OBSERVATIONAL ASTRONOMY – I

Lecture 12

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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.

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

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:

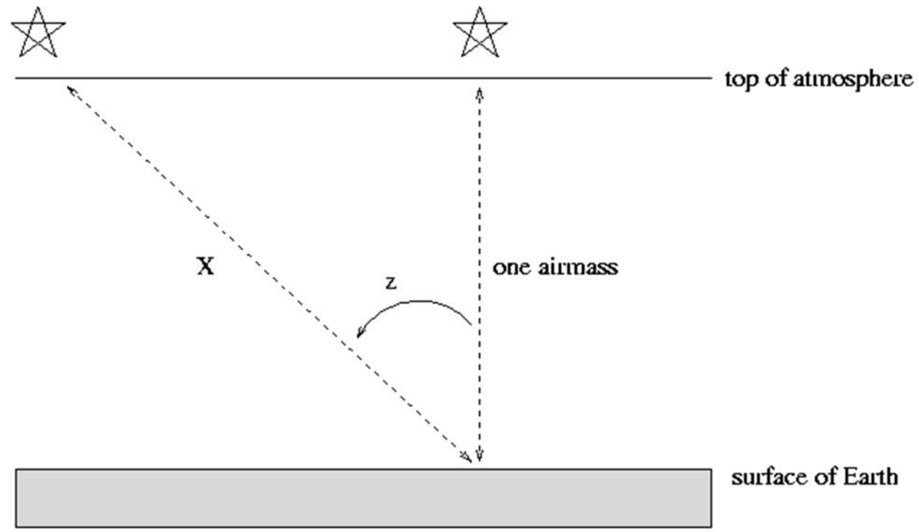
$$m_{obs} = m_{true} + k(\lambda) \sec Z$$

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.