OBSERVATIONAL ASTRONOMY

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Lecture 12

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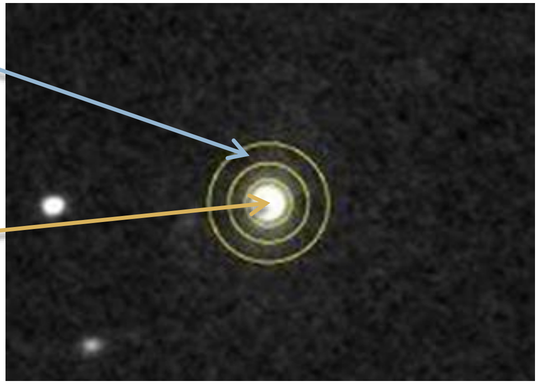
Procedures for photometry

Extracting Photometric Data
Relative Photometry
Instrumental Magnitudes
Extinction

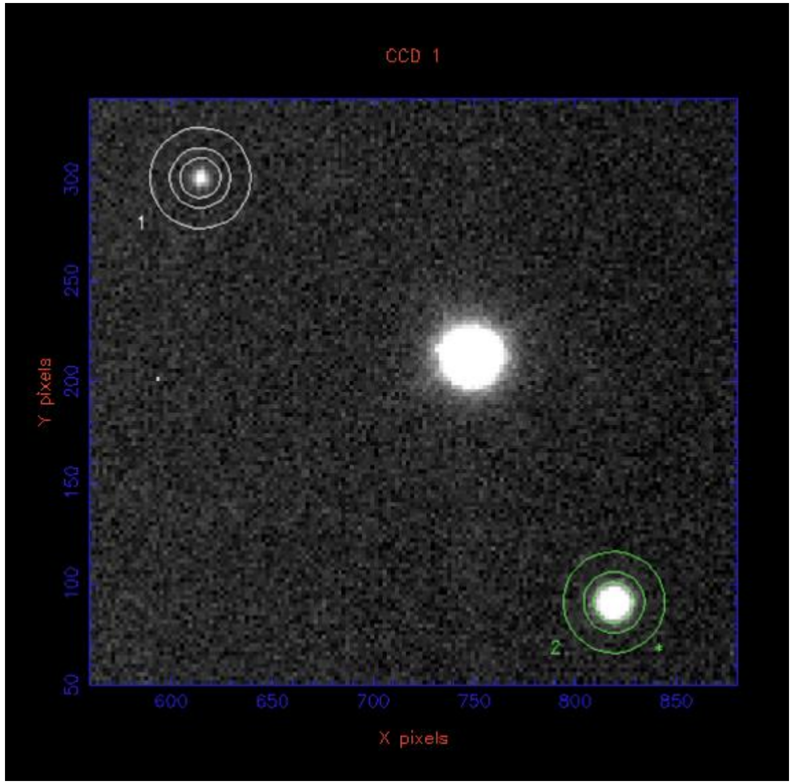
Extracting Photometric Data

- Determining the number of counts from a source in an image is usually a three-step process (we follow a technique known as aperture photometry):
  1. To measure the centre of the source, which we shall assume is a star.
  2. To estimate the sky background at the position of the star.
  3. To calculate the total amount of light received from the star.
- The sky annulus is unlikely to contain counts from the sky alone. There will also be contributions from cosmic rays, hot pixels, faint stars, and the wings of the PSF of the central star. All of these will add a positive skew to the histogram of pixel values in the annulus. The mean of these pixel values will then not be an accurate representation of the sky background.
  Instead, the sky level is usually determined using a more robust estimator, such as **the median**.
- The total signal from the star can then be calculated by summing the counts from each pixel that falls inside the aperture (usually a **circle** or **ellipse**), and then subtracting the determined sky background from each pixel.



Relative Photometry

- Even if the intrinsic brightness of the star is constant, the number of counts we detect might change, due to transparency variations or seeing variations. To obtain an accurate light-curve we need to correct for these effects, using a **comparison star**.
- This is a second star which is known (or assumed) to have a constant flux. We assume that the comparison star is affected in the same way as our target star by seeing and transparency variations (this is a very good assumption).
- Therefore, if transparency or seeing variations cause the counts from the target star, N_t, to halve, they will also cause the counts from the comparison star, N_c, to halve.
  The ratio N_t/N_c is therefore corrected for transparency and seeing variations. Correcting aperture photometry this way is known as relative photometry.



Courtesy of Vik Dhillon

Calibrated Magnitudes (1)

- Once the sky-subtracted signal from an object, measured in **counts**, is extracted from an image, it is useful to convert it to a calibrated **magnitude** in a photometric system:
  - Calculate the instrumental magnitude, from the counts per second.
  - Determine the extinction coefficient, and correct the instrumental magnitude to the above-atmosphere value.
  - Repeat the above steps for a standard star and use the resulting above-atmosphere instrumental magnitude of the standard star to calculate the zero point.
  - Use the zero point to transform the above-atmosphere instrumental magnitude of the target star to the required photometric system.

Procedures for photometry

- If we have standard stars in the CCD field that we are observing, then its fairly easy to calibrate, as we can just use the N_t values as our measure of intensity.
- If not then we need to observe standard stars in separate CCD frames, and as the PSF will vary between different frames, we need to find a true measure of the brightness of the stars.

$$N_t = C_i \int_0^{rmax} 2\pi r \left(1 + r^2/R_0^{\,2}\right)^{-\beta} dr$$

r_{max} is chosen so that we get all of the light.

(The Moffat function, see the previous lecture)

Instrumental Magnitudes (1)

- We have the sky-subtracted signal from our target object, in counts, N_t. We convert this to an instrumental magnitude, using the formula:

$$m_{inst} = -2.5 \log_{10} (N_t / t_{exp})$$

where t_{exp} is the exposure time of the image in seconds.

- The instrumental magnitude depends on the characteristics of the telescope, instrument, filter and detector used to obtain the data.
- We need to compare the instrumental magnitudes of stars of known magnitude with their true magnitudes, to calculate the offset, and thus to calculate the true magnitudes of all of the stars in the frame.
- The relationship between instrumental magnitudes and calibrated magnitudes can be understood as follows. The counts per second N_t / t_{exp} is proportional to the flux, F_λ. Hence

$$m_{inst} = -2.5 \log_{10} (c\, F_\lambda) = -2.5 \log_{10} (F_\lambda) + c'$$

Instrumental Magnitudes (2)

- Therefore, instrumental magnitudes are offset from calibrated magnitudes by a constant:

$$m_{calib} = m_{inst} + m_{zp}$$

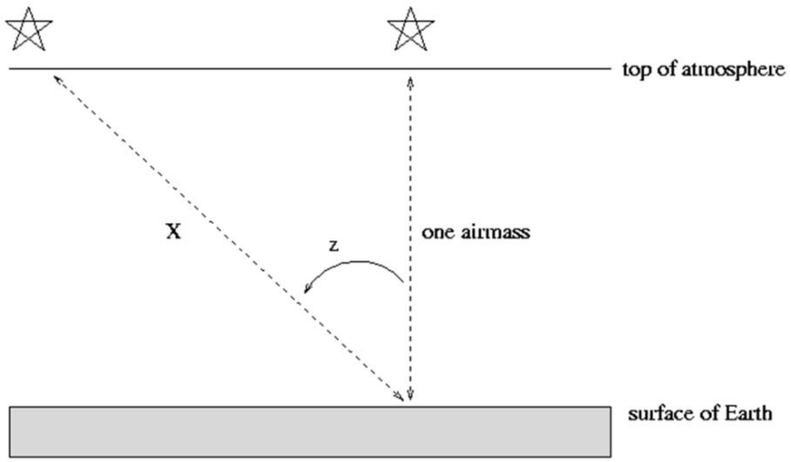
where the constant, m_{zp}, is known as the **zero-point**.

- The zero-point depends upon the telescope and filter used. We can understand this because if we used a larger telescope to observe a star, the instrumental magnitude would change, but the calibrated magnitude must not!
- An object with a calibrated magnitude equal to the zero-point gives one count-per-second at the telescope.
- For example, suppose the zero-point of a telescope/filter combination is m_{zp} =19.0. If we observe a star with m_{calib} =19.0, then it follows that, for this star m_{inst} =0. By definition then, this star gives one count-per-second.

$$m_{inst} = -2.5 \log_{10} (N_t / t_{exp})$$

Atmospheric absorption

- The next step is to convert the instrumental magnitude, which is measured on the surface of the Earth, to the instrumental magnitude that would be observed above the atmosphere.
- Atmospheric absorption is proportional to the airmass, which is proportional to the secant of the angular distance from the zenith. Strictly this assumes a plane parallel atmosphere, but this is a good approximation for $z < 70°$.



$$X = \sec Z = [\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos h]^{-1}$$

ϕ is the latitude of the observatory, h is the hour angle of the source, and δ is the declination of the source.

Atmospheric extinction

- The effect of atmospheric extinction on photometry is usually expressed as:

$$m_{obs} = m_{true} + k(\lambda) \sec Z = m_{true} + k(\lambda)\, X$$

Here, m_{true} is the magnitude of the source outside the Earth's atmosphere, m_{obs} is the magnitude observed,

$k(\lambda)$ is the "extinction coefficient" [magnitudes per unit airmass].

- The dominant source of extinction in the atmosphere is Rayleigh scattering by air molecules. This mechanism is proportional to λ^{-4}, which means that extinction is much higher in the blue than in the red.
- The extinction coefficients $k(\lambda)$ have been carefully measured and tabulated for a number of observatories.

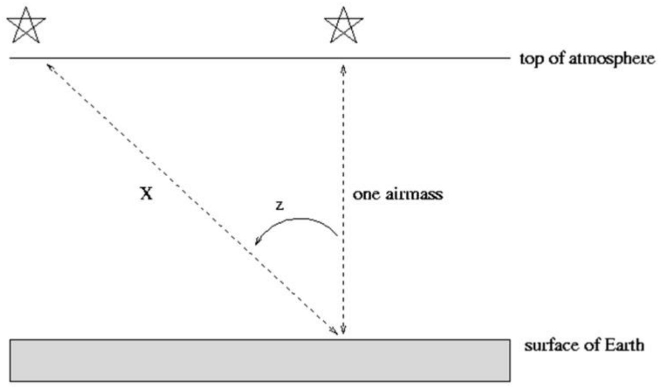
The extinction coefficients on a typical (undusty) night on La Palma

Filter	λc (Å)	k
U	3660	0.55
B	4380	0.25
V	5450	0.15
R	6410	0.09
I	7980	0.06

Extinction coefficient (1)

- However, the extinction can vary from night to night depending on the conditions in the atmosphere, e.g. dust blown over from the Sahara can increase the extinction on La Palma during the summer by up to 1 magnitude.
- How do we find k in practice?
  if we plot instrumental magnitudes vs airmass for a particular star, k is just the slope of the line that passes through the observed points:

$$k = \frac{\Delta m_{inst}}{\Delta X}$$



Extinction coefficient (2)

- Even two measurements of the instrumental magnitude of a star at two different zenith distances is enough to estimate k (although less accurate): subtracting $m_{z1} = m_0 + k \sec Z_1$ from $m_{z2} = m_0 + k \sec Z_2$ eliminates m_0, allowing k to be derived.
- For more accurate photometry: observe a set of standard stars (of known magnitude) at different airmass.
- Note that no explicit extinction correction is required when performing relative photometry: the target and comparison stars are always observed at the same airmass and hence suffer the same extinction. Hence, the variation due to extinction present in the comparison star is removed from the target star.

Colour term (1)

- For **very accurate** photometry, the wide bandpass of broad-band filters has to be taken into account when correcting for extinction.
- There is a colour term, caused by the variation in spectral profile of the stars and the filter response over the passband.
- Because extinction is so strongly colour dependent, a blue object actually loses more light to the atmosphere than a red one. The solution is to introduce additional colour-dependent secondary extinction coefficients, which modify the above extinction correction equation to:

$$m_{obs} = m_{true} + k_1(\lambda)\sec Z + k_2(\lambda)\,(B\text{-}V) + k_3(\lambda)\,(B\text{-}V)\sec Z$$

(B-V) is the colour of a star. Other colours can be used, e.g. (V-R).

Colour term (2)

$$m_{obs} = m_{true} + k_1(\lambda) \sec Z + k_2(\lambda)\ (B\text{-}V) + k_3(\lambda)\ (B\text{-}V) \sec Z$$

- Solve for k_1, k_2 , k_3 from stars of known magnitude.
- Usually k_2 is negligible (usually of order a hundredth of a magnitude), often k_3 is too.
- In this case we can now simply convert the values of m_{inst} to m_{true} using the value of k_2 that we solve for, and the value of z for each observation.
- However if k_2 and/or k_3 is not zero, we need to know **(B-V)** for the star to calculate the true magnitude, but we do not. In this case we must observe a set of standard stars (of known magnitudes) at different Z and in two passbands, for instance B and V, and use:

$$V_{obs} = V_{true} + k_1(\lambda) \sec Z + k_2(\lambda)\ (B\text{-}V) + k_3(\lambda)\ (B\text{-}V) \sec Z$$
$$B_{obs} = B_{true} + k_4(\lambda) \sec Z + k_5(\lambda)\ (B\text{-}V) + k_6(\lambda)\ (B\text{-}V) \sec Z$$

Calibrated Magnitudes (2)

- Now we can find the above-atmosphere instrumental magnitude of any object. If the above-atmosphere instrumental magnitude of our standard star is $m_{std,0,i}$, then:

$$m_{zp} = m_{std} - m_{std,0,i}$$

- The calibrated magnitude of our target star, m_{calib}, can then be found using:

$$m_{calib} = m_{zp} + m_{0,i}$$

where $m_{0,i}$ is the above-atmosphere instrumental magnitude of our target star.

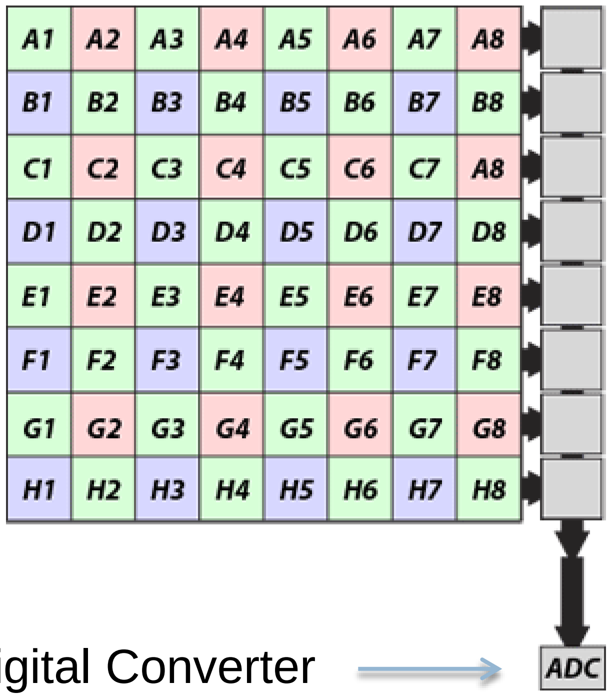
- Each filter in a photometric system will have a different zero-point. Once the zero-point has been measured for a particular telescope, instrument, filter and detector combination, it **should** remain unchanged, although dirt and the degradation of the coatings on the optics will cause minor changes to the zero point on long timescales. To determine the zero points for the UBVRI system, the photometric standards measured by Landolt can be used.

CCD Gain

CCD Gain (1)

- What is relationship between electrons in a CCD and pixel values?

The readout register is shifted to the right by one pixel, and the pixel at the bottom right is shifted into a readout capacitor. What's next?



Analog-to-Digital Converter

CCD Gain (2)

- The steps involved in reading the value of a pixel are something like this:
  1. Electrons transferred to "amplifier"; really a capacitor. Units are **coulombs**.
  2. The voltage induced by this charge is measured. Units are **volts**.
  3. An Analog-To-Digital (A/D) unit converts the voltage into some other voltage, which may have only one of several discrete levels. Units are still **volts**.
  4. The voltage is converted into a number which is passed from the hardware to the computer software as the pixel's value. Units are **counts**, also called "Analog-to-Digital Units" (**ADUs**).

CCD Gain (3)

- In both steps 3 and 4, one can scale the result by any arbitrary factor and the relative pixel values will remain the same. Some software allows the user to modify the scaling factor dynamically; others have a fixed setting.
- The end result is that there is some factor which relates the initial number of electrons in a pixel to the final number of counts reported by camera software. The ratio of these two numbers is the **gain** of the camera:

$$gain = \frac{Number\ of\ electrons\ per\ pixel}{Number\ of\ counts\ per\ pixel}$$

CCD Gain factor (1)

- How should one choose the gain factor? There are several criteria.
  1. **Full-well depth vs. largest pixel value:**
     Each CCD is designed to hold only so many electrons within a pixel before they start to leak outwards to other pixels. This maximum size of a charge packet on the chip is called the **full well depth.**
     There is also a "maximum possible number" in the Analog-to-Digital converter. Most CCDs use 14-bit, 15-bit, or 16-bit A/D units: the corresponding maximum pixel values are
     $2^{14} = 16384$, $2^{15} = 32768$, and $2^{16} = 65536$.
     It is logical to arrange the gain so that very roughly, the number of electrons in the full-well depth corresponds to the maximum pixel value.

CCD Gain factor (2)

- How should one choose the gain factor? There are several criteria.

  2. **Readout noise vs. smallest pixel value:**
     What are the SMALLEST values that make sense? A typical **readout noise** is 3 or 10 electrons. Therefore, if two pixels have values which differ by only 2 electrons, it's not easy to tell the difference between them. The smallest difference one can represent in an integer image is 1 count. To some extent, it makes sense to arrange the gain so that 1 count corresponds to some moderate fraction of the readout noise. Any finer measurement of the pixel values would yield differences which would be essentially random.

Why should we care about the Gain?

- For everything what we discussed previously and where we used the **Counts** we **must** use the number of **electrons** (photons). They can be obtained from the counts using the gain factor (photon per data unit).

$$Number\ of\ electrons = gain\ *\ Number\ of\ counts$$

Example: CCD Gain (ALFOSC)

- ALFOSC - the Alhambra Faint Object Spectrograph and Camera – is an instrument on the NOT telescope built to allow the acquisition of both images and spectra.

- The detector (CCD14) is an **CCD231-42-g-F61** back illuminated, deep depletion CCD with 2048 x 2064 pixels.
- Readout Noise is **~4.3 e^-/pix**
  the gain is **0.19 e^-/ADU**.
- Dark current is **1.3e-/pix/hour**
- Dynamical range is **32 bit.**
- Full-well capacity – **135000 electrons (700 kADUs).**
  Good (linear better than ±1%) up to ~113500e^- (600 kADUs)

Example: CCD Gain (BFOSC)

- BFOSC - Bologna Faint Object Spectrograph & Camera – is an instrument built to allow, with a simple configuration change, the acquisition of both images and spectra.

- The detector is an **EEV LN/1300-EB/1** CCD with 1300 x 1340 pixels, AR Visar coated, back illuminated.
- The detector Readout Noise is **3.06 e^-/pix** and the gain is **2.22 e^-/ADU**.
- Dynamical range is **16 bit**.
- Full-well capacity – **117000 electrons.**