PHY2003 ASTROPHYSICS I

Lecture 3. Optical and Near-Infrared Detection and Resolution

CCD detectors

The goal of all detectors is to record the photons collected by a telescope. The success with which they do this is called the quantum efficiency (QE) of a detector.

$$QE = \frac{\text{No. photons detected}}{\text{No. photons incident}}$$

Any detector has a QE that varies with wavelength *i.e.* $QE(\lambda)$

The CCD is a silicon chip composed of a rectangular array of square cells, each typically ~ 15 microns wide. A voltage is applied via microelectronics to make each cell isolated from its neighbours, in effect a single potential well.

Photons are recorded via the photoelectric effect. When a photoelectron is created in a cell, the voltage differences keep it there.

When placed at a focal plane, the CCD records the photon image as an array of electronic charge.

When the exposure is finished, the voltages around the cells are manipulated so that the charge flows out of the CCD into an electronic circuit called an Analogue to Digital Converter (ADC).

The ADC is a digital circuit that simply outputs a number (0–65535) that is proportional to the input current.

The final image is then displayed as an equivalent array of numbers called "counts" or Analogue-Digital Units (ADUs), arranged in pixels (picture elements), where each pixel is equivalent to a single original silicon cell.

As ADUs $\propto I \propto Ne \propto N\gamma$, we record a digital image where the value per pixel is directly proportional to the number of photons incident on the respective CCD cell.

Astronomical CCD cameras have three major advantages for the detection of optical photons:

- The photoelectic effect is linear.
- Some modern materials have very high quantum efficiencies, with $QE(\max) > 0.9$.
- A CCD records photons in digital form ready for computer processing.

Signal-to-Noise

Astronomers (and all other scientists) need to decide whether they have really detected something.

If we are simply dealing with photons, then these follow Poisson statistics. This tells us that if we count N events, the 1σ uncertainty on that measurement is $\pm\sqrt{N}$ *i.e.* 67% of the time the true average count is in the range $N \pm \sqrt{N}$.

If we count 100 photons, the uncertainty (noise) is 10. If we count 10000 photons, the uncertainty (noise) is 100. This is a large figure, but relative to the measurement it is much less.

We define whether an object or feature is clearly detected by measuring the Signal-to-Noise Ratio, or S/N.

For photons counting detectors (*i.e.* CCDs!), the signal is the number of photons detected N_γ, and the noise is random uncertainty caused by Poisson statistics

$\sqrt{N_\gamma}$.

Unfortunately, in all cases, there is more noise than just due to photons alone. The most important source is the Earth's sky. When we measure the brightness of an object, the photons will also contain photons from the sky, as the Earth's atmosphere emits a weak glow. Therefore the signal-to-noise in this case is

$$\boxed{S/N = \frac{N_\gamma}{\sqrt{N_\gamma + N_{sky}}}}$$

For bright sources $N_\gamma >> N_{sky}$, so in this case

$$S/N \simeq \frac{N_\gamma}{\sqrt{N_\gamma}} = \sqrt{N_\gamma}$$

For the faintest objects observed, $N_{sky} >> N_\gamma$, so in this case.

$$S/N \simeq \frac{N_\gamma}{\sqrt{N_{sky}}}$$

Angular Resolution

The resolution of a telescope is the minimum angle between two objects where the telescope can image the two objects distinctly.

$D =$diameter of primary, $\lambda =$wavelength of light.

From basic diffraction theory for constructive interference,
$n\lambda = d \sin\theta$.

At small angles in radians, $\sin\theta \simeq \theta$, and $n = 1$,

$$\theta_{min} \simeq \lambda/D$$

In practice, astronomers measure small angles in arcseconds, where $1^\circ \equiv 60$ arcminutes, 1 arcminute $\equiv 60$ arcseconds. In arcseconds,

$$\theta_{min} \simeq 206,265\lambda/D$$

Taking into account the circular diffraction pattern gives an extra factor of 1.22.

$$\boxed{\theta_{min} = \frac{1.22 \times 206,265\lambda}{D}}$$

Because the diameter of the telescope main optics D dictates the sensitivity and the resolution, telescope names often include D i.e. the 8.2m Very Large Telescope, the 2.4m Hubble Space Telescope and the 0.35 QUB Teaching Observatory.

Example: Uranus appears to be 4 arcsec in diameter. Can the human eye and the 4.2-m William Herschel Telescope resolve Uranus at 550nm?

In practice, most optical telescopes cannot achieve this because of the atmosphere. Winds and turbulence throughout the atmosphere refract the incoming light on timescales of $0.1 \rightarrow 0.001$ seconds.

The incoming starlight is blurred into a "seeing" disk around 1 arcsec in diameter. This is what is theoretically achieved by a $D = 12.6$ cm telescope!

Until the 1990's all optical telescopes had to cope with this limitation, which is why all astronomers use arc seconds as a unit of angular measurement. Now there are two ways around this.

(a) **Get rid of the atmosphere!** The 2.5-m Hubble Space Telescope (HST) achieves its theoretical diffraction limit.

(b) **Adaptive Optics** attempts to sample the incoming light on timescales of 0.01 seconds to rebuild the incoming wavefront. This is done by reflecting the collected light onto a small deformable mirror whose shape can be altered on timescales of ~ 0.01 seconds or faster.

But the technique only works reliably in the near-Infrared at $\lambda > 10^{-6}$m, and over distances of ≤ 30 arc sec.

Spatial Resolution

The amount of detail seen on an astronomical object depends on your angular resolution and the distance to the object. As the smallest angular detail is θ_{min}, if an object is d distant then the smallest physical size Δ that can be resolved is given by

$$\Delta = \theta_{min} d \ \ (\theta_{min} \text{ in radians})$$

Example: Alpha Centauri is the nearest solar-type star to our Solar system at a distance of 1.34 pc. Can the 10-m Keck I Telescope resolve this star using adaptive optics at a wavelength of $\lambda = 2.2 \times 10^{-6}$m?

In the Solar system, distances between objects are normally measured in Astronomical Units (au). Even at the distance of Jupiter (5.2 au), an optical telescope hampered by atmospheric "seeing" of 1 arcsecond can usually only resolve features larger than $3,800$ km.