Steps to Photometry

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Step 1: The Photon Path
Spectrum of Vega
Scattering & Absorption by the Earth’s Atmosphere

![Graph showing atmospheric transmission vs wavelength](image-url)
Mirror Reflectivity

![Mirror Reflectivity Graph](image-url)

Reflectivity vs. Wavelength (μm)
Filter Transmission
Detector Efficiency
\[
\int_{v_1}^{v} \frac{\eta_v F_v}{h \nu} d\nu = 5.88 \times 10^{10} \, \gamma \, s^{-1} \, \text{cm}^{-2}
\]
Step 2: Systematic Errors

- Imaging detectors suffer from a number of errors that must be corrected before the data can be used for photometry.
- Goal is to make the DNs from the FITS files proportional to the brightness of the astronomical source.
Bias & Dark Current

• Even a zero second exposure gives non-zero DN
  – Dark current masquerades as real signal
  – Bias & dark current can be subtracted either by
    1. Take a dark frame of the same exposure time as the science image—takes care of bias too, or
    2. Take an image of blank sky—takes care of bias, dark & can be used to subtract the sky brightness! (can be hard to find blank sky)
Flat Field

- Every pixel in the detector array has a slightly different response to light
  - Some pixels are more efficient than others
- Need to correct for pixel-to-pixel variations by constructing a flat field
  - Make a flat field by observing a uniform source, e.g., the twilight sky
  - *Divide dark-subtracted images by the flat field*
Photometry

• The light from a star is spread over several pixels
• How do we sum the light to get a measure of the total signal from the star?
  1. Identify the location of the star (RDPIX)
  2. Select the associated pixels by making a mask
  3. Sum up the light (TOTAL)
     – Subtract the sky background if necessary
$R = \sqrt{x^2 + y^2}$
\[ R = \sqrt{(X - X_0)^2 + (Y - Y_0)^2} \]
Step 3: Modeling the Noise

- What is the SNR of a given observation?
- How do I choose and optimize the photometric parameters
  - Exposure time required?
  - Aperture diameter?
  - Location and size of sky annuli?
How to Begin

• Write down an expression for the signal and use error propagation to find the noise
  – Express results as signal-to-noise ratio vs. photometric parameters
The Model

- The purpose is to *estimate* the noise contributions
  - Often getting the answer to within a factor of two is fine
  - Make simplifying assumptions—so long as you can justify them
A Photometric Model

• What parameters describe the measurement?
A Photometric Model

- **Star**
  - Brightness
  - Center \((x_0, y_0)\)
  - Width \((\sigma)\)
- **Sky background in annulus**
  - \(B\)
- **Detector**
  - \(QE,\) readnoise, dark current
- **Aperture sizes**
  - \(r_1, r_2, r_3\)
Photometric Model

- Write down an expression for the signal, $S_i$, in units of photoelectrons
  - In an individual pixel
    \[
    S_i = F_i + I_i + B_i + E_i
    \]
  - $F_i$ is the stellar signal $= f_i t$ at pixel $i$ [e$^-$]
    - Different for every pixel
  - $I_i$ is the dark charge $= i_i t$ [e$^-$]
    - Varies from pixel to pixel, for SNR model assume constant
  - $B_i$ is the sky background $= b_i t$ assumed uniform [e$^-$]
    - Varies from pixel to pixel, for SNR model assume constant
  - $E_i$ is the readout electronic offset or bias [e$^-$]
    - Varies from pixel to pixel, for SNR model assume constant
The Stellar Signal

- The stellar signal is found by subtracting the background from $S_i$ and summing over the $N$ pixels that contain the star
  \[ F_i = S_i - (I_i + B_i + E_i) \]
  \[
  F_N = \sum_{i=1}^{N_1} F_i = \sum_{i=1}^{N_1} S_i - (I_i + B_i + E_i)
  \]
  \[
  N_1 = \pi r_1^2
  \]
- Error in $F_N$ is due to noise in the signal itself, $F_N$
- Noise due to dark charge, $I$
- Noise from the background, $B$
- The read out noise $\sigma_{RO}$
Noise Sources

\[ F_N = \sum_{i=1}^{N_1} F_i = \sum_{i=1}^{N_1} \left[ S_i - (I_i + B_i + E_i) \right] \]

\[ \sigma_F^2 = F_N + \frac{N_1 (B_i + I_i + \sigma_{RO}^2)}{\text{Signal Noise}} + \frac{N_1 (B_i + I_i + \sigma_{RO}^2)}{\text{Noise within } r_1} + \frac{N_1 (B_i + I_i + \sigma_{RO}^2)}{\text{Noise within } r_2 < r < r_3} \]

\[ N_1 = \pi r_1^2, \quad N_{23} = \pi r_3^2 - \pi r_2^2 \]

- How do we choose \( r_1, r_2, r_3 \)?
  - Signal increases with \( N_1 \)
  - Noise increases with \( N_1 \) and decreases with \( N_{23} \)
Signal-to-Noise

How do we choose $r_1$, $r_2$, $r_3$?

- Signal increases with $N_1$
- Noise increases with $N_1$ and decreases with $N_{23}$
An Example

• Suppose the stellar signal has a 2-d Gaussian shape

\[ F_i = \frac{F_0}{2\pi\sigma^2} \exp \left[ -\frac{1}{2} \left( \frac{r_i}{\sigma} \right)^2 \right], \quad r_i^2 = (x - x_0)^2 + (y - y_0)^2 \]

\[ F_N = \int_0^\infty 2\pi r F_i dr \]

– This tells us how \( F_N \) changes with aperture radius
Star Profile
SNR vs. $r_1$

- $F_0 = 100 \text{ e}^-$
- $B_i = 100 \text{ e}^-$
- $I_i = 0 \text{ e}^-$
- $\sigma_{RO} = 10 \text{ e}^- \text{ rms}$
- $N_{23} >> N_1$