F_0 = 3.63\text{x}10^{-20}$ ergs / cm^2 / s/ Hz

  This is roughly the flux of Vega at 5500 Å

$$m_\nu = -2.5 \log \frac{F}{F_0} = -2.5 \log F_\nu - 48.6$$

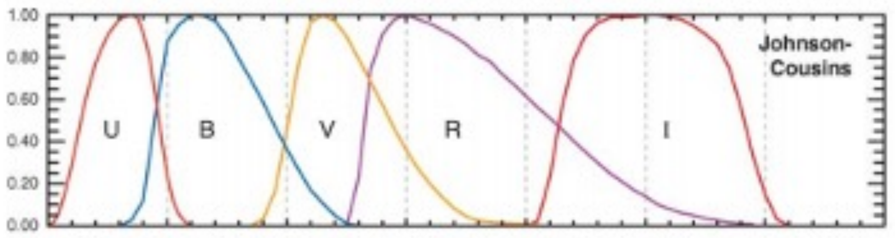
(where F_ν is in units of ergs/cm^2/s/Hz)

$$F_\nu = F_0 10^{-0.4\, m_\nu}$$

- So, Vega will have a magnitude of 0 at 5500 Å, but will deviate from zero at different wavelengths/bandpasses to the extent to which its spectrum deviates from a flat F_ν spectrum

Bandpass magnitudes vs monochromatic magnitudes

- So far we've defined monochromatic magnitudes, m_λ and m_ν
- Usually, magnitudes are used for fluxes integrated over some bandpass, i.e., photometry
- For observations in some filter bandpass $T(\lambda)$



$$m = -2.5 \log \frac{\int F_\lambda \lambda\, T(\lambda) d\lambda}{\int F_0 \lambda\, T(\lambda) d\lambda}$$

where $T(\lambda)$ gives the transmission profile of the bandpass

the extra factor of λ in there is so that the system is defined for photon flux not energy flux (the hc cancels out in numerator and denominator)

Bandpass magnitudes

$$m = -2.5\log \frac{\int F_\lambda\, \lambda\, T(\lambda) d\lambda}{\int F_0\, \lambda\, T(\lambda) d\lambda}$$

- The integrals could also be written as integrals over frequency

$$m = -2.5\log \frac{\int F_\nu/\nu\, T(\nu) d\nu}{\int F_0\, /\nu\, T(\nu) d\nu}$$

- For STMAG, F_0 is independent of λ
- For ABNU, F_0 is a constant $F_{\nu,}$ so $F_{0\lambda}$ is proportional to λ^{-2}
- Note that the magnitude will be roughly independent of the width of the filter bandpass, since the integrated flux is relative to the integrated flux of the reference system

VEGAMAG

- For VEGAMAG, the reference flux F_0 is the spectrum of the star Vega
- To translate VEGAMAG to a flux, you need to know the spectral energy distribution of Vega
- VEGAMAGs give the flux of a star relative to the flux of Vega, so, by definition, Vega has a magnitude of 0 in all bandpasses

What photometric systems are used?

- The UBVRIJHK system is a ~VEGAMAG system
- The SDSS ugriz system is a ~ABNU system
- The STScI STMAG system is a STMAG system
- Even if the bandpasses were the same, the magnitude of a star in two different systems would be different!
- All systems are normalized around 5500 A, so the difference grows as one moves away from this wavelength

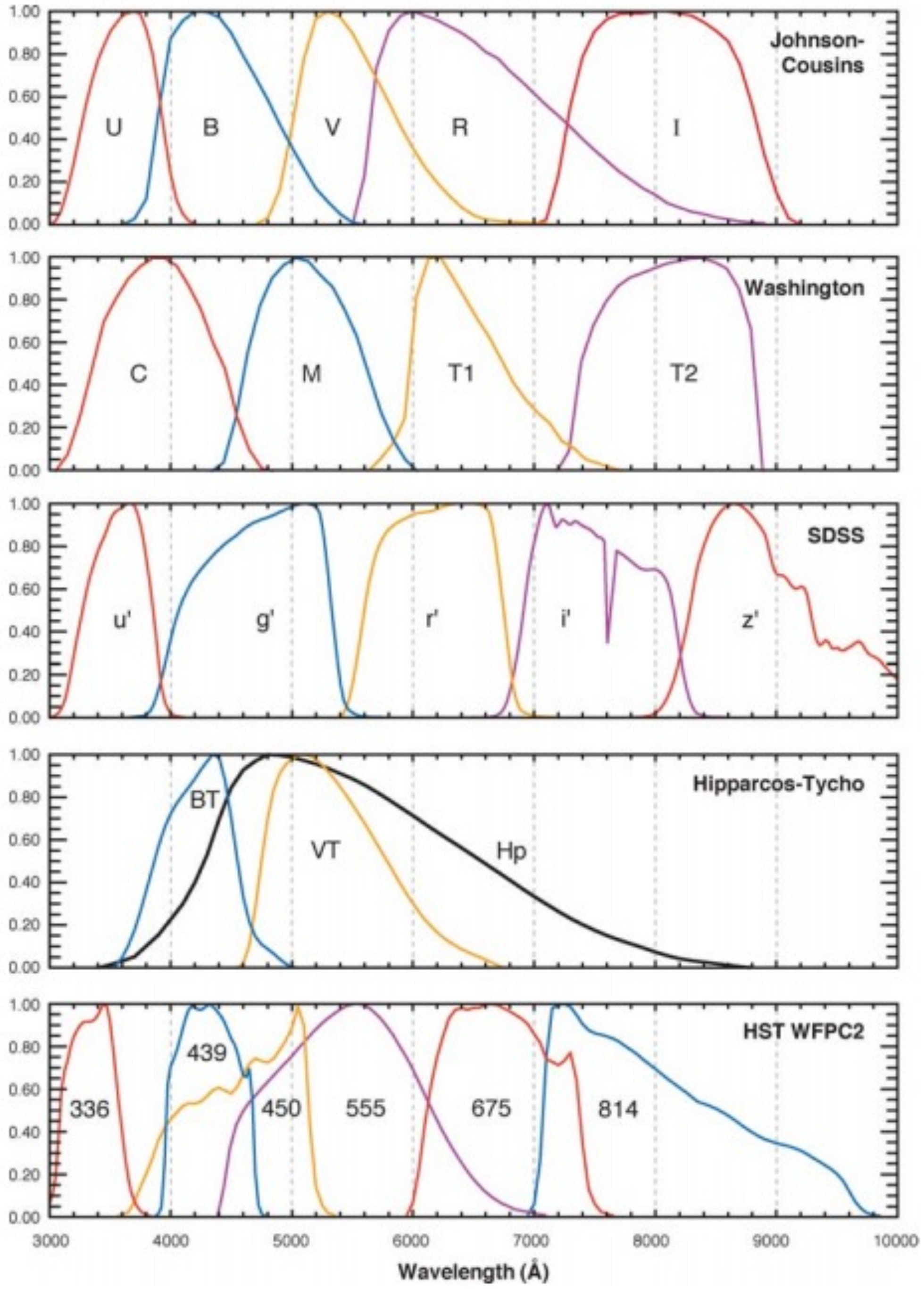
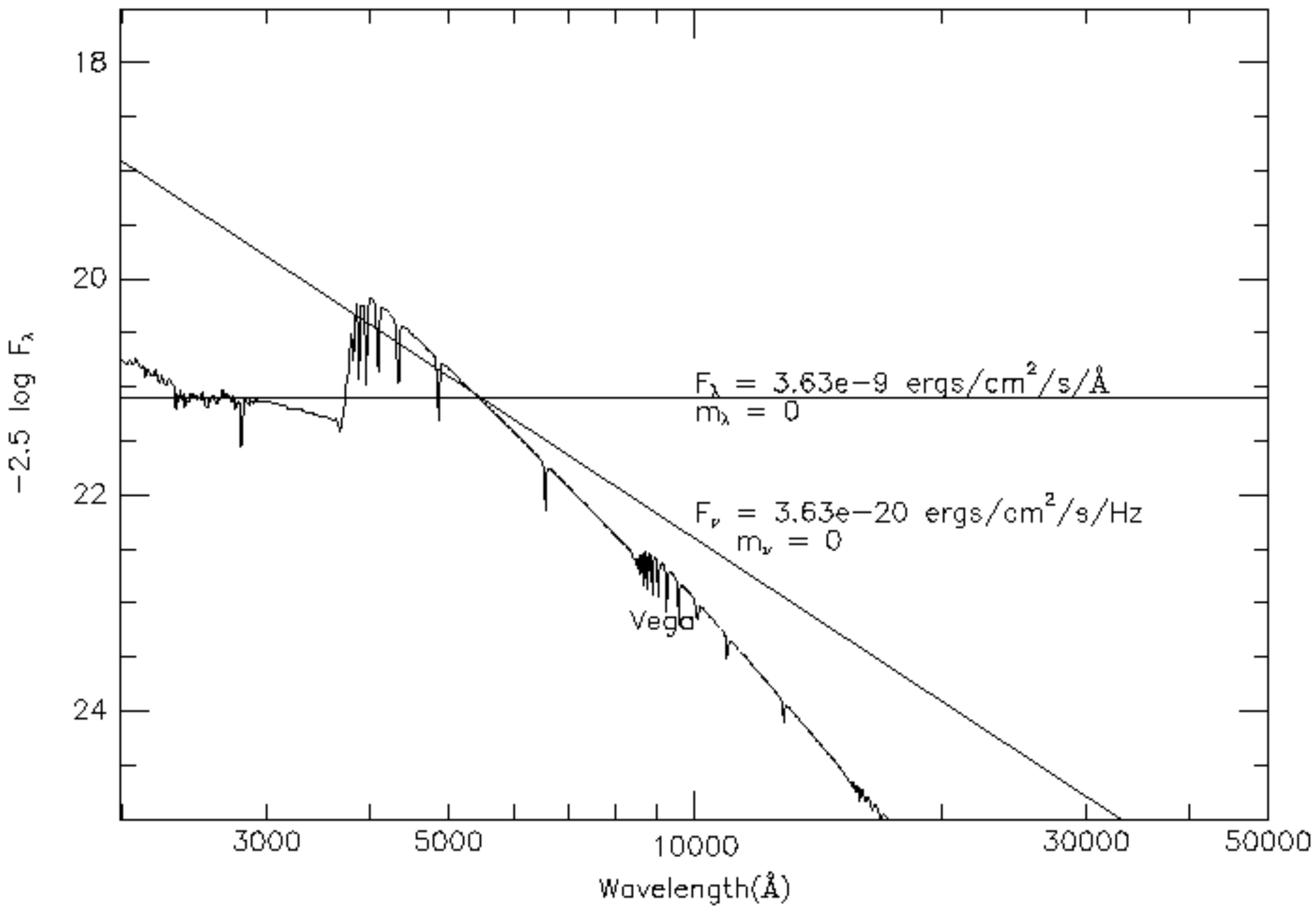


Figure 1 Schematic passbands of broad-band systems.

Differences between magnitude systems



- If you had the spectrum of an object on this plot, the difference between the location of the spectrum and one of the reference spectra would give you the magnitude of the object
- Again, usually, magnitudes are used for fluxes, i.e. integrals over a range in the spectrum

Why are there different systems?

- STMAG and ABNU are conceptually much simpler
- However, absolute fluxes are hard to measure, while relative fluxes are easier, e.g. the flux relative to Vega (or some set of stars that have been measured relative to Vega)
  - No astrophysical or artificial source has a “flat” spectrum!
- If you care about actual fluxes, you need to figure out how to do the absolute fluxes and, if you do this well, using STMAG or ABNU makes simpler physical sense

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Magnitude – flux conversion

Converting magnitudes to fluxes

- To convert from a magnitude in some bandpass to a flux in that bandpass:
    - Roughly: look up the flux of the reference spectrum at the central wavelength of the bandpass, which gives the flux for an object with m=0, and scale by the observed magnitude, to get approximate flux density at the central wavelength; multiply by the filter width to get the fluxx
    - More precisely: integrate the reference spectrum over the bandpass, and scale by the observed magnitude

Photometric system data

Vega Flux Zeropoints

Quantity	U	B	V	R	I	J	H	K	Notes and units
λ_{eff}	0.36	0.438	0.545	0.641	0.798	1.22	1.63	2.19	microns
$\Delta\lambda$	0.06	0.09	0.085	0.15	0.15	0.26	0.29	0.41	microns, UBVRI from Bessell (1990), JHK from AQ
f_ν	1.79	4.063	3.636	3.064	2.416	1.589	1.021	0.64	$x10^{-20}$ erg cm^{-2} s^{-1} Hz^{-1}, from Bessell et al. (1998)
f_λ	417.5	632	363.1	217.7	112.6	31.47	11.38	3.961	$x10^{-11}$ erg cm^{-2} s^{-1} A^{-1}, from Bessell et al. (1998)
Φ_λ	756.1	1392.6	995.5	702.0	452.0	193.1	93.3	43.6	photons cm^{-2} s^{-1} A^{-1}, calculated from above quantities

These are for the Vega magnitude system and the Bessell et al. (1998) Johnson-Cousins-Glass System.

AB Flux Zeropoints

Quantity	u	g	r	i	z	Notes and units
λ_{eff}	0.356	0.483	0.626	0.767	0.910	microns, from Fukugita et al. (1996)
$\Delta\lambda$	0.0463	0.0988	0.0955	0.1064	0.1248	microns, from Fukugita et al. (1996)
f_ν	3631	3631	3631	3.631	3631	Jy or $x10^{-23}$ erg cm^{-2} s^{-1} Hz^{-1}
f_λ	859.5	466.9	278.0	185.2	131.5	$x10^{-11}$ erg cm^{-2} s^{-1} A^{-1}, calculated from above quantities
Φ_λ	1539.3	1134.6	875.4	714.5	602.2	photons cm^{-2} s^{-1} A^{-1}, calculated from above quantities

mistake

These are for the SDSS filters on the AB system. Data from Fukugita et al. (1996) repeat their Table 1, rows 1 and 6.

Note that the AB system is defined such that a source with $F_{nu} = 3.63 \times 10^{-20}$ erg cm^{-2} s^{-1} Hz^{-1} has AB mag = 0 in every filter, and in general ABmag = - 2.5 log F_{nu} - 48.6.

ST Magnitudes

The ST magnitude system is defined such that an object with constant flux $F_{lambda} = 3.63 \times 10^{-9}$ erg cm^{-2} s^{-1} A^{-1} will have magnitude ST = 0 in every filter, and in general STmag = - 2.5 log F_{lambda} - 21.1. A fairly comprehensive list of HST filters and their zeropoints is available on the WFC3 Photometric Zeropoints page at STScI (*Thanks to Molly Peeples for sharing the link!*).

From http://www.astronomy.ohio-state.edu/~martini/usefuldata.html

Estimating flux for objects

- In some cases, e.g., for observation planning, we may want to estimate the flux we will receive in different bandpasses, or as a function of wavelength, for some object of a given magnitude in one band pass
    - Done in many exposure time calculators
    - For example, estimate the flux as a function of wavelength for an object with V=17
- Clearly, we also need some information about the spectral energy distribution (SED), e.g., a blackbody temperature, spectral type, etc.
    - Various libraries of spectra, e.g., of stars or galaxies, are available
- To get an estimate of the flux as a function of wavelength for your object:
    - Get the flux in the SED at the central wavelength of the desired bandpass
    - Get the flux in the reference spectrum for the photometric system at this wavelength
    - Scale the SED such that the flux divided by the reference flux is $10^{-0.4m}$
    - This gives you the desired flux as a function of wavelength
    - If you want the flux is some other bandpass, read it off at the effective wavelength of the desired bandpass
- To do this to higher precision, integrate over the bandpass rather that using the flux at the central wavelength

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Colors

What is a color?

- A color gives the relative amount of flux in one range of wavelength to that in another
  - Color is a ratio of fluxes
- If we use magnitudes, the ratio of fluxes corresponds to a difference in magnitudes
- However, the reference system comes into it: a color is the ratio of fluxes between two different bandpasses *relative to the same ratio in the reference flux*
- So, for example:

$$B - V = mB - mV = -2.5\log\frac{\int F_\lambda \lambda\, TB(\lambda) d\lambda}{\int F_0 \lambda\, TB(\lambda) d\lambda} + 2.5\log\frac{\int F_\lambda \lambda\, TV(\lambda) d\lambda}{\int F_0 \lambda\, TV(\lambda) d\lambda}$$

$$= -2.5\log\frac{\int F_\lambda \lambda\, TB(\lambda) d\lambda}{\int F_\lambda \lambda\, TV(\lambda) d\lambda} + 2.5\log\frac{\int F_0 \lambda\, TB(\lambda) d\lambda}{\int F_0 \lambda\, TV(\lambda) d\lambda}$$

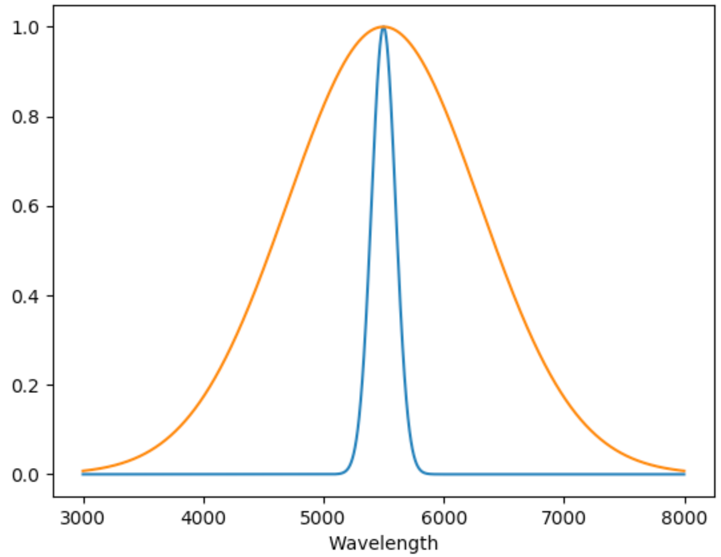
$$= -2.5\log\frac{\int F_\lambda \lambda\, TB(\lambda) d\lambda / \int F_\lambda \lambda\, TV(\lambda) d\lambda}{\int F_0 \lambda\, TB(\lambda) d\lambda / \int F_0 \lambda\, TV(\lambda) d\lambda}$$

Application

- A color in the SDSS system, e.g. g-r gives the ratio in flux between the g and r bandpasses, *relative to that ratio for an object with a flat* F_ν
  - *g-r* = 0 means the object has a spectral shape similar to that of a flat F_ν source
- A color in the UBVRI system, e.g., B-V gives the ratio in flux between the B and V bandpasses*, relative to that ratio for an object with an A0V spectrum*
  - B-V = 0 means the object has a spectral shape similar to that of an A0V star
  - B-V = 2.5 means that the object has 10 times more flux in the V bandpass than the B bandpass relative to that flux ratio in an A0V star
- Why "similar" and not the same?
  - Different spectral energy distributions could give the same total flux in a bandpass

Colors

- While it seems that one could define a color just as a ratio of fluxes without regard to a reference flux, consider the case where different bandpasses might have different widths
  - You wouldn't want a color to change if you were comparing a narrower bandpass at one wavelength to a broader one at another!



ASTR 535 : Observational Techniques

Light, magnitudes, and the signal equation

Signal equation

Learning objectives

- Understand the signal equation and the terms in it.
- Understand what the signal equation is and is not used for

What objects emit and what we observe

- We've been discussing flux, surface brightness, luminosity and the quantities used to measure them
- In an actual observation, the amount of signal we detect depends on the tools we use to collect it: e.g., the collecting area of our telescope and the amount of time we collect for
  - Photon flux is the number of photons per unit area per unit time
  - **Signal** is the number of photons from an object detected in an observation
- When making actual observations, however, we generally don't detect all of the flux that objects emit in our direction
  - Some of it may be absorbed in the Earth's atmosphere
  - It may not be fully reflected by the mirrors of a telescope
  - It may be attenuated by things we put in its path, like optics or a filter
  - Our detectors may not be perfectly efficient in detecting it

Signal equation

- The *signal equation* relates the incoming flux to the observed signal

$$\mathrm{S} = \ \mathrm{Tt} \int F_\lambda \frac{\lambda}{hc} a_\lambda m_\lambda i_\lambda f_\lambda d_\lambda \, d\lambda$$

where

T : telescope area

t : exposure time

a_λ : atmospheric transmission function

m_λ : mirrors (telescope) transmission function

i_λ : instrument transmission function

f_λ : filter transmission function

d_λ : detector response function

Note that all of the transmission/response function may be a function of wavelength

Observed photon flux, S’

Given

$$S = Tt \int F_\lambda \frac{\lambda}{hc} a_\lambda m_\lambda i_\lambda f_\lambda d_\lambda \, d\lambda$$

We can define the observed photon flux, S’:

$$S' = \int F_\lambda \frac{\lambda}{hc} a_\lambda m_\lambda i_\lambda f_\lambda d_\lambda \, d\lambda$$

$$S = S' \, T \, t$$

When we make an observation, we observe S : we don’t need to separately know S’, T, and t

Formulating things in terms of S’ is helpful to determine how our signal will scale with exposure time and/or collecting area

Using the signal equation

- We generally want to measure the flux/photon flux from the object
- However, this is **not** usually done with the signal equation
  - Many terms are hard to measure to high accuracy
  - Some terms may vary with time
- What **is** the signal equation used for?
  - Terms are generally well enough approximated to predict observed photon flux for an object with an estimated brightness

  →Exposure time calculator
  - Given an estimate for the observed photon flux, one can determine how much time is required to collect a desired **signal**
  - Accuracy of a measurement depends on the signal
  - For a required accuracy (determined by scientific goal), determine minimum exposure time to achieve the associated required signal

Other uses of the signal equation

$$S = \mathrm{Tt} \int F_\lambda \frac{\lambda}{hc} a_\lambda m_\lambda i_\lambda f_\lambda d_\lambda \, d\lambda$$

- By observing object(s) of known brightness, use signal equation to estimate the **throughput** of your observing system
  - Example: SDSS-V commissioning!
  - Might also see *effective area* of an observing system (e.g., here)
- We've mentioned that one generally doesn't go backward from observed signal to intrinsic flux using the signal equation because it is hard to know all of the terms to sufficient accuracy
  - Generally, if we want to know the intrinsic flux, we usually measure signal relative to some other object of known intrinsic flux
  - At some point, you need to measure the intrinsic flux of **some** object! For this, you work hard to understand all of the terms in the signal equation, and use it!

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Light, magnitudes, and the signal equation

Photometry

Learning objectives

- Understand the distinction between estimating count rates from an understanding of all of the terms in the signal equation vs. measuring the overall throughput (zeropoint) by observing stars of known brightness.
- Know what instrumental magnitudes and zeropoints are. Understand the ideas behind the use of transformation coefficient.

Measuring brightnesses of objects

- If we don’t use the count equation to go from observed signal to intrinsic flux, how do we do it?
- Measure brightnesses relative to some other source of known flux

Differential photometry

- If there are stars of known brightness (reference stars) in the same field as the object for which you're trying to measure the brightness, then the atmospheric term cancels out, under the approximation that the atmosphere doesn't vary over the angular distance between the two objects
  - Clearly, only true to some level of accuracy!
  - Can work even if the weather is *"non-photometric",* i.e., there are clouds
- Determine ratio of program object signal to reference star signal and multiply reference star flux by that ratio to get program object flux
- In magnitudes, get the magnitude difference corresponding to the signal ratio

Differential photometry in practice: simple case

- Measure the signal of an object in the frame with known brightness/magnitude (reference star)
- Determine *instrumental magnitude*

$$m = -2.5 \log S/t$$

  - sometimes people might not normalize by t
  - Sometimes people might add some arbitrary constant, e.g. 25, to make instrumental magnitude positive
- Given known magnitude of the reference star, determine *instrumental zeropoint*

$$M = m + Z$$

- Determine instrumental magnitude of target object
- Add instrumental zeropoint to get calibrated magnitude!

Instrumental Zeropoint

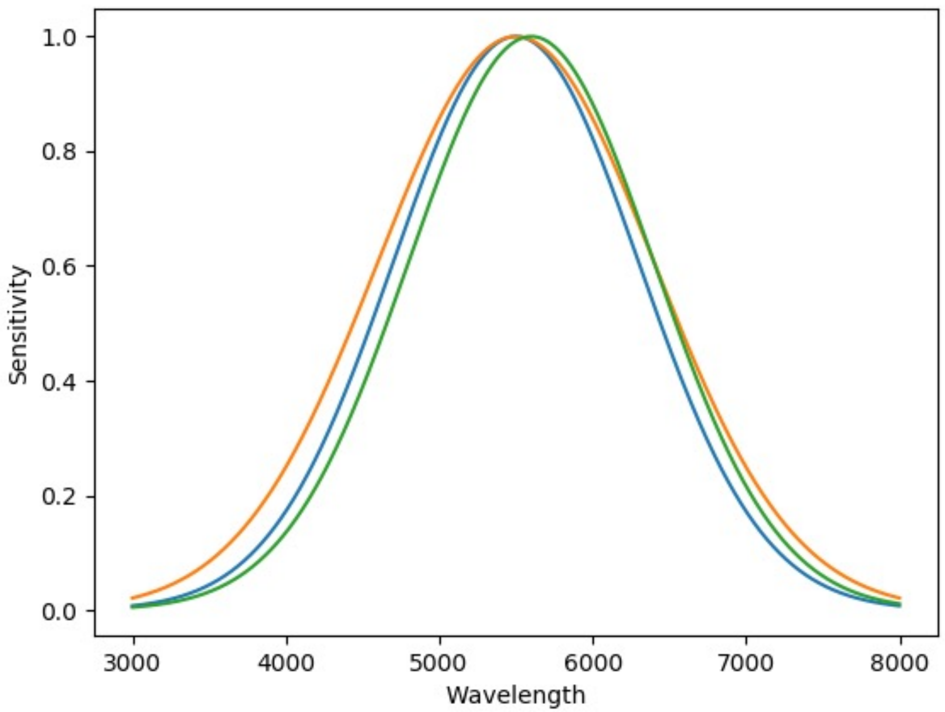
$$M = m + Z$$

where lower case m is the instrumental magnitude and upper case M is the standard magnitude of the reference object (don't confuse this with absolute magnitude!)

- Instrumental zeropoint gives the sensitivity of the system
- It is the magnitude of a star that would have an instrumental magnitude ($-2.5 \log S/t$) of 0, i.e. a star that produces 1 photon per second
- The larger the zeropoint, the more sensitive the system

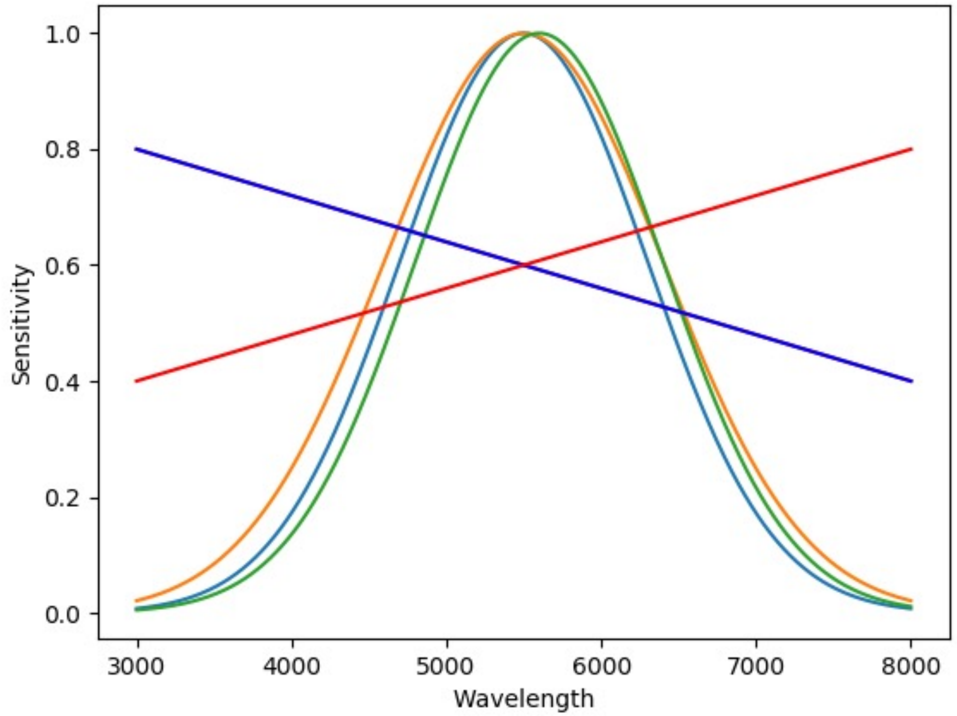
Real world issue: filter/sensitivity variation

- The simple prescription works exactly only if the wavelength dependence of your observing sensitivity matches that of the system in which the reference star brightness was measured
- In practice, there are small differences, e.g., from variations in filter profiles, detector sensitivities, etc.



Accounting for sensitivity differences

- To zeroth order, this doesn’t matter: you collect a little more or less light, at a slightly different range of wavelength
- However, consider two different objects that measure, that might have different spectral energy distributions (SEDs), i.e., a bluer object and a redder object
- If your sensitivity is a little bit ”redder”, you’ll get more extra signal in the red star than in the blue star
- In practice, you’ll measure a different zeropoint, i.e., a different sensitivity, for the blue star and the red star



Transformation coefficients

- Can calibrate this out to first order by using a *transformation coefficient*, parameterizing the difference in SED by the color of the object

$$M = m + t\,\mathit{color} + Z$$

- As previously discussed, the color in magnitudes is given by a difference in magnitudes in two different bandpasses. Since we want to measure the color in the region of the spectrum where our desired filter is, usually the color is taken between the observed filter and one at an adjacent wavelength, e.g., if you’re working in the V bandpass, you might use B-V, or V-R as the color

Multi-bandpass photometry

- If you're observing in multiple bandpasses, e.g., if you want to be measuring colors of your object, there is a separate transformation equation for each filter, e.g.

$$B = b + t_B\,(B\text{-}V) + Z_B$$

$$V = v + t_V\,(B\text{-}V) + Z_V$$

$$R = r + t_R\,(V\text{-}R) + Z_R$$

with a separate transformation coefficient and zeropoint for each filter

These are derived by observing multiple reference stars, where the reference stars must span a range of color; generally, this is done using a least squares fit, e.g., m-M as a function of color

Multi-bandpass photometry

Once you've determined the transformation coefficients and zeropoints from the reference stars, you apply them to get the standard magnitudes for the target object(s)

$$B = b + t_B\,(B\text{-}V) + Z_B$$

$$V = v + t_V\,(B\text{-}V) + Z_V$$

Note that we've defined the transformation term using the standard magnitude, not the instrumental one

This is fine even if you don't know that for your target object(s), so long as you have instrumental magnitudes in each filter, it's just a matter of linear algebra to simultaneously solve for the two standard magnitudes (two equations with two unknowns).

Subtleties

- Transformation coefficients parameterize spectral energy distributions as a function of colors
- However, it is possible for two objects to have different SEDs but still have the same color
- Transformation coefficients work to the extent that the SEDs of the program objects are similar to those of the reference (standard) objects
- The larger the differences in program SED to standard SED, the larger the potential systematic errors
- The more different the response function is from the standard response function, the larger the potential systematic errors

Simple differential photometry

- Before we leave differential photometry, note that in some applications, you may not even care about zeropoints or transformation coefficients!
- This is often the case when studying *variability* of objects, where the science comes from the change of flux, without necessarily needing to know what the flux is

All-sky photometry

- What if you don't have reference stars with known magnitude in the same field as observations of your program object?
- Need to compare with reference stars in other observations
- Now, atmospheric effects don't cancel out! Need to account for different atmospheric absorption in different directions
  - As we'll discuss, this can be characterized as a function of *airmass* : how thick the column of atmosphere is in a given direction
  - That only works if conditions are "photometric"