ASTR 535 Lecture Notes

Jon Holtzman

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course website: http://astronomy.nmsu.edu/holtz/a535

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Properties of light, magnitudes, errors, and error analysis

Light

Wavelength regimes:

- gamma rays
- x-rays
- ultraviolent (UV)
  - near: 900–3500 Å
  - far: 100–900 Å

  The 900 Å break is because of the Lyman limit at 912 Å. This is where neutral hydrogen is ionized, so the universe is largely opaque to wavelengths shorter than this.
- visual (V): 4000–7000 Å (note that 'V' is different from 'optical', which is slightly broader: 3500–10000 Å. The 3500 Å cutoff is due to the Earth's atmosphere being opaque to wavelengths shorter than this).
- IR
  - near: 1–5 μ (1–10 μ in online notes)
  - mid: (10–100 μ)
  - far: 5–100 μ (100–1000 μ)
- sub-mm 500–1000 μ
- microwave
- radio

Quantities of light:

- Intensity $I(\theta, \phi)$ [erg s^{-1} Ω^{-1} ν^{-1}] Encapsulates *direction* light is coming from. Also known as radiance.

- Surface Brightness (SB) [erg s^{-1} cm^{-2} ν^{-1} sterradian^{-1}] amount of energy *received* in a unit surface element per unit time per unit frequency (or wavelength) from a unit solid angle in the direction (θ, ϕ), where θ is the angle away from the normal to the surface element, and ϕ is the azimuthal angle. SB is independent of distance unless considering cosmological scales, where the curvature of spacetime has an effect.

- Flux (F): amount of energy passing through a unit surface element in all directions, defined by

$$F_\nu = \int I_\nu \cos(\theta) \mathrm{d}\Omega \tag{1}$$

  where dΩ is the solid angle element, and the integration is over the entire solid angle. The $\cos(\theta)$ factor is important for, e.g., ISM where light is coming from all directions, but for tiny objects, θ is negligibally small and can be dropped. Integrates over *all* directions. Also known as irradiance.

- Luminosity (L): [erg s^{-1}] *intrinsic* energy emitted by the source per second ($\sim$ power). For an isotropically emitting source,

$$L = 4\pi d^2 F \tag{2}$$

  where d = distance to source. Also known as radiant flux.

What to measure for sources:

- Resolved: directly measure surface brightness (intensity) distribution on the sky, usually over some bandpass or wavelength interval.

- Unresolved: measure the flux. Diffraction is the reason stellar surfaces cannot be resolved. Because of this, we cannot measure SB, so we measure flux, integrated over the entire object.

Note that Luminosity can only be calculated if the distance is known.

Questions:

- What are the dimensions of the three quantities: luminosity, surface brightness (intensity), and flux?

- How do the three quantities depend on distance to the source?

- To what quantity is apparent magnitude of a star related?

- To what quantity is the absolute magnitude related?

Amount of light emitted is a function of wavelength, so we are often interested in e.g. flux per unit wavelength or frequency, also known as *specific* flux. Using $\lambda = \frac{c}{\nu} \rightarrow \frac{\mathrm{d}\lambda}{\mathrm{d}\nu} = \frac{-c}{\nu^2}$

$$\begin{aligned}
\int F_\nu \mathrm{d}\nu &= \int F_\lambda \mathrm{d}\lambda \\
F_\nu \mathrm{d}\nu &= F_\lambda \mathrm{d}\lambda \\
F_\nu &= F_\lambda \frac{\mathrm{d}\lambda}{\mathrm{d}\nu} \\
&= -F_\lambda \frac{c}{\nu^2} \\
&= -F_\lambda \frac{\lambda^2}{c}
\end{aligned}$$

Note that a constant F_λ implies a *non*-constant F_ν and vice versa. Depending on where you are, a constant chunk of 1 Hz is not the same wavelength range, depending on where you are.

Units: often cgs, magnitudes, Jansky (a flux density unit corresponding to 10^{-26} W m^{-2} Hz^{-1})

There are often variations in terminology

Terminology of measurements:

- photometry (broad-band flux measurement) SB or flux, integrated over some wavelength range.
- spectroscopy (relative measurement of fluxes at different wavelengths) $f(\lambda)$
- Spectrophotometry (absolute measuremnet of fluxes at different wavelengths) $f(\lambda)$
- astrometry: concerned with positions of observed flux, not brightness, but direction.
- morphology: intensity as a function of position; often, absolute measurements are unimportant. Deals with *resolved* objects, intensity as function of position.

Generally, measure *flux* with photometry, and flux *density* with spectroscopy (down to the resolution of the spectrograph). In practice, with most detectors, we measure photon flux [photons cm^{-2} s^{-1}] with a photon counting device, rather than energy flux (which is done with bolometers). The monochromatic photon flux is given by the energy flux (F_λ) divided by the energy per photon ($E_{photon} = \frac{hc}{\lambda}$), or

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

Magnitudes and photometric systems

Magnitudes are related to flux (and SB and L) by:

$$m_1 - m_2 = -2.5 \log \frac{b_1}{b_2}$$

or for a single object:

$$\begin{aligned} m &= -2.5 \log \frac{F}{F_0} \\ &= -2.5 \log F + 2.5 \log F_0 \end{aligned}$$

where the coefficient of proportionality, F_0, depends on the definition of photometric system; the quantity $-2.5 \log F_0$ may be referred to as the photometric system zeropoint. Note that this relationship holds regardless of what photometric system you are using. Inverting, one gets:

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

Just as fluxes can be represented in magnitude units, flux densities can be specified by monochromatic magnitudes:

$$F_\lambda = F_0(\lambda) \times 10^{-0.4\mathrm{m}(\lambda)}$$

although spectra are more often given in flux units than in magnitude units. Note that it is possible that F_0 is a function of wavelength.

Since magnitudes are logarithmic, the $difference$ between magnitudes corresponds to a ratio of fluxes; ratios of magnitudes are generally unphysical. If one is just doing relative measurements of brightness between objects, this can be done without knowledge of F_0 (or, equivalently, the system zeropoint); objects that differ in brightness by ΔM have the same ratio of brightness ($10^{-0.4\Delta M}$) regardless of what photometric system they are in. The photometric system definitions and zeropoints are only needed when converting between calibrated magnitudes and fluxes. Note that this means that if one references the brightness of one object relative to that of another, a magnitude system can be set up relative the brightness of the reference source. However, the utility of a system when doing astrophysics generally requires an understanding of the actual fluxes.

Monday, January 25

There are three main types of magnitude systems in use in astronomy. We start by describing the two simpler ones: the STMAG and the ABNU mag system. In these simple systems, the reference flux is just a constant value in F_λ or F_ν. However, these are not always the most widely used systems in astronomy, because no natural source exists with a flat spectrum.

The STMAG (Space Telescope Mag) is relative to a source of constant F_λ. In this system, $F_{0,\lambda} = 3.60 \times 10^{-9}$ erg cm^{-2} s^{-1} Å^{-1}, which is the flux of Vega at 5500 Å; hence a star of Vega's brightness at 5500 Å is defined to have m=0. Alternatively, we can write

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

for F_λ in cgs units.

In the ABNU system, things are defined relative to a source of constant F_ν and we have

$$F_{0,\nu} = 3.63 \times 10^{-20} erg\ s^{-1}\ cm^{-2}\ Hz^{-1}\ 10^{-0.4\mathrm{m}_\nu}$$

or

$$m_{ABNU} = -2.5 \log F_{nu} - 48.6$$

for F_ν in cgs units. Again, the constant comes from the flux of Vega.

Magnitudes usually refer to the flux integrated over a spectral bandpass. In this case, F and F_0 refer to fluxes integrated over the bandpass. The STMAG and ABMAG integrated systems are defined relative to sources of constant F_λ and F_ν systems, respectively.

$$m_{STMAG} = -2.5 \log \frac{\int F_\lambda \lambda \mathrm{d}\lambda}{\int 3.6 \times 10^{-9} \lambda \mathrm{d}\lambda}$$
$$m_{ABNU} = -2.5 \log \frac{\int F_\nu / \nu \mathrm{d}\nu}{\int 3.6 \times 10^{-20} / \nu \mathrm{d}\nu}$$

These should have the same value at 5500 Å. The factors of λ and ν come from the conversion factor hc/λ, where the constants, h and c, cancel out in the fractions in each equation.

Note that these systems differ by more than a constant, because one is defined by units of F_λ and the other by F_ν, so the difference betwen the systems is a function of wavelength. They are defined to be the same at 5500 Å. (Question: what's the relations between m_{STMAG} and m_{ABNU}?)

Note also that, using magnitudes, the measured magnitude is nearly independent of bandpass width, so a broader bandpass does not imply a brighter (smaller) magnitude, which is not the case for fluxes. The reference is being integrated as well, so they cancel.

The standard UBVRI broadband photometric system, as well as several other magnitude systems, however, are not defined for a constant (flat) F_λ or F_ν spectrum; rather, they are defined relative to the spectrum of an A0V star. Most systems are defined (or at least were originally) to have the magnitude of Vega be zero in all bandpasses (VEGAMAGS); if you ever get into this in detail, note that this is not exactly true for the UBVRI system.

For the broadband UBVRI system, we have

$$m_{UBVRI} \approx -2.5 \log \frac{\int_{UBVRI} F_\lambda(object) \lambda \mathrm{d}\lambda}{\int_{UBVRI} F_\lambda(Vega) \lambda \mathrm{d}\lambda}$$

(as above, the factor of λ comes in for photon counting detectors). This gives the magnitude in U, B, V, R, *or* I, by integrating over that same bandpass. The UBVRI filter set had overlapping bandpasses, so there was a switch to interference filter: the ugriz system used by SDSS (explained below... I think).

Here is a plot to demonstrate the difference between the different systems.

While it seems that STMAG and ABNU systems are more straightforward, in practice it is difficult to measure absolute fluxes, and much easier to measure relative fluxes between objects. Hence, historically observations were tied to observations of Vega (or to stars which themselves were tied to Vega), so VEGAMAGs made sense, and the issue of determining physical fluxes boiled down to measuring the physical flux of Vega. Today, in some cases, it may be more accurate to measure the absolute throughput of an instrumental system, and using STMAG or ABNU makes more sense.

Colors

Working in magnitudes, the difference in magnitudes between different bandpasses (called the color index, or simply, color) is related to the flux ratio between the bandpasses, i.e., the color. In the UBVRI system, the *difference between magnitudes*, e.g. B-V, gives the ratio of the fluxes in different bandpasses *relative to the ratio of the fluxes of an A0V star in the different bandpasses (for VEGAMAG)*. Note the typical colors of astronomical objects, which are different for the different photometric systems.

A stars have color 0, have same SED as Vega. *O* stars have color less than 0, while coolor stars have color greater than 0. In sloan system, have g-r (ugriz). g-r=0 indicates constant F_ν.

$$m = -2.5 \log \frac{\int_B F_\lambda \mathrm{d}\lambda}{\int_V F_\lambda \mathrm{d}\lambda}$$

Which is closer to the UBVRI system, STMAG or ABNU?
What would typical colors be in a STMAG or ABNU system?

Wednesday, January 27

UBVRI magnitudes-flux conversion

To convert Vega-based magnitudes to fluxes, look up the flux of Vega at the center of the passband

Observed fluxes and the count equation

Errors in photon rates

Noise equation: how do we predict expected errors?

Error propagation

Determining sample parameters: averaging measurements

Random errors vs systematic errors