OBSERVATIONAL ASTROPHYSICS AND DATA ANALYSIS

Lecture 13

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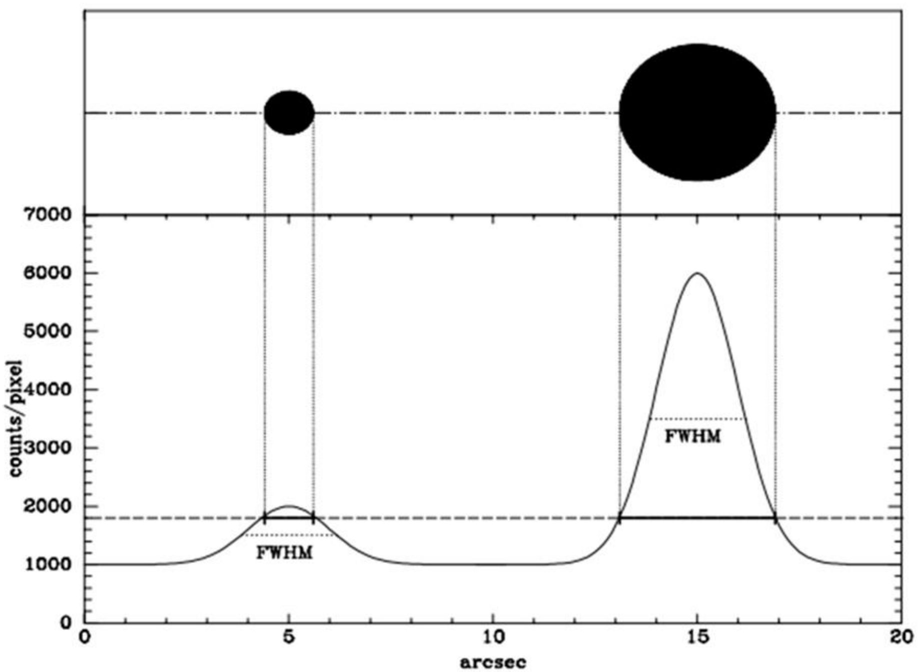
Aperture Correction

- The **point spread function** (PSF) is the shape of the CCD image of a point (unresolved) source of light.
- Since the PSF is the shape of a point of light on the CCD, and since all stars are points, then all stars have exactly the same shape and size on the CCD.
- The PSF does not have an edge. The intensity of the star fades smoothly to zero with increasing radius, but there is no place that we could call an "edge".

Aperture Correction



- Brighter stars may look bigger, but that is caused by the following effect: the shape of the faint and bright star are exactly the same, we are simply looking at a larger diameter at a given intensity for a bright star than for a faint star.

Aperture Correction

- If we want to measure all the light from a star, how far out in radius do we have to go?
  - One logical answer might be: as big as possible, to get "all" the light from the star. This is **not** a good answer.
  - Reducing the object aperture **reduces** both sky noise and readout noise.

- **But**, a small aperture will only encompass a fraction of the total light from the star! However, if the seeing were constant, any aperture would measure the same fraction of light for any star, and when comparing one star with another the effect would cancel out.

Aperture Correction

- The problem is that seeing is not constant. A small aperture might measure 0.5 of the total light from a star on one CCD image, then, if the seeing worsens, the same size aperture might measure only 0.4 of the light from the star on the next CCD image.
- Seeing affects mostly the inner Gaussian core of the image. Using an aperture 4 to 10 times the diameter of the typical FWHM will get most of the light. In this size aperture, reasonable variations in the seeing will not result in measurable variations in measured counts.

Aperture Correction

- However, for faint objects, an aperture 4 times the FWHM will contain a lot of sky signal. This will result in a low S/N ratio.
- Aperture Correction: If we measure the bright object in a small aperture (say radius = 1 FWHM) and also in a bigger aperture which gets "all" the light (say 4 FWHM) we can easily find the ratio of light in the small to large aperture (which we express as a magnitude difference).

Aperture Correction

- The aperture correction is defined as:

$$\Delta = m_{inst}(4\ \mathrm{FWHM}) - m_{inst}(1\ \mathrm{FWHM})$$

(Δ is always a negative number)

- How do we use the aperture correction?

$$\mathrm{total} = m_{inst}(1\ \mathrm{FWHM}) + \Delta$$

- "Total" is our estimate of the total instrumental magnitude in the faint star, m_{inst}(1 FWHM) is the measured magnitude in the small aperture for the faint star, and Δ is the aperture correction derived from a bright star in the same frame.

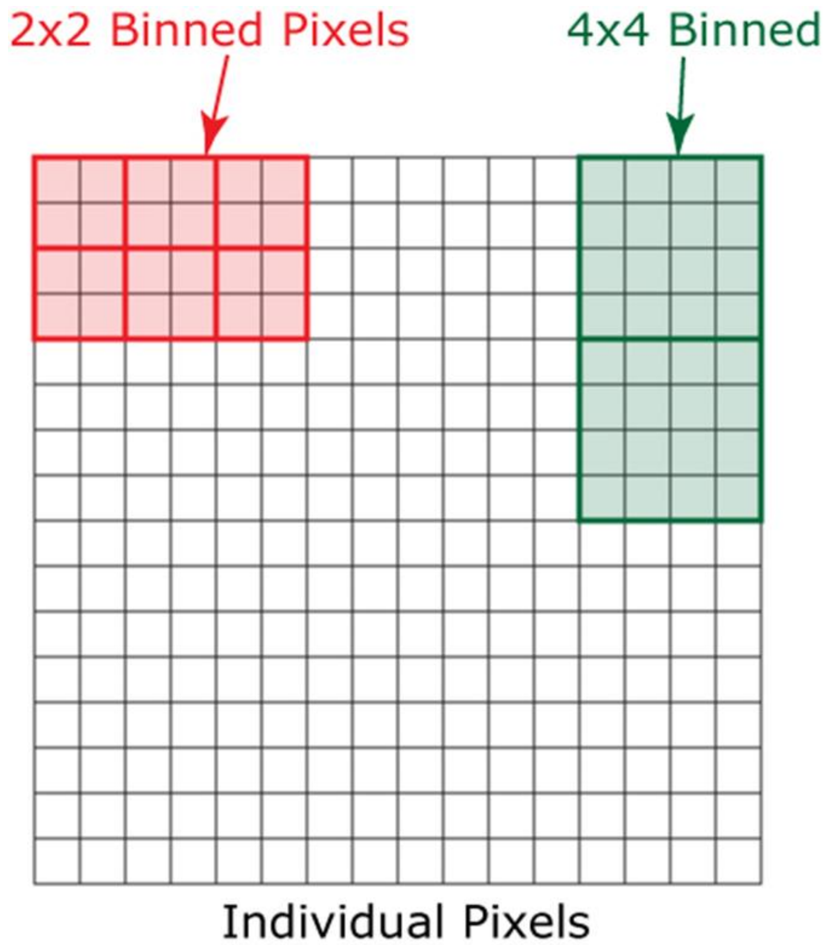
Aperture Correction

- There must be an optimum aperture size that gives the maximum S/N.
- The optimum size of the small aperture has been studied by several authors.
- The optimum aperture seems to be achieved when the measurement aperture has a diameter about $1.4 \times$ FWHM of the PSF. At this aperture, the aperture correction is about −0.3 mag.
- However, the S/N does not appear to be too sensitive to the exact small aperture size.

Improving the Signal to Noise

- On-chip binning – Most CCDs have the option of *binning*: combining a set of adjacent pixels into a single pixel produced as output. For example, a square of 4 pixels on the CCD chip might be reported as one pixel containing their combined value. But you only have to read the output capacitor out once and you only get one lot of readout noise.

On-chip binning



- This way you reduce readout noise at the expense of resolution. Resolution should always be smaller than the characteristic size of the star images.

Profile Fitting

- Profile fitting is used most commonly in crowded fields, where it is difficult or impossible to define a sky aperture free of stars (or galaxies).
- It does however offer an advantage in precision even in sparse fields, because it weights the data more correctly.

Profile Fitting

- Basic assumption is that the intensity profile (which is in principle a 2 dimensional function) is the same for all stars in a particular CCD image.
- Intensity profile is determined by seeing or by diffraction, or occasionally by aberrations.
- If it is determined by aberrations you need to be very careful, because the assumption that the profile is the same at all positions on the CCD may not be correct.

Profile Fitting

- From a set of isolated, comparatively bright (but not saturated) stars in the frame, determine the image profile, this is called the **Point Spread Function (PSF).**
- For ground based data an empirical approximation to the PSF is the Moffat function:

$$f(r) = C_i \ (1 + r^2/R_0{}^2)^{-\beta} + B_i \quad (r < r_{max})$$

$$f(r) = B_i \ (r > r_{max})$$

$\mathbf{R_0}$ is the characteristic radius of the star image, **r** is the distance from the centre of the image, **β** describes the overall shape of the PSF, $\mathbf{B_i}$ is the background in the region of star **i**, and $\mathbf{C_i}$ is the relative brightness of star **i**.

Profile Fitting

$$\text{FWHM}=2\ R_0\sqrt{2^{1/\beta}-1}$$

- Fit this function for each of the stars in the image to the data, using a least squares or similar technique.
- For each star determine B_i and C_i. R and β are constant within an image.

Profile Fitting

- Then we have a set of scaling factors, which can be converted to a relative magnitude.
- We need aperture photometry of one star, either from this CCD frame or from another, this can be a bright isolated star with high S/N, this gives the magnitudes of all of the stars in the frame.
- The fit gives the correct weighting, rather than adding in lots of pixels with very little signal, S/N from profile fitting is usually at least a factor of 2 higher than from aperture photometry.
- Profile fitting can cope with fields in which stars are close or their images even overlap.

Profile Fitting

- For ground based data the PSF is determined by the seeing, and must be redetermined for each CCD image.
- For space based (e.g. Hubble Space Telescope) data the PSF is fixed, and is often available as part of the standard calibration data produced with the observations. It still depends upon the passband (filter).

Procedures for photometry

- For each star calculate an instrumental magnitude:

$$m_{inst} = -2.5 \log (D_i / t)$$

D_i is a measure of the total brightness in the star image; t is exposure time.

- 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.

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 C_i 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.

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

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

Atmospheric absorption

- 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 $z < 70°$.
- The effect of atmospheric extinction on photometry is usually expressed as:

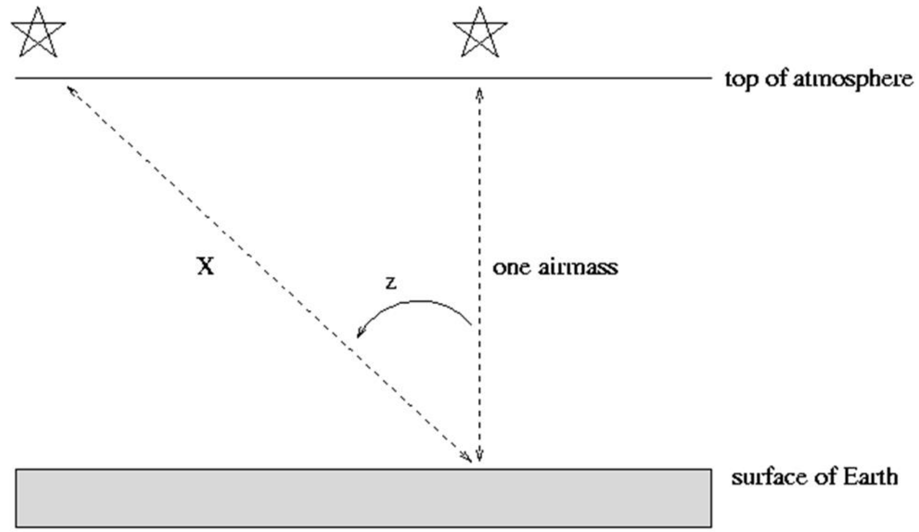
$$m_{obs} = m_{true} + k(\lambda) \sec Z$$

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].

Atmospheric absorption

Absorption ∝ sec z for a plane parallel atmosphere



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

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

Atmospheric absorption

- The extinction coefficients $k(\lambda)$ have been carefully measured for a number of observatories.
- 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:

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

Atmospheric absorption

- Observe a set of standard stars (of known magnitude) at different airmass and at different colour.
- There is a colour term, caused by the variation in spectral profile of the stars and the filter response over the passband.

Procedures for photometry

$$m_{inst} - m_{true} = C_1 + C_2 \sec(z) + C_3 (B-V) + C_4 (B-V) \sec(z)$$

(B-V) is the colour of a star, and measures the ratio of the intensity in the V band to that in the B band. Other colours can be used, e.g. (V-R)

- Solve for C_1, C_2, C_3, C_4 from stars of known magnitude.
- Usually C_3 is negligible, often C_4 is too. In this case we can now simply convert the values of m_{inst} to m_{true} using the values of C_1 and C_2 that we solve for, and the value of z for each observation.

Procedures for photometry

- However if C_3 and/or C_4 is not zero, we need to know (B-V) for the star to calculate the true magnitude, and we do not. In this case we must observe in two passbands, for instance B and V, and use:

$$V_{inst} - V_{true} = C_1 + C_2 \sec(z) + C_3 (B_{inst} - V_{inst}) + C_4 (B_{inst} - V_{inst}) \sec(z)$$

$$B_{inst} - B_{true} = C_5 + C_6 \sec(z) + C_7 (B_{inst} - V_{inst}) + C_8 (B_{inst} - V_{inst}) \sec(z)$$

Image Intensifiers

- An image intensifier is a device which amplifies light signals by:
  - converting photons to electrons via the photoelectric effect at a photocathode,
  - accelerating the electrons them via electrostatic forces,
  - having them impact on an output phosphor releasing a shower of photons,
  - recording the output photons using a photographic emulsion or some more modern detector (or indeed the human eye).

Image Intensifiers

- The gain of an image intensifier is the ratio of the number of output photons to the number of input photons.
- Some means must be used to focus the electron beam, i.e. to ensure that there is a one to one mapping between the position of impact of the incident photon on the photocathode, and the position of release of the output shower on the phosphor. Image tubes are either electrostatically or magnetically focussed.

Image Intensifiers

- Often several (up to 4) stages of intensifier are used, leading to a total gain of order 10^6.
- Image intensifiers are now used very little in the optical, where CCDs have taken over, because:
  - Photocathodes have lower QE than CCDs.
  - Intensifiers require high voltage supplies, and are unreliable for instance in damp conditions.
  - They suffer from saturation effects when used in photon counting mode.

Image Intensifiers

- Image intensifiers remain popular in the ultraviolet because:
  - QE of CCDs drops because the electrodes they rely on are opaque at UV wavelengths.
  - QE of Image Intensifiers is higher because photocathodes respond more efficiently to higher energy photons.
  - Photon rates from astronomical sources are lower, so saturation effects are less serious, and CCD readout noise becomes more serious (photon counting detectors are noise free).

Microchannel Plate intensifiers

- A microchannel plate is a modern image intensifier.
- It consists of a thin disk of lead oxide glass with numerous microscopic channels running parallel to each other from one face to the other.
- A potential of a small number of kiloVolts is applied between one face and the other.
- Each channel acts like a tiny image intensifier. electrons hitting the walls eject additional electrons resulting in a cascade of electrons.

Microchannel Plate intensifiers

- Microchannel plate still needs a photocathode and an output phosphor.
- Advantages over conventional image intensifiers:
  - Channels or pores confine the electron shower so that the resolution is better.
  - Voltages are lower (~2 kV as opposed to ~30 kV for gain of 10^6).
- Pores are either slanted in opposite directions in a stack, or curved:
  - To allow the electrons to hit the walls to provide the gain
  - So that positive ions produced from residual gas within the tube hit the walls and are absorbed before they acquire enough energy to generate a cascade.

Photon Counting Detectors

- Run an image intensifier at high gain (~10^6), and image the output phosphor onto a CCD or similar solid state detector.
- For each photon incident at the photocathode there is a large splash of photons at the detector.
- Read this out and centroid using hard wired logic or software on a fast computer.
- Record in solid state or computer memory a photon at the location of the centroid.
- In this way build up the image photon by photon.

Saturation in Photon Counting Detectors

- If more than one photon arrives in a particular location within the frame time of the detector then one or both will be lost.
  - There is a limit to the count rate in a particular location
  - In some devices there is also a limit to the total count rate in the frame.
  - Unlike CCDs, you cannot remove saturation by taking short exposures.
  - Photon counting detectors are therefore most useful in the Ultraviolet, where photon rates are low.

Noiseless detectors

- Photon counting detectors have no readout noise and have a potential advantage for all ultra-low light level applications.

The Image Photon Counting System

- Developed in the 1970s by A. Boksenberg and J. Fordham at University College London.
- Early generations used 4 stage magnetically focussed Image Intensifiers, and Plumbicon TV readout.
- In later generations the Intensifier is replaced by a Microchannel plate, and the Plumbicon by a CCD.

The Multi-Anode Microchannel Array

- Developed for space applications (particularly ultraviolet).
- Used a position sensitive anode instead of an output phosphor and light sensitive detector.
- Anode consists of two perpendicular sets of coding electrodes.

S/N with a photon counting detector

- Going back to our case of aperture photometry:

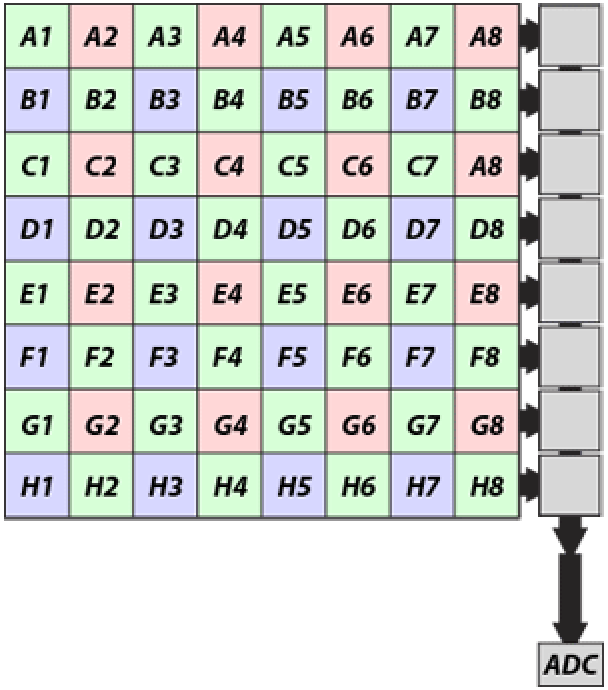
$$S/N = n_* / \sigma_* = N_{star} / \sigma_*$$
$$\sigma_*^2 = 2\,\alpha\,N_{sky} + N_{star} + 2\,n_{pix}\,\sigma_R^2$$
$$N_{star} = \eta\,\varepsilon_{atm}\,\varepsilon_{tel}\,\varepsilon_{filt}\,\varepsilon_{win}\,\varepsilon_{geom}\,\varphi_*\,\Delta\lambda\,A\,t$$
$$N_{sky} = \eta\,\varepsilon_{atm}\,\varepsilon_{tel}\,\varepsilon_{filt}\,\varepsilon_{win}\,\varepsilon_{geom}\,\varphi_{sky}\,\Delta\lambda\,A\,t$$

- For a photon counting detector η is generally lower than for a CCD, as it is given by the photocathode efficiency. However σ_R is 0. If φ_* and φ_{sky} are faint, A is small, or $\Delta\lambda$ is narrow, or if t must be short because good time resolution is required, then it is possible that S/N might be higher with the Photon Counting Detector than with the CCD.

CCD Gain

- 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?



CCD Gain

- 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

- 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

- 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

- 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.

CCD Gain

- 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.**