Lecture notes 1: The human eye

The human eye is not much in use as a professional tool of astronomy. On the other hand, it is of great interest to understand how it works and by doing so we may illustrate many of the principles and problems that we will meet later in the course.

The eye and brain work together, and the brain can correct for many of the aberrations suffered by the eye. Thus the brain compensates for the fact that the image on the retina is inverted and for chromatic aberration.

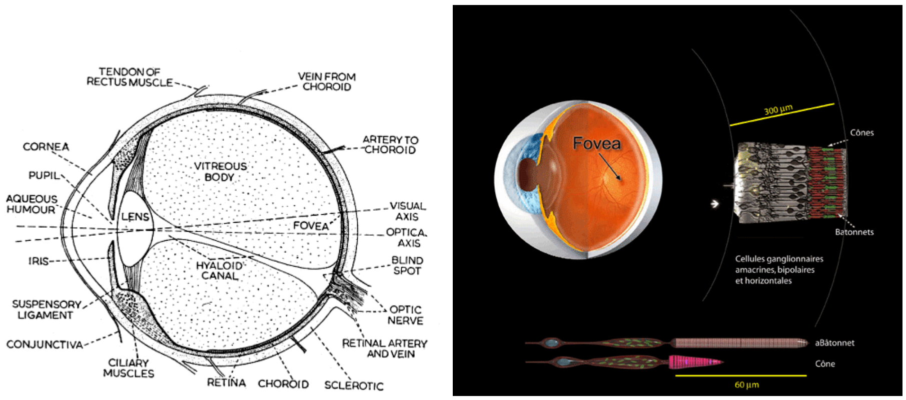

Figure 1: Cross section of the human eye (left), illustration of the eyes receptor cells; cones, used for color vision with the iodopsin layers arranged to the rigth, and rods with rhodopsin layers. Light enters these cells from the left before being absorbed by either iodopsin or rhodopsin.

Light is focussed on the retina, where there are two types of receptors: rods and cones. Cones for color reception, rods for black and white with higher sensitivity.

In the rods a pigment known as rhodopsin absorbs radiation. A protein with a weight of some 40 000 amu, arranged in layers 20 nm thick and 500 nm wide. Under influence of light a small fragment, a chromophore, will will split off. The chromophore is a vitamin A derivative called retinal (or retinaldehyde) with a molecular weight of 286 amu. The portion left behind is a colorless protein called opsin. The moment of visual excitation occurs during this break off process as the cell's electrical potential changes. This change in potential can then propagate along nerve cells to the brain. The rhodopsin molecule is then (slowly) regenerated.

The response of cones is similar, but in this case the pigment is known as iodopsin which also contains the retinaldehyde group. Cone cells come in three varieties with different spectral sensitivities (see figure 2).

In bright light much of the rhodopsin is broken up into opsin and retinaldehyde, and the rod sensitivity is much reduced so that vision is primarly provided by the cones, even though their light sensitivity is only of order 1% of the rods.

The three varieties of cones combine to give color vision. At low light levels only rods are triggered by the ambient radiation and vision is then in black and white.

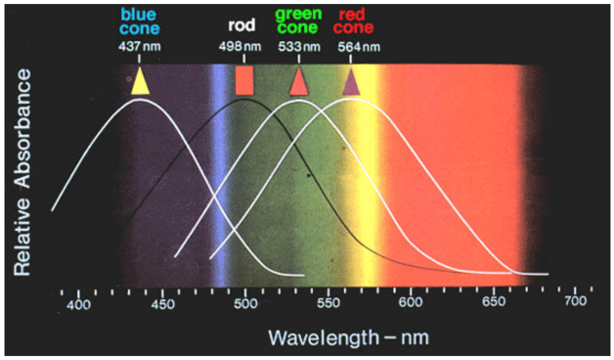

Figure 2: Absorption curves for the various types of cones and for rhodopsin.

Upon entering the dark from a brightly lit region rhodopsin will build up over a period of roughly 30 min, thus dark-adaptation takes this long and is based on rod cells. Somewhere between 1–10 photons are necessary to trigger an individual rod. However, several rods must be triggered in order to result in a pulse being sent to the brain as many rods can be connected to a single nerve fibre. The total number of rods is of order 10^8, of cones 6×10^6, these must share some 10^6 nerve fibres. Thus there are roughly 100 visual receptors per nerve fibre, note that there can be many cross connections between groups of receptors. Cones are concentrated towards the fovea centralis which is the region of most acute vision, while rods are most plentiful towards the periphery of the field of view. Weak objects are thus most easily visible with averted vision, *ie* when it is not looked at directly. In sum with all these effects the eye is usable over a range of illuminations differing by a factor $10^9 - 10^{10}$.

The Rayleigh limit of the eye, roughly given by λ/D where λ is the wavelength of the observed light and D is the size of the observing aperature, is of order 20 arcsec when the iris has its maximum diameter of 5–7 mm. However, for two separate images to be distinguished, they must be separated by at least one unexcited receptor cell, so even on the fovea centralis resolutin is limited in practice to between 1 arcmin an 2 arcmin. This is much better than elsewhere on the retina, since the fovea centralis is populated by small, tightly packed, singly connected cones. The average resolution of the eye lies between 5 arcmin and 10 arcmin. The effect of granularity of the retina is countered by rapid oscillations of the eye through a few 10 arcsec with a frequency of a few Hz, so that several receptors are involved in the detection when averaged over time.

The response of the eye to changes in illumination is logarithmic; if two sources A and B are observed to differ by a given amount, and a third source C is seen to lie midway between them, then the energy from C will differ from A by the same factor as it differs from B. The faintest stars visible at a good site (magnitude 6^{m}) corresponds to a detection of approximately 3×10^{15} W. Sensitivity will vary between indivduals and decreases with age, the retina of a 60 year old person will receive some 30% of the light seen by a person of 30-years.

The system used by astronomers to measure the brightness of stars is a very old one, and is based on the sensitivity of the eye. Hipparchos' catalogue of stars divided the stars into six classes from the brightest, of the first rank or magnitude, to the dimmest of the sixth magnitude. The present day system is based on this after the work of Norman Pogson put the magnitude scale on a firm basis in 1856. Pogson suggested a logarithmic scale that approximately agreed with earlier measurements: the difference between stars of magnitude m_1 and m_2 are given by

$$m_1 - m_2 = -2.5 \log \left(\frac{E_1}{E_2} \right)$$

where E_1 and E_2 are the energies per unit area at the surface of Earth for the two stars.

Exercises

1. Vega has a magnitude of roughly 0.0, Polaris a magnitude of 2.0. Estimate the magnitudes of the stars in Orions belt as well as Betelgeuse, Rigel, and Bellatrix. What is the magnitude of the weakest star you can find in the sky?

2. Mizar and Alcor in Ursa Majoris are separated by some $11'$. Can you separate them and see both stars? Estimate their magnitudes as well.