ASTR:4850 - Aperture Photometry & Extinction Correction

1 Introduction

In this lab, we will determine the apparent magnitudes of stars on CCD images by comparing the count rates from the stars with those from the Landolt standard star. The magnitudes of 298 standard stars were measured in five filters (Johnson $UBVRI$) by Landolt (1992) over the course of a decade and are tabulated at this URL. We do not have the same Johnson $UBVRI$ filters, so filter transformations are needed to convert the magnitudes from UBVRI to the magnitudes in our filters. But for simplicity of this exercise, we directly adapt the Johnson magnitudes in the closest filters (e.g., $blue \sim B, green \sim V$, and $red \sim R$).

2 CCD Data Reduction

To accurately measure the flux of light from a star, we need to correct for imperfections in the response of the CCD and also in the response of the telescope. In the lab on "Readout Noise and Dark Current", you already learned about bias and dark current in CCDs. It is essential to subtract a bias or dark frame from each astronomical exposure. The CCD camera mounted on the VAO or the IRO has very low dark current, as you should have found in the S/N ratio lab. The dark current is also negligible for short exposures, so it is OK to use either bias or dark frames for subtraction.

One usually takes several bias (or dark frames) and combines them into a single master bias image by combining the images using a median filter, i.e. the value of each pixel in the master bias is the median of the values for that pixel in the input bias images. Write a python program to load all bias images, take the median value for each pixel, and then write out a FITS file with your master bias image. *What advantages are there to using a master bias image over a single bias image? Explain in your lab report's Procedure section.*

The quantum efficiency of CCDs can vary from pixel to pixel. Also, every optical system suffers from variations in its response across the field of view and localized variations due to imperfections such as dust. To correct for these variations, one attempts to uniformly illuminate the telescope field of view and then takes a 'flat field' frame. This frame is then used to correct for the response across the field of view. In practice, one divides the value in the each pixel in astronomical image by the value for the corresponding pixel in the flat field. *Think about this for a moment and convince yourself that it is the correct way to apply the flat field calibration - if one region of the camera has a higher quantum efficiency, what will that mean about the number of counts in that region in the astronomical image and in the flat field? Explain in your lab report's Procedure section.*

Usually, one takes several flats and then calculates the median in each pixel. To keep the units of the reduced image in close to ADUs, one usually normalizes the flat field frame before doing the division. Typically one divides the flat field frame by its median so that the flat field correction for pixels with near the median response is near 1. *Why is use of the median preferred to use of the mean in calculating flats? Explain in your lab report's*

Procedure section.

The process of correcting for instrumental imperfections is called 'data reduction'. Essentially, one is attempting to produce an image that most accurately presents the true spatial distribution of flux on the sky (in the selected waveband). Represented as an equation,

Reduced image = (Raw Image - Master Bias Image)/(Normalized Flat Field)

Write a python program to calculate reduced images and compare it with the dark-subtracted Raw Image. Make sure you normalize the flat field to its median before applying the flat field correction.

Think about why we didn't divide the dark-subtracted sky image with a flat field in the S/N lab? And why flat-field-division is necessary for photometry?

3 Apparent Magnitudes from Differential Photometry

The model we use for the response of the system to a star is as follows. Let Q be the count on a pixel of the CCD due to the emission of a star, then

$$Q = AFt/h\nu \tag{1}$$

where F is the flux of radiation from the star (Joule/s/m^2), t is the exposure time, $h\nu$ is the energy per photon, and A is the effective collecting area of the entire system that includes atmosphere, telescope, and instrument. Given fluxes F_a and F_b from two stars at the same wavelength, the difference in their magnitudes (or the relative magnitude) is defined as

$$m_a - m_b = -2.5 \log\left(\frac{F_a}{F_b}\right). \tag{2}$$

So if we have observations of two stars with the same telescope, instrument, and filter under the same atmospheric conditions, then these observations are sufficiently characterized by observables Q_a and t_a and Q_b and t_b only, because $A_a = A_b$ and $h\nu_a = h\nu_b$. The relative magnitude defined in the previous equation can be expressed by these observables:

$$m_a - m_b = -2.5 \log\left(\frac{Q_a/t_a}{Q_b/t_b}\right) \tag{3}$$

Obviously, the camera must be unsaturated and have linear response to flux for these equations to be valid. In addition, the raw counts on the CCD must be corrected for the bias level, the dark current, the flat field (*image reduction*), and the background to recover Q (*background subtraction*).

4 Atmospheric Extinction Correction

Even at wavelengths where the atmosphere is almost transparent, there is a non-negligible amount of atmosphere extinction on the radiation measured on the ground. At optical
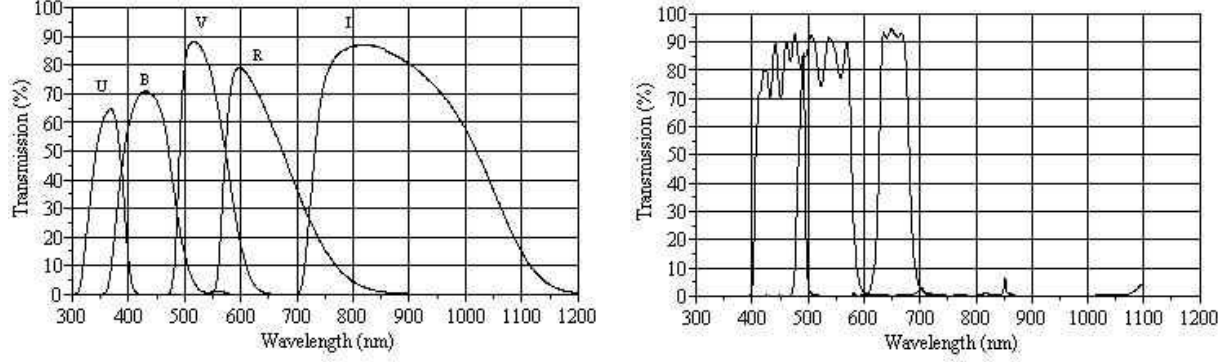
Figure 1: Filter transmission curves for Johnson UBVRI and Astrodon Blue, Green, Red.

wavelengths, the main contributors of extinction include aerosol and molecular scatterings (Rayleigh-Cabannes law) and ozone absorption.

It is straightforward to express the extinction correction if the atmosphere can be modeled as a set of absorbing plane-parallel layers, characterized by the opacity $\kappa_\lambda(z)$ and density $\rho(z)$. The optical depth of this plane-parallel atmosphere depends on the zenith angle α:

$$\tau_\lambda = \sec\alpha \int_0^\infty \kappa_\lambda(z)\rho(z)dz = \tau_{\lambda,0}\sec\alpha \tag{4}$$

where $\sec\alpha = 1/\cos\alpha$ is called the airmass and $\tau_{\lambda,0} = \int \kappa_\lambda(z)\rho(z)dz$ is the vertical optical depth. Simple radiative transfer (absorption only) shows that the transmitted intensity is:

$$I_\lambda(\alpha) = I_{\lambda,0}\exp(-\tau_{\lambda,0}\sec\alpha) \tag{5}$$

where $I_{\lambda,0}$ is the intensity above the atmosphere. Equivalently, we can express this relation in magnitudes:

$$m_\lambda(\alpha) - m_{\lambda,0} = -2.5\log[I_\lambda(\alpha)/I_{\lambda,0}] = 2.5\log(e)\tau_{\lambda,0}\sec\alpha = k_\lambda\sec\alpha \tag{6}$$

Rearrange the equation, we have the extinction-corrected magnitude:

$$m_{\lambda,0} = m_\lambda(\alpha) - k_\lambda\sec\alpha \tag{7}$$

where $m_{\lambda,0}$, $m_\lambda(\alpha)$, and $k_\lambda \simeq 1.09\tau_{\lambda,0}$ are the extinction-corrected magnitude, the observed magnitude at zenith angle α, and the extinction coefficient of the atmosphere. k_λ has a unit of magnitude per airmass. As any quantities of the atmosphere, it varies with time and location.

Using the equation above, we can measure k_λ by observing a photometric standard star at two airmasses. For simplicity, we assume the mean extinction curve of the Lick Observatory: https://mthamilton.ucolick.org/techdocs/standards/lick_mean_extinct.html. Interpolate this curve to the central wavelengths of your filters to obtain your extinction coefficients (see filter transmission curves in Fig. 1).

5 Finding Magnitudes in One Filter

The goal is to determine the magnitude of a star in your target image by comparing its *count rate* with that of a photometric standard star in a Landolt field (Eq. 3). Landolt (1992) provides finding charts and $UBVRI$ magnitudes of 298 photometric standard stars along the celestial equator. We will do aperture photometry in DS9 and python, similar to what we did in the S/N ratio lab. *It is required that you record both the DS9 analysis and the python analysis in your lab report.*

5.1 CCD Image Reduction

The first step is to reduce the images by subtracting a master bias and dividing by a normalized flat field. You will use python for the image reduction and you may find the python code you wrote in the previous labs useful for this purpose.

- Collect twilight flat field images, Messier target images, and Landolt standard star images taken through the same filter.

- Collect bias images and dark images taken by the same camera at the same temperature as the above images.

- Make master dark images and normalized master flat field image.

- Reduce the CCD images of the target field and the Landolt field as described in §2. i.e., your sky images should be bias subtracted and flat-field divided.

5.2 Photometry with DS9

Next we do photometry on the reduced images manually with DS9 to intuitively understand the procedure. The photometry result also serves as a sanity check to the python code that you will develop in.

- Choose a non-saturated, well-detected star in the target field (hereafter, the "source").

- Use the finding chart to identify the standard star in the Landolt field (hereafter, the "standard"). You may need to invert the X-axis of the image (in DS9, use Zoom - Invert X) to match the finder chart. If multiple standard stars are present in the same field (e.g., Landolt 95 276), choose the brightest one.

- Use the tabulated magnitudes and colors of the standard to calculate its magnitudes in your filter. In this lab, we use the following approximation: $blue \sim B, green \sim V$, and $red \sim R$ (Fig. 1 shows a comparison between these filters).

- Calculate the number of ADU counts in a circular aperture centered on the source and the standard. The circle should be large enough to capture most of the counts from the star, but not so large that it includes extraneous sky background. As a trade-off between maximizing S/N and minimizing flux loss, we usually choose an aperture size that is $\sim 2\times$ the optimal aperture size that you measured in the S/N lab.

- Make sure the circular apertures for the source and the standard have the same size so that their flux losses due to the finite aperture size cancels out.

- Estimate the background count with a concentric annulus. Calculate the number of ADU counts in an annular region centered on the source and the standard star. The inner radius should be larger than the radius of the circle to avoid any covariance. The area of the annulus should be several times the area of the circle, but not include any other sources, to reduce background noise in the measurement.

- Find the net counts from (circle counts) - (annulus counts)*(area of circle)/(area of annulus), as in the S/N lab. As a reminder, the second term is to subtract counts from the sky and instrumental background.

- Estimate the S/N of the aperture photometry as in the S/N lab. This provides error estimates of the counts and count rates, which will be used to estimate the magnitude error.

- Find the net count rates by dividing the net counts by the exposure time.

- Use Eq. 3 to find the relative magnitude before atmospheric extinction correction. What you get from Eq. 3 is actually $m_a(\alpha_a) - m_b(\alpha_b)$, where α_a and α_b indicate that the source and the standard were observed at two different airmasses (so they have different amount of extinction corrections).

- Find the airmasses of the target field ($\sec \alpha_a$) and the standard star field ($\sec \alpha_b$) based on Latitude of the observing site, the RA, the Dec, and the hour angle of the image center given in the FITS header (OBJCTRA, OBJCTDEC, OBJCTHA). Hint: think about the RA and Dec of local Zenith when the image was taken and recall that LST = HA + RA. You can check your results using this online calculator (http://www.convertalot.com/celestial_horizon_co-ordinates_calculator.html) and compare them with the numbers you took in your observing log.

- Interpolate the Lick observatory extinction curve to the central wavelength of your filter to get the extinction coefficient k_λ.

- Apply a *differential* extinction correction to the relative magnitude from the previous step with the following equation:

$$m_{a,0} - m_{b,0} = [m_a(\alpha_a) - m_b(\alpha_b)] - k_\lambda(\sec \alpha_a - \sec \alpha_b), \tag{8}$$

  This can be easily derived from Eq. 7.

- Now you can find the extinction-corrected magnitude of the source ($m_{a,0}$) by moving $m_{b,0}$ to the right side of the equation above, because $m_{b,0}$ is the tabulated magnitude of the standard star given in Landolt (1992).

- Estimate the uncertainty of your result by propagating errors in the count rates of the source and the standard star.

5.3   Python Automation

Once the DS9 analysis is done, the next step is to automate photometry measurements with a Python code so that you can measure the magnitudes for many stars.

You may find functions in the astropy-affiliated package `photutil` useful for this work. For example, you may find the aperture_photometry function useful for calculating the net count for a star at any given position, aperture size, and background annulus size. You may also want to use the centroid function in `photutils` to automatically find the centroid coordinates of stars to center your apertures more precisely. The centroid algorithm is described in § 5.1.1 of the CCD textbook.

Select at least 10 stars cross the target field and make sure the star chosen for the DS9 analysis is at the top of the list (so that we can easily compare the DS9 result and the python result). Show the positions of the 10 stars in the image with a figure and report the results in a table that gives the source number, the X coordinate, the Y coordinate, the net count in the chosen aperture, the count rates, and the extinction corrected magnitudes.