Telescopes and Detectors

1 Reflection and Refraction

Telescopes and lenses work because of the way light behaves at the interface between two different media. The speed of light slows when it passes from air to another denser medium. This is because light is an oscillating electromagnetic wave, and many molecules have their electric charge unevenly distributed. The passing oscillating wave causes the molecules to oscillate, and this slows the light down. The speed of light is not constant in a medium, shorter λ radiation will be slowed the most. The ratio

$$n = \frac{c}{v} \tag{1}$$

is called the index of refraction. Because the light slows, the direction of travel changes. This is called **refraction**. At each boundary, some of the light gets refracted and some gets reflected. The relation between the incident angle, θ_1, and the refracted angle, θ_2, is called **Snell's Law**:

$$\frac{n_2}{n_1} = \frac{sin(\theta_1)}{sin(\theta_2)} \tag{2}$$

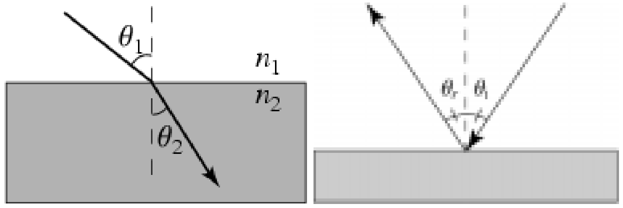

Figure 1: Snell's law and the law of reflection.

The relation between the indicent and reflected waves, or the law of reflection, is that they are equal with respect to the normal, *i.e.* $\theta_i = \theta_r$.

2 Telescopes

2.1 Image Formation & Focal Length

A mirror is described by a radius of curvature, and a **focal point** and the distance to the focal point, the **focal length**, f. The focal point is the point at which incident parallel rays travelling toward the mirror will meet after reflection. The distance from the mirror to the focal point is called the focal length. Rules of image formation:

- any incident ray traveling parallel to the principal axis of the mirror will pass through the focal point
- any ray passing through the focal point, will emerge parallel to the principal axis

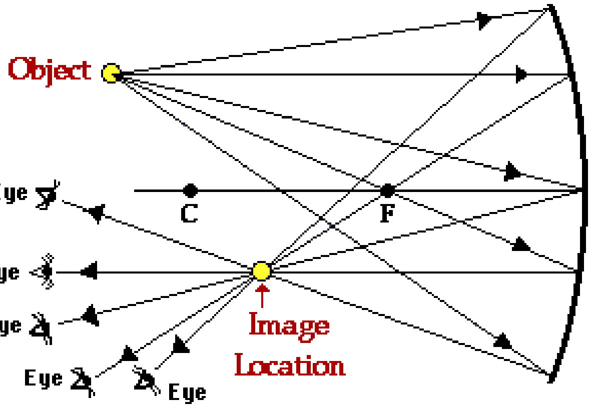

Figure 2: Formation of an image with a concave mirror.

If we are collecting light from an extended source, the amount of energy gathered by the mirror will be directly proportional to the area of the aperture (mirror), D^2 (where D is the mirror diameter. The incoming energy will be spread across a corresponding region of the image. The amount of energy per unit area per unit time in the image will be inversely proportional to the image area. The area of the image is proportional to the square of its lateral dimension, f. Thus the flux density (or brightness) of the image will be proportional to $(D/f)^2$. The term:

$$f/\# = \frac{f}{D} \tag{3}$$

is called the f-number or f-ratio, and it is given by the focal length divided by the diameter of the primary mirror or lens. The smaller the f-ratio, the "faster" the telescope (*i.e.* it concentrates more light in a small area).

2.2 Magnification

The main purpose of a telescope is to collect light. They can also magnify images (magnification is the ratio of the angular size of the object seen through an instrument relative to the angular size without the instrument). However, for most images in astronomy, magnification is not important. The magnifying power, M, is given by

$$M = \frac{fl_{obj}}{fl_{eye}} \tag{4}$$

where fl_{obj} is the focal length of the objective and fl_{eye} is the focal length of the eyepiece. From this equation it can be seen that the greatest magnification is with a long focal length telescope and short focal length eyepice. However, since most objects we will look at are not resolved (*e.g.* they are point sources), the magnification is irrelevant. The most important criteria for most applications is the telescopes **light gathering power**, or how many photons it collects. This is proportional to the area of the primary.

2.3 Resolution

Because of the wave nature of light, any time there is an obstacle that it interacts with (such as an aperture, mirror, lens etc.) if the path lengths of light from different regions is different, the waves can interfere with each other and will be be either out of phase (in which case they cancel and no light is visible) or in phase (causing a concentration of light). Thus, although stars are so far away that they appear effectively as point sources, the image made at the telescope will have a finite size because of this phenomenon of **diffraction**. The **resolution** is the smallest angular separation between 2 stars that can be resolved by the instrument. For a telescope of diameter D meters, at wavelength λ [m], the resolution in arcsec is given by

$$\theta = 2.5 \times 10^5 \frac{\lambda}{D} \tag{5}$$

We rarely achieve the **diffraction limit** of a telescope in the optical, but it is possible in the infrared at times from the ground. One of the reasons we don't achieve the diffraction limit is because of the effect of **seeing**. Seeing is the blurring of an image caused by turbulence in Earth's atmosphere. Air of different densities has different indices of refraction, n, and this causes the light to be refracted slightly differently. In other words, the atmosphere acts as if it is full of small lenses which re-directs the light slightly – and this blurs the image (makes it wider). you can see this effect on the bottom of a swimming pool on a sunny day; you never see images of the sun, just bright lines dancing over the bottom of the pool. This is an amplified example of "seeing" – but through a very thick "atmosphere" indeed. (See Fig. 6 for the effect on an image).

2.4 Types of Telescopes

There are many different telescope optical configurations, and they all have different advantages. Most telescopes have a **primary** mirror, which is the main light collector, and some have a **secondary** mirror which redirects the light to a desired focus. Some of these different configurations are shown in Fig. 7.

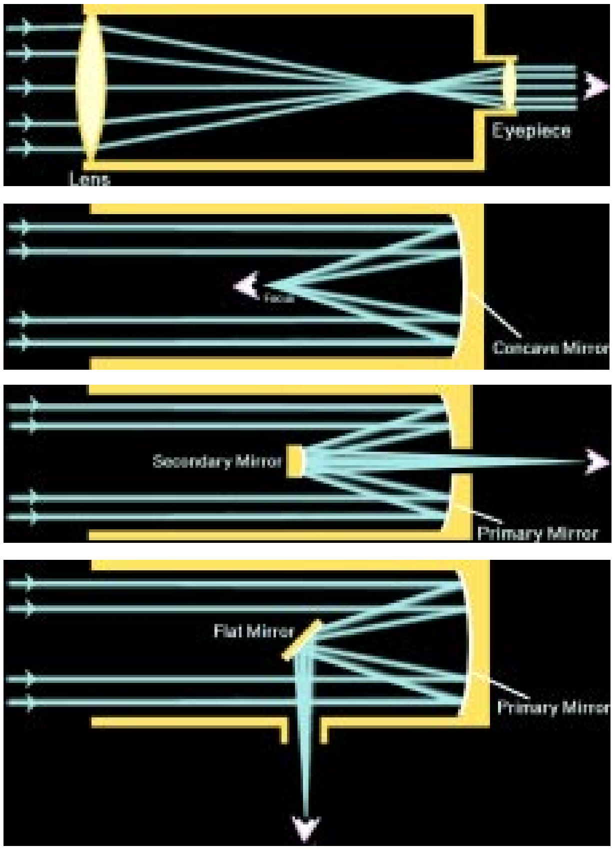

Figure 3: Examples of a 4 telescope types, showing the light paths for (a) a refractor; (b) prime focus reflector; (c) cassegrain focus reflector; (d) newtonian focus reflector.

2.5 Image problems and cures

- **coma** – Off axis light gets distorted into a comet-like appearance. The correction is to either put a thin lens, or corrector plate in front of the system, or to make the primary mirror a little hyperbolic.

- **chromatic aberration** – Because light of different wavelengths refracts differently (by different amounts) in glass, the focus of a lens will be different for different colors. A series of lenses can correct for this. Not present on reflectors.

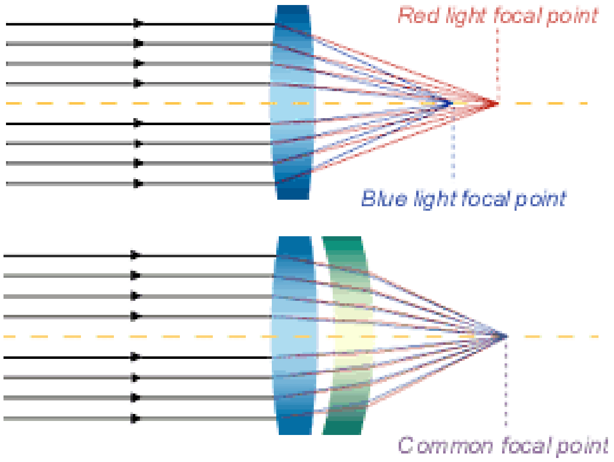

Figure 4: Chromatic aberration and its solution.

- **astigmatism** – Off axis rays in the horizontal and vertical plans focus at different points. Multiple lens components can correct for this in refractors, and a corrector plate can correct for this in a reflector.
- **spherical abberation** – Parallel light striking the spherical mirror near the center will come to a focus farther from the mirror than does light striking the mirror off axis. The solution is to create an aspherical or parabolic mirror - but this is more expensive.

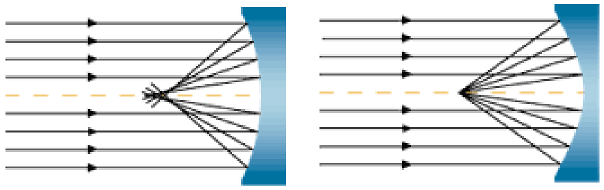

Figure 5: Spherical aberration, and the image from a parabolic mirror.

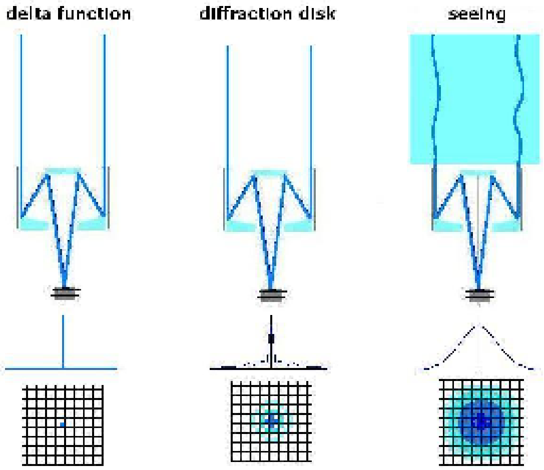

Figure 6: Ideal image from a point source, the effect of the wave nature of light (diffraction), the effect of the Earth's atmosphere "seeing".

3 Photoelectric Photometer

The photomultiplier is a light sensitive electrode which emits e^{-} when photons strike it as a result of the photoelectric effect. The e^{-} are accelerated by electrodes (which are called dynodes) and are collected at an annode. Each time the electrons strike a dynode, they produce a secondary shower of electrons. Typically the photomultiplier tube will experience a gain of about 10^6, e.g. for every incident photon there will be 1 million electrons detected out the back. These require very stable power supplies.

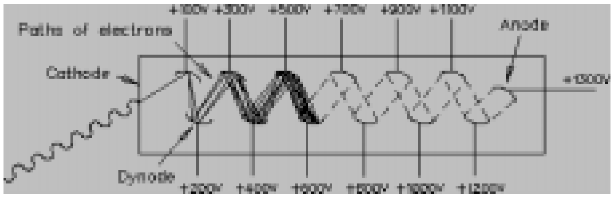

Figure 7: Layout of a photomultiplier tube.

Limitations and characteristics

- Typical optical tubes have low response toward the IR QE peaks near 30% at 4000 $\AA$
- Excellent response time – limited around 50 ps (due to electron travel time in tube). In otherwords, excellent instrument for very high time resolution applications.
- Highly linear in very low light level conditions.

4 Photography

The photographic process is a chemical reaction which occurs when light strikes film. All photographic processes rely on oxidation-reduction reactions.

- Emulsion contains crystals of silver halide (AgBr, Agcl, AgI or a combition) suspended in a gelatin.
- Light striking the emulsion creates a latent image
    1. Quantum of light frees an e$^-$
    2. e$^-$ is captured by Ag$^+$ ion
    3. Ag$^+$ ions migrate to neutralize charge
    4. Lattice alows migrated Ag$^+$ ions to form a speck of Ag grain
    5. This is called the latent image – which is proportional to the number of photons
- The image is made visible with a developer, which reacts with the silver halides and creates metallic silver. The greater the intensity of light, the greater the density of silver. By adding e$^-$ to the silver halide, we liberate the Ag, and this binds to the latent image specks.
- After developing, a stopbath is used to render the developer inactive.
- Then a fixer is applied to break up the non-exposed silver salts, so that these areas become transparent on the film.

If T is the ratio of the transmitted to incident intensity of light, then

$$log_{10}\frac{1}{T} \propto m_{Ag} \tag{6}$$

where m_{Ag} is the mass of silver. If D is the density or mass of metallic Ag per unit area, then

$$D = log_{10}\frac{1}{T} = -log_{10}(T) \tag{7}$$

Hurter and Driffield Curve describes the linearity of the photographic process. The dynamic range over which film behaves in a linear manner is only about 2.5.

- **low exposure** – optical density not dependent on Exposure, E, where E is the intensity of light × the exposure time.
- **medium exposure** – Linear (useful) region where $D \propto log_{10}(E)$
- **high exposure** – Saturation - where all grains are developed to Ag

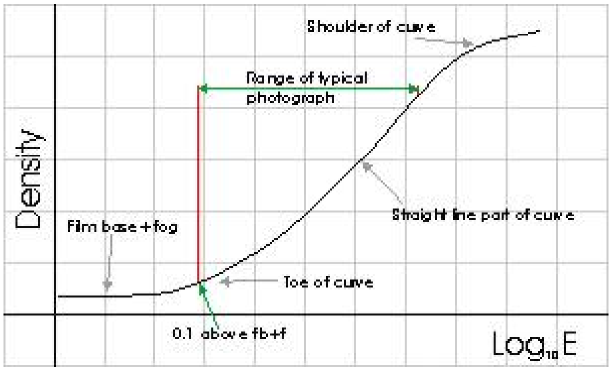

Figure 8: HD curve for photographic exposure.

The speed of film is a measure of D for a given E. A slow speed film has small grains and thus high resolution, and a high speed film has large grains and a low resolution, so there is always a trade-off. Another factor in selecting the film is the contrast (γ). Low contrast films have small changes in optical density with large changes in exposure, and the films are fast. High contrast films give very large changes in density with small changes in exposure, and they are slow (typically the film is black and white).

5 Charge Coupled Devices

The charge coupled device was conceived at Bell Labs in 1970 (Boyle & Smith, 1970), and the first one was produced by Fairchild Electronics with a format of 100 × 100 pixels in 1974. The first astronomical use was at Kitt Peak National Observatory in 1979. A CCD is a Si-based semiconductor arranged as a 2-D arrange of elements. The operation of a CCD depends on the photoelectric effect in semiconductors (such as Si).

- Incoming photons of light greater than the energy gap can excite electrons, which are then free to move about the material. Limitations:
    - low E photons will pass through with no effect
    - Not very sensitive to UV and blue – although we overcome this by coating the detectors with organic dyes.
    - High energy cosmic rays can trigger events
- The charge generated is collected in a series of electrodes, or pixels. The electrons are kept from moving between the pixels by external voltages.

- A time varying voltage can change the electric potentials to move the charge across the CCD and down to be read out and digitally encoded. This charge transfer process is nearly noise free and 100% efficient.

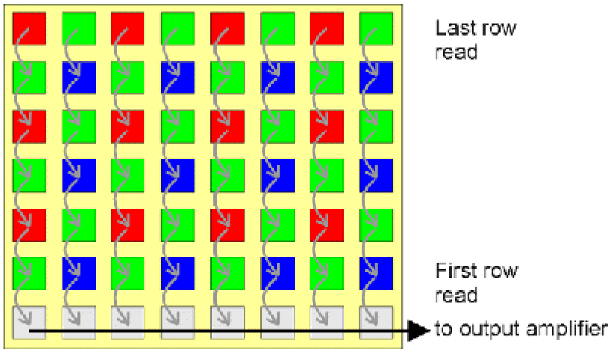

Figure 9: Readout pattern of a charge-coupled-device.

CCD detectors must be operated at temperatures near 150K, so are mounted at the end of a LN_2 dewar. Amateur CCD cameras are cooled electrically. At room temperatures, there is a lot of signal coming from the CCDs when there is no light. This is called dark current.

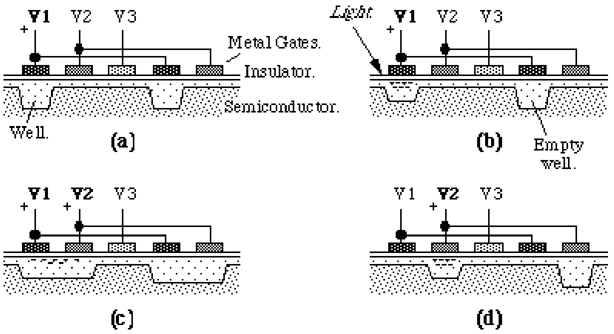

Figure 10: Schematic view of the CCD gates which control the voltages and charge transfer.

Device	QE	DR	Linear	Precision	Area
CCD	90%	10^5	yes	med-high	small
PMT	30%	10^6	yes	vhigh	vsmall
Photo	low	2.5	no	med	large

Note: DR = Dynamic range

6 Spectroscopy

6.1 Dispersion – the Grating Equation

Diffraction gratings function by the principle of interference. As light is reflected off of a grooved surface, the light will have taken different path lengths. Parallel light of wavelength $= \lambda$ coming in at incident angle α to the grating normal, comes in to two adjacent grooves, separated by d. Geometry shows that the path difference, ΔS is given by

$$\Delta S = d(sin\beta + sin\alpha) \tag{8}$$

Light from adjacent grooves will be in phase and interfere consstructively if ΔS is equal to integral multiples (m) of the wavelength λ:

$$m\lambda = d(sin\beta + sin\alpha) \tag{9}$$

where m is the spectral order.

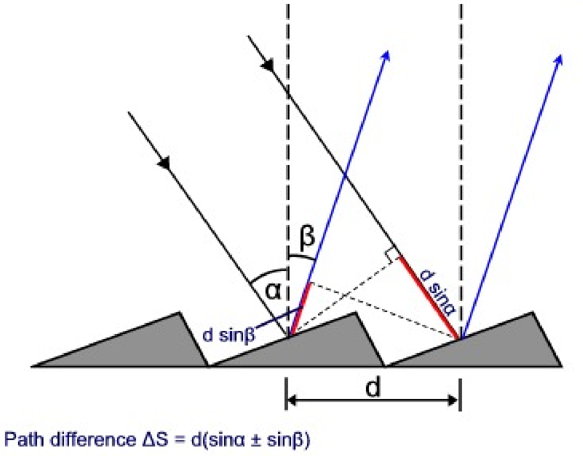

Figure 11: Interference of light from a spectroscopic grating.

6.2 The Spectrometer

Basic elements of a spectrometer:

- **slit** – focal point of the telescope brought to slit.
- **collimator** – parallelizes the light
- **diffraction grating** – disperses the light – each λ of light comes off the grating at a different angle
- **lens** – focuses the dispersed beam of light on the detector (typically a CCD)

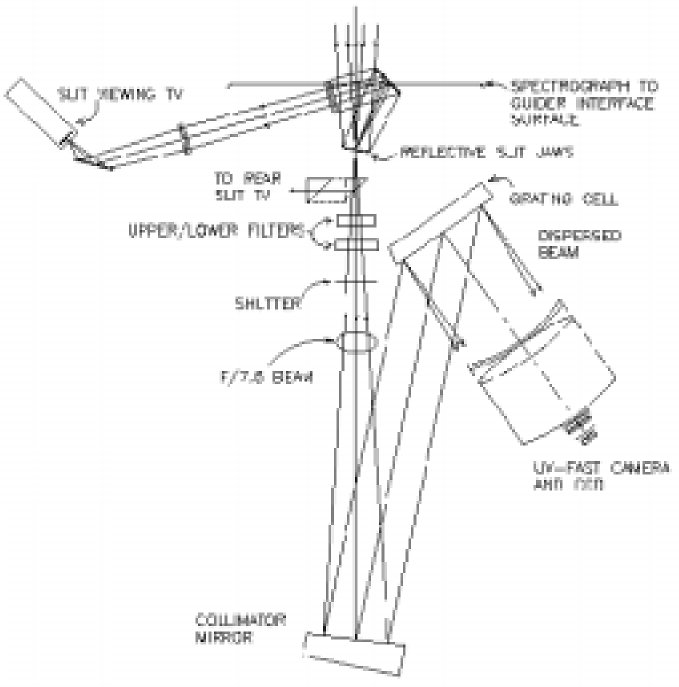

Figure 12: Optical layout of the Kitt Peak RC Spectrograph, showing the major elements.

[1] Boyle, W. and G. Smith (1970), “Charge Coupled Semiconductor Devices”, *Bell Systems Technical Journal* **49**, 587.