XIV. Photometry [v1.3.4]

A. Overview

- The starting point of nearly all observational inquiry in Astronomy is photometry
  - Establishes the existence of an object
  - Establishes the flux of a given object
  - Establishes (often crudely) the object's spectral energy distribution (SED)
  - Gives the first clues to the object's origin/nature
- High-precision photometry is an art (and science)
  - Obtaining high quality imaging is only the start
  - Calibration is challenging
  - Aperture choice is often subjective
- Variability abounds
  - Do not presume your object has a constant flux
  - Many phenomena change on days to year timescales
  - This includes the location of the source!
- References

B. Luminosity (L)

- The physical quantity of Photometry
  - Describes the energetics of the phenomenon
  - Direct insight into the mechanism(s) that power it
- Bolometric luminosity
  - Total energy emitted per unit time
  - erg/s
  - Example: An idealized star (black body) with radius R

$$L = \sigma T^4 \, 4\pi R^2 \tag{1}$$

  - A few known sources
    - Sun: $L_\odot = 3.9 \times 10^{33}$ erg/s
    - M87 galaxy: $L_{\rm M87} \approx 10^{43}$ erg/s
    - 3C273 (quasar): $L \approx 10^{45}$ erg/s
    - GRB: $L \approx 10^{53}$ erg/s [if isotropic!]
- Specific luminosity
  - Energy emitted per unit time per unit energy interval
    - L_λ: erg/s/Å
    - L_ν: erg/s/Hz

    - ▲ Equivalence: $L_\nu d\nu = L_\lambda d\lambda$
  - ◇ The specific luminosity is often the only quantity we can measure (not Bolometric)

C. Flux

- One of the fundamental observables of astronomy
  - ◇ We observe only a portion of the Luminosity emitted by a source
  - ◇ Proportional to the area of our telescope
  - ◇ cm^{-2}
- Bolometric flux f_B
  - ◇ Almost never measure f_B for a continuum source (i.e. something emitting at a wide range of frequencies)
  - ◇ May be reported for an emission line
- Specific flux f_λ (or f_ν)
  - ◇ Standard result of spectroscopic observations
  - ◇ Also what one measures in a filtered image
    - ▲ e.g. R-band refers to flux at $\lambda \approx 6000$Å
    - ▲ The measurement is truly a convolution of f_λ of the source with the transmission of the filter T_λ
- Converting to Luminosity (Local universe)
  - ◇ Simple, isotropic source at a physical distance r

$$f_B = \frac{L_B}{4\pi r^2} \qquad f_\lambda = \frac{L_\lambda}{4\pi r^2} \tag{2}$$

  - ◇ Anisotropic source at a physical distance r
    - ▲ Photons are not uniformly emitted
    - ▲ Define $f(\theta)$ and integrate over the sky

$$L = r^2 \int f(\theta) d\Omega \tag{3}$$

- Cosmological distance ($r \gg 1\,\mathrm{Mpc}$)
  - ◇ Expansion of the Universe matters!
    - ▲ Sets the distance
    - ▲ And redshifts the photons!

$$\lambda_{\mathrm{observed}} = (1+z)\lambda_{\mathrm{emitted}} \tag{4}$$

  - ◇ Introduce the luminosity distance D_L
    - ▲ It is set by the cosmology of the universe
    - ▲ And the redshift of the source

- ▲ It is defined to evaluate the Bolometric luminosity:

$$L_B = f_B \, 4\pi D_L^2 \tag{5}$$

- ▲ It may be calculated by integrating the inverse of Hubble's expansion parameter

$$D_L(z) = c\,(1+z) \int_0^z \frac{1}{H(z')} dz' \tag{6}$$

- ◇ D_L may also be used for the Specific luminosity:

$$L_\nu = \frac{f_\nu \, 4\pi D_L^2}{1+z} \tag{7}$$

- ▲ Extra $(1+z)$ factor is for the energy interval in L_ν

- Subtleties of the r^{-2} law
  - ◇ For essentially all astronomical sources, they are far enough away to treat as a point source
  - ◇ Can ignore the fact that one part of the object may be closer to us than another

D. Magnitudes

- A painful, astronomer-driven approach to expressing fluxes and luminosities
  - ◇ Driven by our eyeballs (logarithmic sensitivity)
  - ◇ Perhaps a little more convenient
    - ▲ $f_\lambda = 2.7 \times 10^{-16}$ erg/s/Å at 5000Å vs $m_V = 18\,\mathrm{mag}$
  - ◇ Warning: Smaller magnitudes means brighter sources
- AB magnitudes (the most physical)
  - ◇ Apparent (i.e. observed flux)
    - ▲ Specific flux (defined at a specific frequency or wavelength)

$$m_{AB} = -2.5 \log_{10}(f_\nu) - 48.6 \tag{8}$$

    - ▲ Inverting

$$f_\nu = 10^{-0.4(m_{AB}+48.6)} \;\; (\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}) \tag{9}$$

  - ◇ Absolute: Value one would measure *if* the source were at 10 pc
- Color
  - ◇ Simple difference of any two magnitudes
    - ▲ This means a ratio of two fluxes
    - ▲ Relative energy output at two frequencies
  - ◇ Useful for describing the spectral shape of the source
    - ▲ Is it a blackbody?

- ▲ Or a power-law?
- ▲ Or some combination?
- ◇ Convention is to subtract the redder band from the bluer
  - ▲ e.g. $m_U - m_B$
  - ▲ e.g. $m_8 - m_{24}$
  - ▲ Positive values imply a red source

- Vega magnitudes
  - ◇ Traditional system for magnitudes
  - ◇ Defined so that the star Vega has a value of $m = 0$ at all wavelengths!

$$m_{Vega} = -2.5 \log_{10} \left[\frac{\int f_\lambda^{Source} T_\lambda d\lambda}{\int f_\lambda^{Vega} T_\lambda d\lambda} \right] \tag{10}$$

  - ◇ In the visual band ($V; \lambda \approx 5000$Å), $m_{AB}(V) = m_{\text{Vega}}(V)$

- Instrumental magnitudes
  - ◇ It is common to convert the measured counts (or electrons) of a source (per second) into a magnitude

$$m_I = -2.5 \log_{10} N \tag{11}$$

  - ◇ This gives the relative fluxes for objects in your image

- Zeropoint (ZP) magnitude
  - ◇ m_{ZP}
  - ◇ AB Magnitude of a source that would give one count per second for your experimental design
    - ▲ Derived from calibration stars
    - ▲ Provides the conversion from instrumental magnitudes to physical fluxes

$$m_{AB} = m_I + m_{ZP} \tag{12}$$

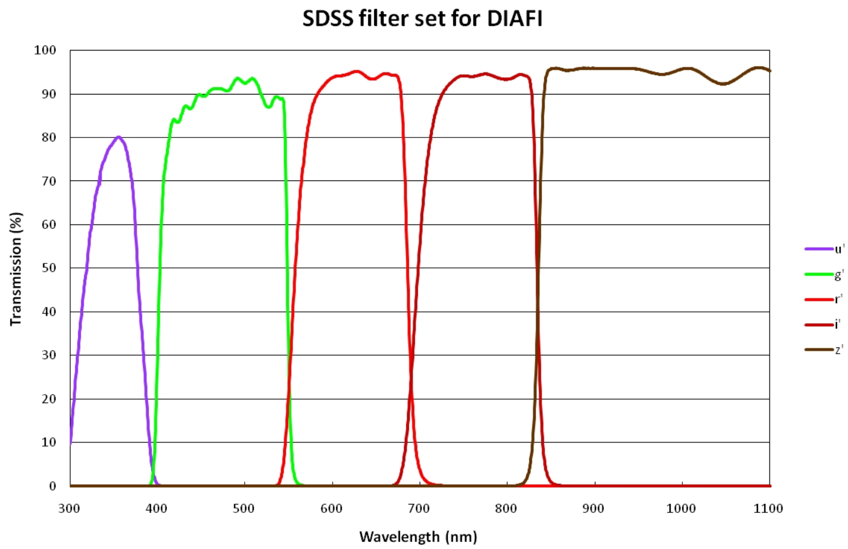
- Errors
  - ◇ Poisson error in the counts gives a Poisson error in the flux
  - ◇ Other sources of error will contribute
    - ▲ Error from sky background
    - ▲ Detector noise
    - ▲ Zeropoint (calibration) error
  - ◇ Simple propagation of error

$$\sigma^2(m) = [2.5 \ln(10)]^2 \frac{\sigma^2(N)}{N_{\text{source}}^2} \tag{13}$$

$$\sigma^2(N) = N_{\text{source}} + N_{\text{sky}} + \sigma_{detector}^2 \tag{14}$$

E. Filters

- Photometry is almost always performed through a custom-made filter
  - ◇ Designed to isolate a specific range of wavelengths (energies)
  - ◇ Even without one, the observed light will be limited to a modest range of energy
    - ▲ Telescope, atmosphere, detector, coatings impose an effective passband
- Characteristics of the filter
  - ◇ Transmission curve: T_λ
    - ▲ Percentage of light that the filter transmits



  - ◇ Passband: FWHM or $\Delta\lambda$
    - ▲ Approximate width of the filter (in Angstroms)
    - ▲ Usually defined as the range where $T_\lambda = max(T_\lambda)/2$
  - ◇ Effective wavelength: λ_{eff}
    - ▲ Approximately the central wavelength of the passband
    - ▲ More formally

$$\lambda_{\text{eff}} = \frac{\int T_\lambda d\lambda}{\int d\lambda} \tag{15}$$

- Filter Flux
  - ◇ A source observed through a filter will give a specific flux that is modulated by T_λ
  - ◇ Explicitly, for an R-band filter:

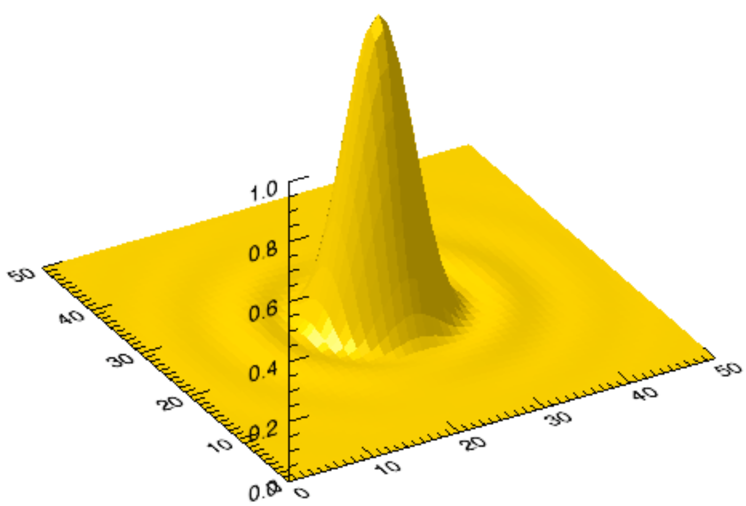
$$f_R = \frac{\int f_\lambda^{Source} T_\lambda^R d\lambda}{\int T_\lambda^R d\lambda} \tag{16}$$

  - ◇ Therefore, this specific flux corresponds to an average over a small range of wavelengths

- Standard filter sets
  - ◇ Kron-Cousins: $UBVRI$
  - ◇ SDSS: $ugriz$
  - ◇ Washington
  - ◇ Near-IR: JHK
  - ◇ Bessel
- Fabricating filters
  - ◇ Transmissive (broad-band)
  - ◇ Reflective (narrow-band)

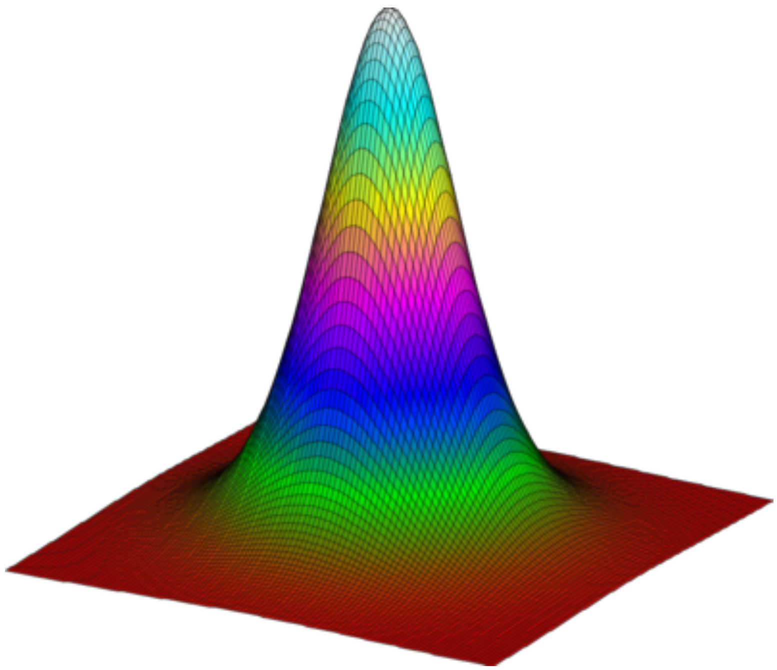
F. Point Spread Function (PSF)

- Definition
  - ◇ Observed distribution of light for an expected, infinitely small source
  - ◇ a.k.a. a point source
  - ◇ Includes the effects of telescope, camera, atmosphere, and detector
- Telescope PSF
  - ◇ Diffraction limits the spatial resolution of the image
  - ◇ Ideal: Airy function with size $\theta = \lambda/D$
  - ◇ Design of primary and secondary (if there is one) affect the image quality
  - ◇ Aberrations



- Camera optics
  - ◇ Additional lenses further affect the image quality
  - ◇ Generally improve it by reducing aberrations
- Detector PSF
  - ◇ Finite pixel size discretizes the image

  - ◇ Generally a minor issue if the pixels are sufficiently small
- Atmospheric PSF
  - ◇ Blurring of the image by scintillation in the atmosphere (Seeing)
    - ▲ Gaussian process (roughly)
    - ▲ Characterized by a FWHM (in arcseconds)
    - ▲ Yields a Moffat profile when convolved with the Airy function



- For well-designed telescopes + cameras, the atmospheric effects dominate
  - ◇ Of course, not true for space satellites
  - ◇ Nor for Adaptive Optics (AO) systems

G. Aperture Photometry

- Formally, the light from any object is smeared out across the entire detector
  - ◇ And beyond!
  - ◇ Never can measure all of the photons
  - ◇ In practice, the wings of the PSF usually fall off exponentially
- Simplest approach: Define an angular aperture and measure the flux within it
  - ◇ Choose a large enough aperture to mitigate seeing
  - ◇ Choose a large enough aperture to capture most of the light ($> 90\%$)
- Trade-offs
  - ◇ Want to avoid neighboring objects
  - ◇ Larger aperture means more noise from the detector and the sky
- Standard aperture

- ◇ Several arcsecond, circular aperture
- ◇ Fixed for all (small) objects in the image

H. Isophotal Photometry

- Many sources are extended
  - ◇ One to many arcseconds
  - ◇ Assymetric morphology
- Isophotes
  - ◇ Series of contours, of constant surface brightness, that trace the light profile
  - ◇ Often ellipsoids fitted to the data
- Isophotal photometry
  - ◇ Measure the flux within the isophotal contours
  - ◇ Maximizes the signal to noise over a simple circular contour
  - ◇ Allows one to estimate the amount of light beyond the measurement
    - ▲ Extrapolation!
    - ▲ Always a dangerous business

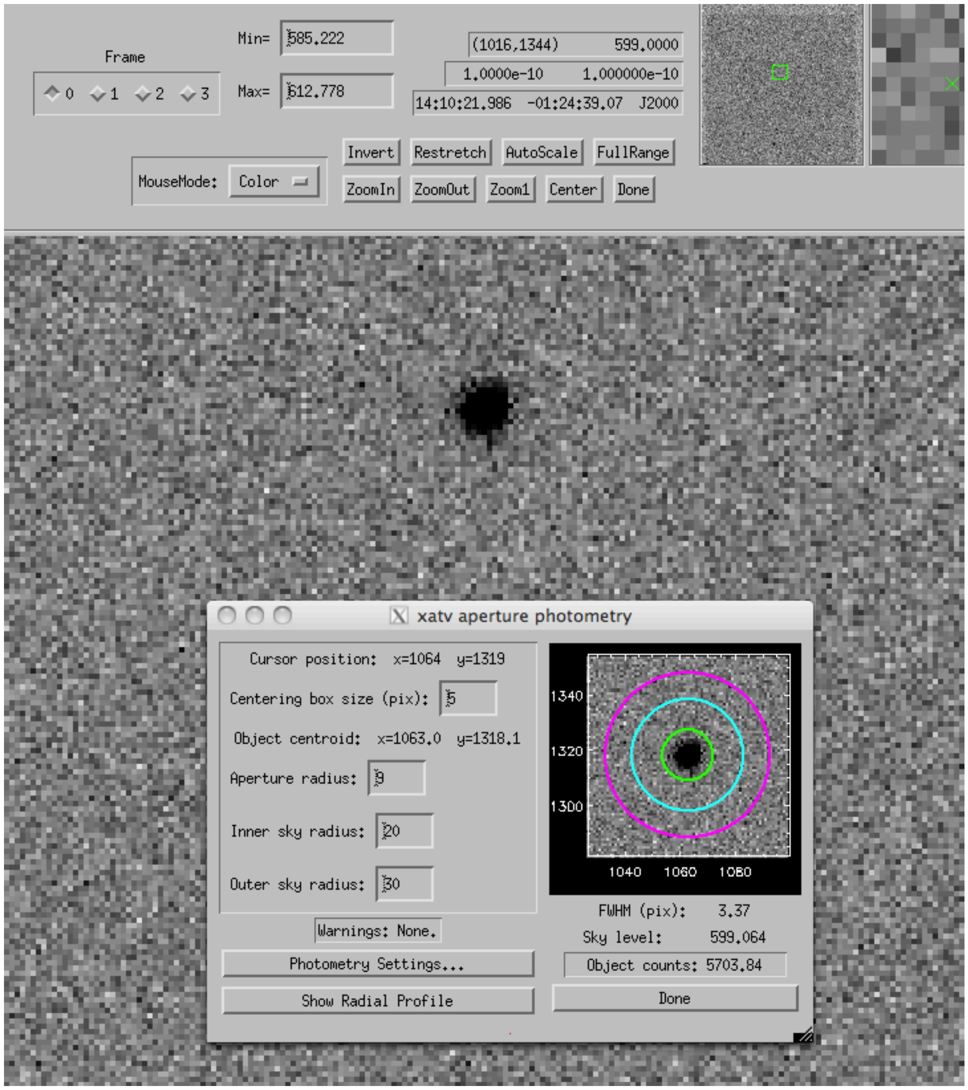
I. Surface Brightness (μ)

- Often, one chooses to characterize the light emitted from portions of an extended source
  - ◇ e.g., the brightness of a galaxy bulge vs. its disk
  - ◇ e.g., the brightness of a nebula as a function of position
- Definition
  - ◇ Flux per unit area
  - ◇ Typically defined in angular area (e.g., one square arcsecond: $\square''$)
  - ◇ Almost always a Specific flux
    - ▲ Usually expressed in magnitudes
    - ▲ e.g. $\mu_R = 26\,\mathrm{mag}/\square''$

J. Background Subtraction

- The observed flux in any aperture includes (at least) two terms
  - ◇ Source
  - ◇ Sky backgrounds
  - ◇ (This assumes you have removed signatures of the detector!)
- Scientifically, we are usually only interested in the Source
  - ◇ Need to assess the sky background
  - ◇ And then remove (subtract) it!

- "Sky Pixels"
  - ◇ Most images have pixels with sources and pixels without
    - ▲ Of course, the regions without obvious sources may still contain faint sources that are below our detection limit
    - ▲ These contribute to our sky background estimate
  - ◇ We refer to pixels from the non-source regions as Sky Pixels
    - ▲ These are used to estimate the sky background
- Assessing the sky background: Off-source
  (a) Take a series of exposures off the field
  (b) Assume the off-source field has a similar sky background
  (c) Measure the level (or generate a sky image)
  (d) Subtract
- Assessing the sky background: Global
  - ◇ Preferred approach for images of very large sources
  - ◇ Crudest method: Take the mode of the full image
    - ▲ Restricting to sky pixels
    - ▲ This is a simple, but relatively stable approach
  - ◇ More careful: Fit a 2D surface to the sky pixels
    - ▲ One always observes spatial variations in the sky background
      - ∘ Some of these are physical (in the sky)
      - ∘ Some of these are due to camera optics
      - ∘ Some of these are due to the detector
    - ▲ Mitigated by fitting a spatially varying function for the sky level
- Assessing the sky background: Local
  - ◇ Idea: Measure the sky background using sky pixels very close to your source
    - ▲ Minimizes the spatial variations noted above
    - ▲ Much simpler than fitting 2D models
    - ▲ This is the preferred approach for small, faint sources
  - ◇ Methodology
    - ▲ Measure the sky background flux around the source
      - ∘ i.e. in an annulus large enough to have good statistics
      - ∘ Use median/mode statistics to ignore outliers
    - ▲ Subtract



K. Calibration

- How do we convert the detected electrons into flux units?
- Idealized
  - ◇ Calculate the efficiency η of our system and proceed
  - ◇ ie., following the *Signal-to-Noise* Lecture

$$f_\lambda = \frac{S_\lambda}{\eta_\lambda t} \frac{h\nu}{A_{\rm eff}} \tag{17}$$

- Complications with idealized approach
  - ◇ Very difficult to measure η from first-principles
  - ◇ Instrument/telescope evolve in time
    - ▲ e.g. Mirror coatings degrade
    - ▲ e.g. Detector may degrade

- ◇ Clouds change the transparency of the sky
- ◇ Atmosphere isn't stable either

- Empirical
  - ◇ Observe a source with a known flux
    - ▲ Using your identical system (telescope, camera, filter, etc.)
    - ▲ On the same night
    - ▲ Ideally, near your source (spatially and temporally)
  - ◇ Analyze to determine η_λ
    - ▲ a.k.a. the zeropoint magnitude (m_{ZP})
- Standard approach
  - ◇ Image a standard star field
  - ◇ "Landolt" is the standard reference
    - ▲ Decades of careful observation
    - ▲ But only in a limited set of filters
    - ▲ Note: He uses 7″ circular apertures!
  - ◇ Make a relative measurement:

$$\frac{f_{\mathrm{object}}}{N_{\mathrm{object}}} = \frac{f_{\mathrm{standard}}}{N_{\mathrm{standard}}} \tag{18}$$

- Catalogs
  - ◇ A growing portion of the sky has been imaged at high precision
  - ◇ These are being calibrated
  - ◇ Examples:
    - ▲ SDSS
    - ▲ 2Mass
    - ▲ USNO (not preferred)
    - ▲ PanStarrs
- Single sources
  - ◇ Some energies have very few calibrated sources
  - ◇ Limited to observing this handful of objects
  - ◇ Examples
    - ▲ Crab Nebula (high energies)
    - ▲ Quasars (radio sources)
- Calibration Issues (1st order effects)
  - ◇ Color terms
    - ▲ The standard sources each have their own spectrum f_λ^S
    - ▲ Because T_λ of the filters is complex, two sources with identical f_λ at $\lambda = 5000$Å will give different f_V

  - ○ This is true for galaxies vs. individual stars
  - ○ And even more true for peculiar objects like quasars
- ▲ Typically, one applies color corrections to account for the differences between the Source and the calibration stars

◇ Airmass

- ▲ As discussed in the *Atmosphere* Lecture, the extinction by the atmosphere is significant [$I = I_0 \exp(-\tau)$]
  - ○ And, wavelength dependent
  - ○ And, it scales with the Zenith Angle (ZA)
  - ○ And, it can vary from night to night!
- ▲ Approach: measure it empirically on a given night by observing standard stars at a range of AM