ASTR 535 Lecture Notes

Jon Holtzman

Spring 2016

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

Friday, January 22

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} $\mathrm{sterradian}^{-1}$] 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 $\mathrm{d}\Omega$ 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 $\lambda = \frac{c}{\nu} \rightarrow \frac{d\lambda}{d\nu} = \frac{-c}{\nu^2}$

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

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:

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

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. 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.

In the STMAG 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 for F_ν instead of F_λ, and we have

$$F_{0,\nu} = 3.63$$

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