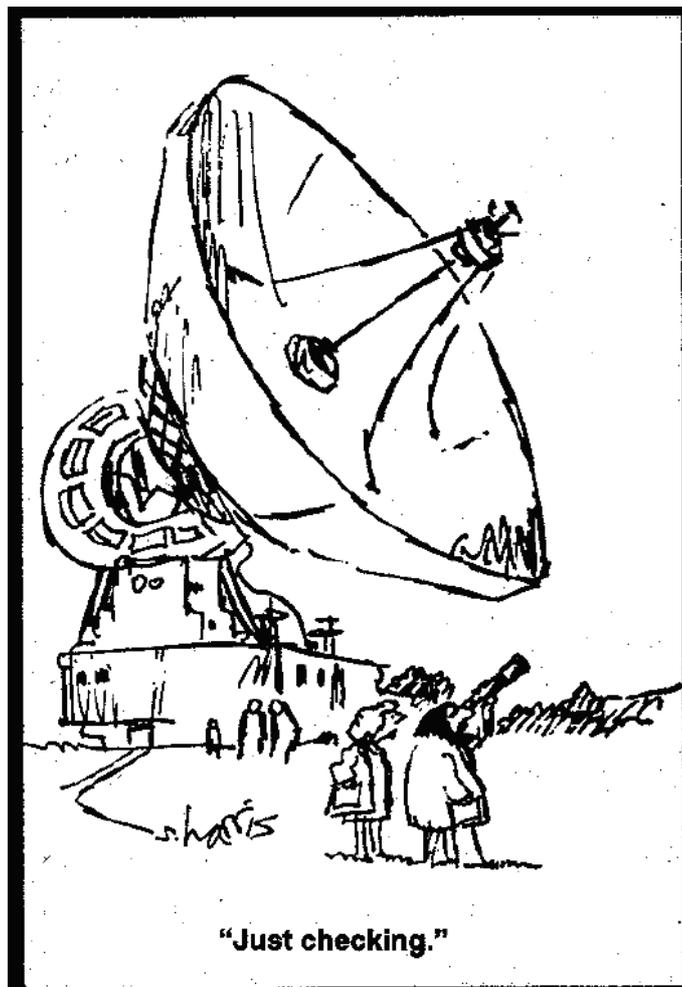


Detectors

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Contents

1	Introduction	3
2	Basic Definitions	4
3	The Eye	6
4	The Photographic Plate	8
5	The photomultiplier	11
5.1	Photocathodes	12
5.2	“Dark count”	12
5.3	Tube voltage	14
5.4	“Dead-time”	15
6	The CCD	23
7	The Photometer	25
8	Elements of positional astronomy	26
8.1	Parallax	26
8.2	Proper motion	29
8.3	Radial Velocity	32

1 Introduction

Various kinds of detectors are used in astronomy to study radiation. By using **area detectors** such as the photographic plate or the charge-coupled device (CCD), we can get information on position - and sometimes information on *changes* in position, which give us the **parallax** and **proper motion** of stars. Most detectors will give us a measurement of the intensity of radiation - leading to **brightness/luminosity, colour/temperature** information. And, when detectors are used in a spectrograph, we can obviously derive spectral information such as element abundances in the outer layers of stars, the surface temperatures and pressures (or gravities) and the (Doppler-shift) velocities in the line-of-sight - called **radial velocities** in astronomy.

For many applications in astronomy, variation with time is important. Stars, for example, are known to vary intrinsically (by pulsating) on time scales from one or two minutes to several years, and extrinsically (by, for example, eclipsing effects in binaries) on time scales from a few tens of minutes to many years. Pulsars exhibit variability (due to rapid rotation) on millisecond scales.

Detectors fall into two main categories:

- **thermal detectors** where the energy of photons is converted into thermal energy in the detector, resulting in a change of voltage (as in a thermocouple) or a change in semiconductor resistance (as in a bolometer), for example.
- **photon counters** where photons interact with material to force the ejection of electrons which can be accumulated and then “read out” as in a CCD or “amplified” to produce a measurable, countable “pulse”

In this lecture, we look at some basic ideas involving optical detectors and some simple principles.

Two later lectures will cover CCD devices in some detail, because they are now so vitally important in optical astronomy and are becoming so in the infrared. Another lecture will cover some of the rather specialised detectors and techniques involved in infra-red astronomy.

2 Basic Definitions

- **Quantum Efficiency.** This is the number of photons actually detected by a device, divided by the number that would be detected by a perfect detector under the same conditions and is usually expressed as a percent

For all detectors, quantum efficiency is a function of wavelength.

The QE may be easy to determine for photon counters, but quite difficult to measure - for example with a photographic plate (where the output is a silver atom) or in the eye (where the output is a nerve cell current). Typical QEs are $\sim 1 - 2\%$ for the human eye, $\sim 1 - 2\%$ for an untreated photographic emulsion, and maybe more than 80% for a CCD in the red.

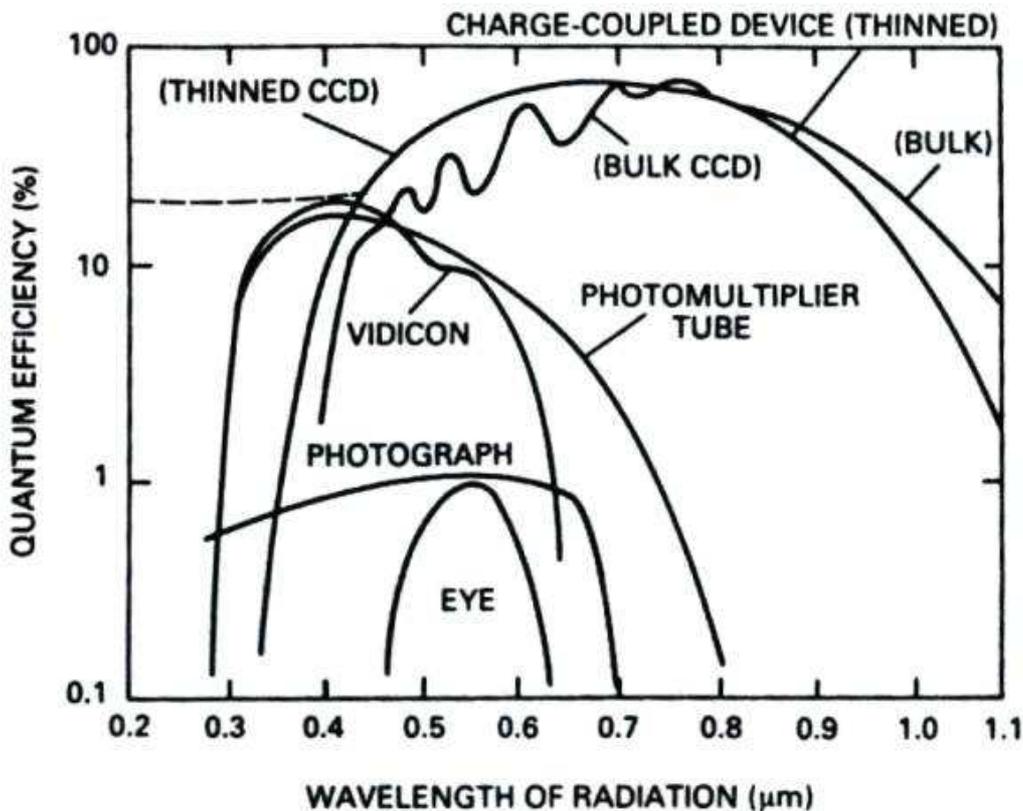


Figure 1: Comparison of quantum efficiencies of some common detectors.

- **Detective Quantum Efficiency (DQE)** arises from consideration of signal/noise and is defined by the input and output signal-to-noise ratios:

$$DQE = (S_{out}/N_{out})^2 / (S_{in}/N_{in})^2$$

One detector might have a better QE than another, but a worse DQE. For any detector, the QE and DQE are only the same if the detector introduces no noise – i.e. if it preserves the distribution of the incident photons.

- **Photon Flux** At low light levels, fluctuations in photon flux arriving from a thermal source (e.g. a star) can be described by Poisson statistics. The probability of n photons from a source arriving in t seconds is

$$P(n, t) = \frac{e^{-N} N^n}{n!}$$

Where N is the average flux from the source. This has the property that the r.m.s. fluctuation is

$$\sigma = \sqrt{N}$$

and this is called the photon noise or “shot noise” which dominates the noise at low light levels in the optical region and is an irreducible minimum noise level in any system. In the case of a “noiseless” readout system (e.g. a photomultiplier + electronics) the signal/noise (S/N) ratio is simply

$$\frac{N}{\sqrt{N}} = \sqrt{N}$$

- **Upper and lower thresholds** These are the lower limit for a triggered response (ultimately, a single photon) and the upper limit, corresponding to the saturation of the detector. The limits could be fixed by the detector itself or the measuring equipment.
- **The dynamic range** is then the difference between the upper and lower limits, often expressed as a factor (eg. this may be tens or hundreds of thousands in the case of CCDs) or in magnitudes for a photographic plate.
- **Noise** is any modification of a signal which reduces the accuracy with which the input signal (eg. flux) can be determined from the measured output (eg. electronic signal). Noise can be inherent in the radiation (“shot” noise) or might arise in the detector or recording electronics (eg. “read-out noise” in CCDs)
- **Background** is any reponse which adds to the signal (eg. light from the nighttime sky). This can usually be subtracted, but will invariably contribute something to the noise level. Sources of background include:
 - **“Dark noise”** arises from the detector even when no light is reaching it. An example is the thermionic noise from photomultipliers.
 - **Sky background** arises from several sources – night sky emission (extreme versions of this are the aurorae) – scattered light from artificial sources, and so on.
 - **Thermal radiation** is not usually important in the visible region but can be dominant in the infrared, where special techniques are required.
 - **Cosmic radiation background** becomes a serious nuisance in the more sensitive detectors. Note that even the eye can be affected at high altitude or in space.

3 The Eye

The eye/brain combination is the most amazing detector/processor system. Some of the important components are:

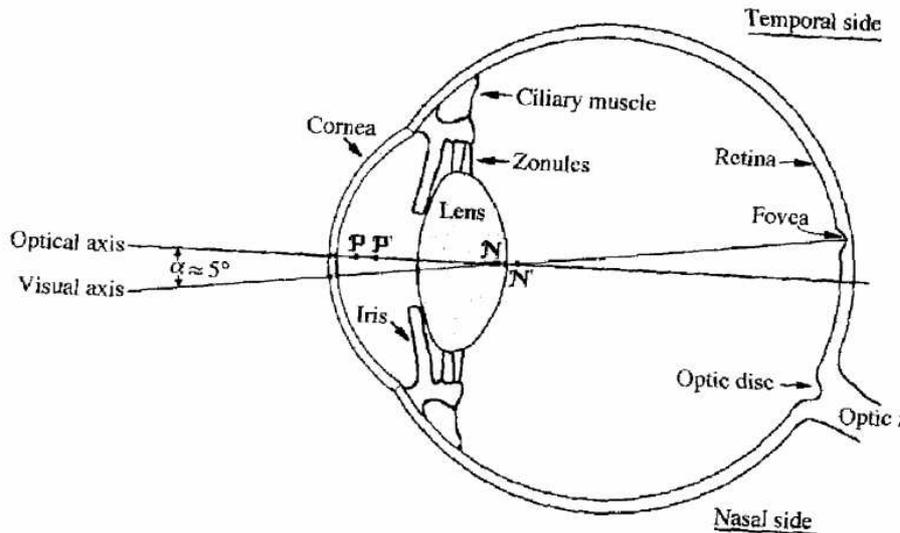


Figure 2: Sketch of some important elements in the eye.

- **The cornea**, the transparent front part of the eye, acts as a primary refracting/focussing element.
- **The iris**, the “colour” part of the eye, is a self-adjusting diaphragm or aperture which controls the amount of light entering the eye.
- **The lens** is a biconvex, slightly adjustable element which, together with the *aqueous humor*, a watery liquid filling the space between cornea and lens, focuses an inverted image on to the retina.

The lens changes curvature continuously to focus on objects at different distances - a quality known as **accommodation**.

The lens surfaces are not spherical and the cells comprising the centre of the lens are denser than those near the edge; both effects partially correct for spherical aberration (this is essentially absent when the eye accommodates at about 0.5m).

The transparency of the eye decreases with age, often accompanied by “yellowing”. An extreme version of this is the cataract.

- **the retina**, a thin layer at the back of the eye. This is composed of a layer of photoreceptors – light detecting cells which convert the light to a neural signal – and a network of nerve tissues to transmit information to the brain. Where the nerves bunch together to leave the eye, there is a “blind spot” on the retina. The light detecting cells are of two types:

- **cones** – about 5 million of them. These are about $1 - 1.5 \mu\text{m}$ in diameter and are responsible for colour vision (with the brain) but only operate in fairly high light levels (“daytime” or **photopic** vision).

The cones are mostly located in the **fovea**, a small area near the centre of the retina with an angular diameter of about two degrees. This is therefore the region with the best colour perception and, because the cones are densely packed, it has the best resolution (about an arcminute).

There are three kinds of cones, differing only in spectral response (S, M and L - with peak responses at around 430, 530 and 560 nm) giving you your colour vision.

- **rods** – about 100 million of them. These are about $2 \mu\text{m}$ in diameter and do not produce colour vision, but are much more sensitive to low light levels (“nighttime” or **scotopic** vision). In strong light levels, the rods saturate. They are connected in groups to a single nerve fibre, effectively giving a larger detector area.

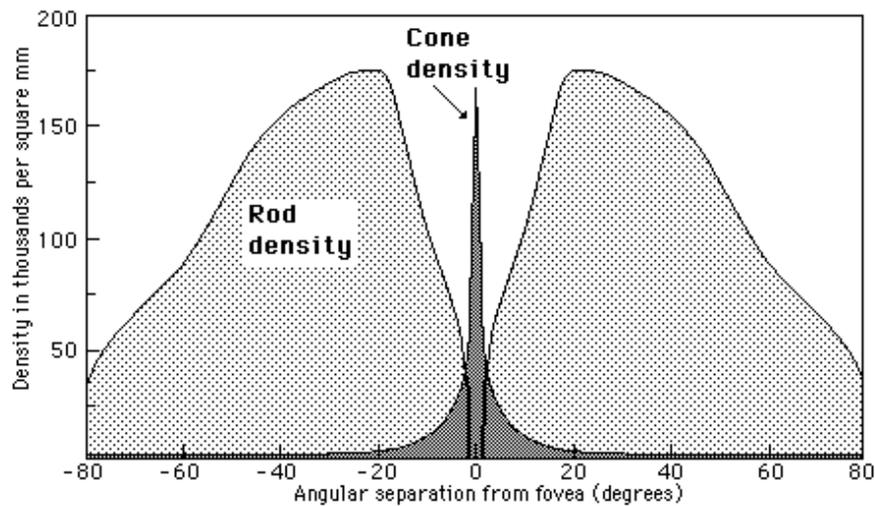


Figure 3: Representation of the distribution of rods and cones on the retina.

Immediately outside the fovea, rods and cones are mixed; further away from the fovea, rods dominate.

- **The brain** uses the differences between the two images – one from each eye – to construct a “three-dimensional” image – to give depth or distance perception. It also manages to “ignore” chromatic aberration effects and to create colour perception.

(see also Brou et al., 1986. *Scientific American*, **255**, No.3, 80)

There are a number of interesting points:

1. The eye, with “gain” control in the opening and closing of the iris and, more importantly, the two types of detector cell, is effective over a working range (dynamic range) of more than a billion to one, far exceeding artificial detectors.
2. As light levels fall, the eye switches to rod vision. Starting from bright light, it takes the eye about half an hour to reach full sensitivity – approximately the time from sunset to the end of “civil twilight”. This is referred to as “**dark adaptation**” and takes longer after

prolonged exposure to ultraviolet (eg. a day on the beach). Deep red light improves the speed of dark adaptation.

Scotopic vision is not colour vision, so everything looks gray at night (unless sufficiently illuminated).

3. With the cones inoperative at low light levels, the fovea effectively becomes another blind spot, so it's harder to see small sources (eg. stars) when looking directly at them. It's better to look slightly to one side – this is called **averted vision**.
4. Assuming the iris has an aperture of around 4mm, the focal length of the eye is about 15mm and the effective wavelength of the eye is about 530 nm, the resolution of the eye is then $\sim 2.4 \mu\text{m}$.

4 The Photographic Plate

The photographic plate, a light-sensitive emulsion coated on a glass or film base, usually used in conjunction with broad band-pass filters, has been in astronomical use for over a century for direct imaging, photometry and spectroscopy.



Figure 4: The great comet of 1882 photographed at the Royal Observatory, Cape of Good Hope (now the SAAO) by David Gill. This was one of the first astronomical photographs ever taken and led to the idea of mapping the sky photographically (the “Carte du Ciel”).

Plates had advantages:

- They were relatively cheap and simple.
- They could store a lot of information. A “slow”, fine-grain emulsion might have a resolution of 100 line pairs/mm and therefore $\sim 10^4$ pixels (“picture elements”) per square mm. A Schmidt plate ($\sim 350 \times 350$ mm) thus contains $\sim 1.2 \times 10^9$ pixels. If each pixel is capable of registering 6 bits of information (2^6 different density levels) then a Schmidt plate can store $\sim 8 \times 10^{10}$ bits (5Gb) of information.
- They could be used for “wide-angle” imaging (Schmidts typically $\sim 6^\circ \times 6^\circ$ fields) and could measure extended objects and/or millions of stars with a single exposure.
- The dimensional stability of glass is very high - made plates good for astrometry, the accurate measuring of positions of objects.

But also significant disadvantages:

- The photographic process is not linear (see **characteristic curve** below).
- The data are not readily available - the plate needs to be scanned by a micro-densitometer of some kind, to digitise the data.
- Calibration is a difficult process with many possible sources of error. The processing procedures can introduce non-uniformity on a plate and from plate to plate.
- The quantum efficiency of the photographic emulsion is typically a percent or so – very low. It can be improved somewhat by various processes (“hypersensitisation”).

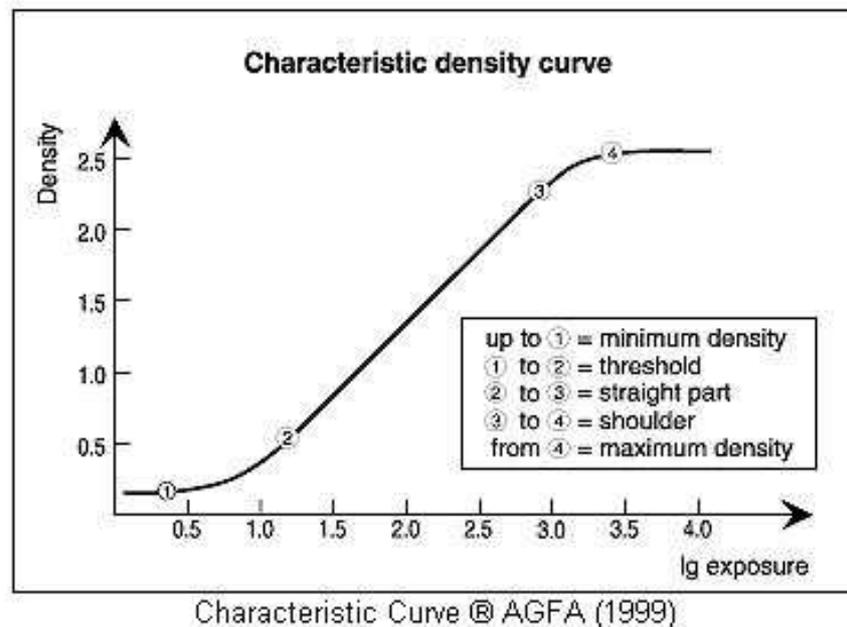


Figure 5: Schematic intensity/density calibration curve for a photographic emulsion – the “characteristic curve”.

The **characteristic curve** is composed of a number of regions (cf. figure):

- below (1), in very short exposures, even the brightest parts of the image don't get significantly above background (“base + fog”);
- between (1) and (2), the brightest parts register, but the faintest don't, which results in a non-linear increase in the intensity/density;
- between (2) and (3), the response is linear (well, $D \propto \log I$) and the gradient (γ) is a measure of the **contrast** of the emulsion;
- between (3) and (4), the brightest parts of the image start to saturate
- beyond (4) everything saturates.

Nowadays, the photographic plate or film is really only used significantly in wide-angle cameras – Schmidt telescopes – but is still extremely useful in some contexts, such as “survey” work (e.g. Edinburgh-Cape survey) and astrometry.

A number of projects are under way (eg. the UK “VISTA” project) to build or upgrade Schmidt-type telescopes with CCD arrays. VISTA will be equipped with *fifty* 2024×4048 CCD detectors, optimised for the red and sixteen $2k \times 2k$ CCDs for the near infrared. Thus a single visible-region “picture” would comprise about 400 million pixels – or about 800 Mb of data. (See www.vista.ac.uk)

Another (small) wide-angle system under construction is the SuperWASP system which will take rapid exposures of selected fields to search for planets (by observing ‘transit’ events). This camera will generate about 8Gb of data per night. Storage systems in the tera- or even peta-byte ranges will be required unless radical techniques are employed.

5 The photomultiplier

A photomultiplier (also called “phototube” or just “tube”) is a device to convert photons into electrons and to “multiply” the electrons into a measurable current or - more usually nowadays - “pulses” of electrons which can be counted by a digital counter (“photon counting”).

A photoemissive photocathode releases electrons when struck by photons (photoelectric effect). The electrons are accelerated towards the first dynode where they strike, releasing more electrons, which are accelerated towards the second dynode, and so on. The various elements are housed in an evacuated “tube”.

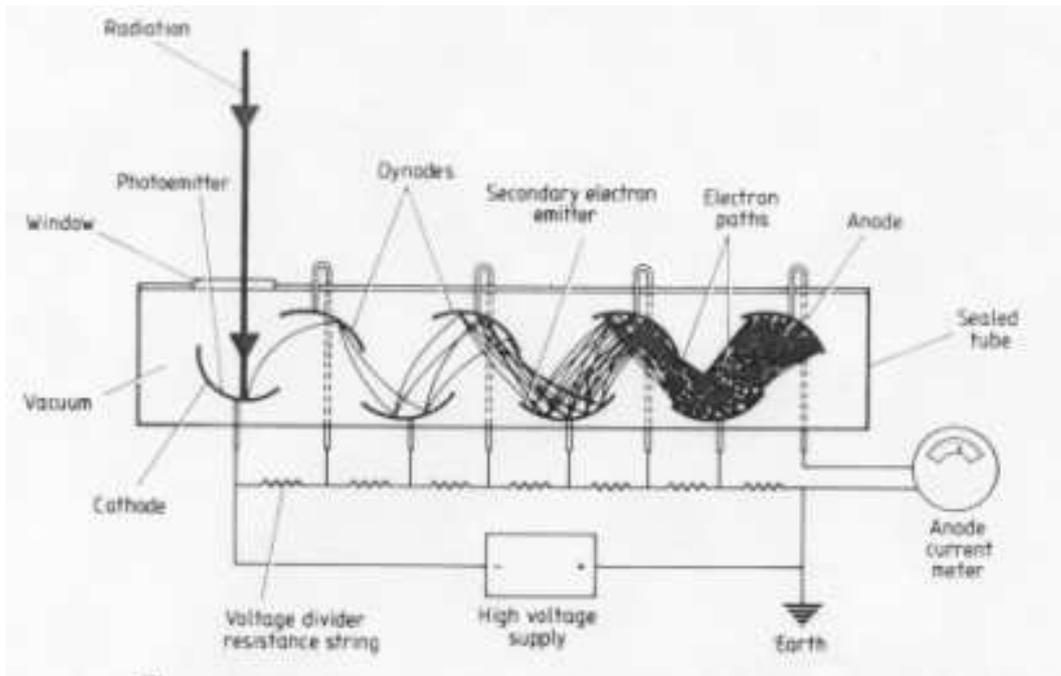


Figure 6: Schematic of the operation of a side-window photomultiplier with an opaque (reflection) photocathode.

The pulse of electrons from each detected photon is “collected” at the anode and usually counted as a single event (pulse-counting) rather than integrated into a total charge (dc integration).

A photomultiplier should be essentially free from “read-out” noise and the main source of noise will be “shot noise” (photon statistics). There are a couple of other important considerations:

If the gain at each stage is g – called the **secondary electron emission ratio** – and there are n dynodes, the total gain is obviously g^n . Since typical gains are ~ 3 – 5 electrons/stage and photomultiplier tubes often have 10-12 dynodes, total gains can be around 10^5 to 10^8 . Note that the secondary electron emission ratio is given by:

$$g = A.E^\alpha$$

where A is a constant, E is the interstage voltage and α is a coefficient determined by the dynode material and geometric structure of the tube (typically, $\alpha = 0.7$ to 0.8). When a voltage V is

applied between anode and cathode, the current amplification (“gain”) is given by:

$$g^n = (AE^\alpha)^n = A^n \left(\frac{V}{n+1} \right)^{\alpha n} = K.V^{\alpha n}$$

Since photomultipliers typically have 10 to 12 stages, the anode output will vary as the ~ 7 th to 10th power of any voltage fluctuation. Clearly, a very stable voltage supply, with minimum ripple, drift and temperature variation, is required.

Some typical photomultiplier types are shown in the figure; the type used will depend on requirements. The linear-focussed tube, for example, has a very fast response time, and the venetian-blind type has a wide cathode.

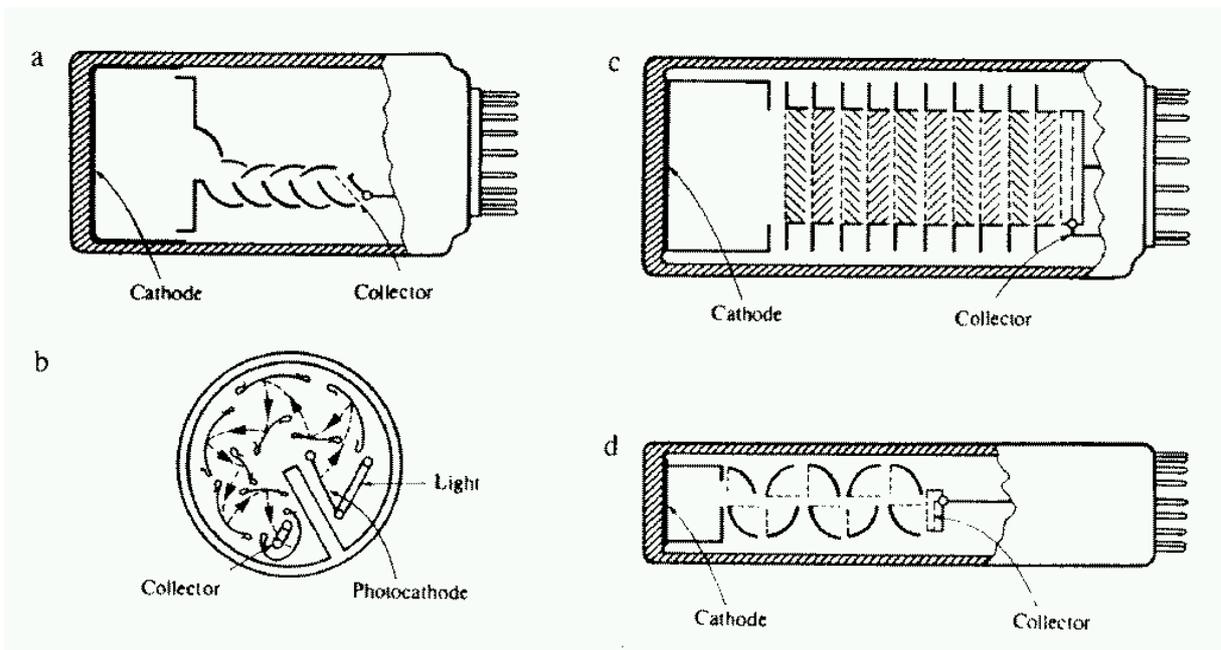


Figure 7: Some examples of photomultiplier structures: (a) Linear-focussed, (b) Circular-cage (“Squirrel-cage”) or circular-focussed, (c) Venetian blind, (d) Box and grid.

5.1 Photocathodes

Some common photocathode materials are AgOCs (S1), Cs_3Sb (S11), ”trialkali” – $(\text{Cs})\text{Na}_2\text{KSb}$ (S20) and GaAs (Gallium Arsenide), and generally give responses from about 300nm to 800nm (near uv - near ir). See Fig 8.

The photo-emissive material on the dynodes is often SbCs or BeCu, for example.

5.2 “Dark count”

Even with no light falling on the cathode, electron pulses still arrive at the anode; these come from a number of sources, for example:

- **Thermally emitted electrons from the photocathode and dynodes.** Thermal electrons from the cathode can be substantially reduced by cooling the tube (this is usually done

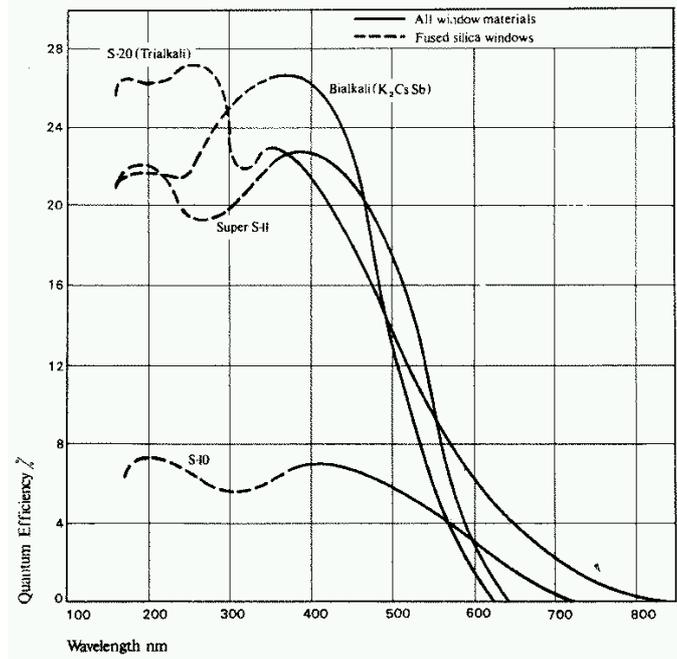


Figure 8: Examples of photomultiplier sensitivities (quantum efficiency) as a function of wavelength.

with a Peltier-effect cooler to about -20°C) and pulses arising from the dynodes can usually be taken out by the “discriminator” (in pulse counting mode) as they will be smaller than pulses from the cathode.

Cooling a GaAs tube from about $+20^{\circ}\text{C}$ to about -20°C will typically reduce the dark count from several thousand per second to about ten per second.

Tubes with smaller cathodes also win here.

- **Electrons generated by positive ions from residual gas in the tube.** These produce “correlated” noise which can be a nuisance. Tubes can be selected for low noise characteristics.
- **Cosmic rays generating Čerenkov radiation.** At sea level, there is something like one particle $\text{sec}^{-1} \text{cm}^{-2}$ – and there’s nothing you can do about it – although the effect will be smaller with a smaller cathode.
- **Radioactive isotopes**, particularly ^{40}K , ^{238}U and ^{232}Th , in the glass envelope. Isotope decay produces Čerenkov radiation and also directly interacting electrons. Generally manufacturers try to select glass low in ^{40}K . Again one can select tubes with low dark counts – which are, of course, more expensive.
- **Leakage currents** in the dynode connections. These can be reduced by proper insulation and keeping things “dry”.
- **Magnetic effects.** It is necessary magnetically to shield the tube as changes in magnetic field (even the orientation of the earth’s magnetic field relative to the tube as the telescope is moved) can have undesirable effects.

Provided the dark count is not too high and, more importantly, is stable (usually effected by cooling the tube to a stabilised temperature), it is not a problem. The usual mode of use in astronomy is to measure a star through a tiny aperture (to exclude the light of other stars) which also includes light from the “background” sky. A measurement is then made of the “empty” sky. The former minus the latter gives a measure of the light from the star alone – and, of course, both measures include a (hopefully small and constant) dark count.

Both the spectral response and sensitivity of a photomultiplier are temperature dependent, so that cooling the tube – or, at least, stabilising the temperature – has the useful effect of stabilising these quantities as well.

5.3 Tube voltage

As noted earlier, the gain of a photomultiplier is very dependent on the applied voltage – so this must be very stable. Such power supplies are readily available (though rarely cheap).

If a constant light source is applied to the tube, and the voltage increased, at first, no counts will be seen because the pulses of electrons at the anode are very small and are eliminated by the electronics (the discriminator). Then the count rate increases rapidly until essentially all the photoelectrons produced at the cathode are being counted as anode “pulses”. As the voltage increases further, dark counts start to increase exponentially and the count rate rises rapidly again (see Fig 2.5)

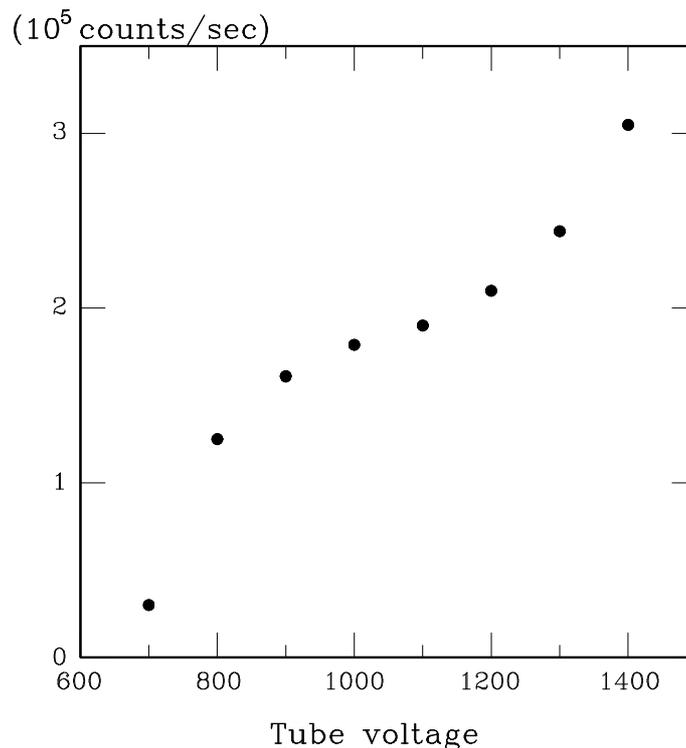


Figure 9: Count rate vs voltage for a constant light source. Best voltage ~ 1050 v.

Clearly, the photomultiplier should be operated on the **voltage plateau** for greatest stability.

5.4 “Dead-time”

The dead-time or, more properly “pulse-coincidence loss” results from the fact that although the photomultiplier is linear in response (up to a certain level – usually much greater than 10^5 counts/sec), the counting electronics cannot separate pulses which completely or almost completely overlap in time of arrival. This results in a kind of saturation effect at high count rates which can, however, be corrected to a high degree of accuracy by simple experiments.

From Bose-Einstein statistics, the probability $P(t)$ that two photons arrive separated by time t is

$$P(t) = \lambda e^{-\lambda t}$$

where λ is the arrival frequency. The number of photons which arrive (“together”) in a very short time interval ρ is given by

$$n_\rho = N \int_0^\rho P(t) dt = N \int_0^\rho \lambda e^{-\lambda t} dt$$

where N is the number of photons arriving in the total measurement time. If that time is 1 sec, the mean number, N is the arrival frequency, λ , and integrating gives

$$n_\rho = N(1 - e^{-N\rho})$$

If n is the number of photons actually counted per second (i.e. with coincidence losses included)

$$n = N - n_\rho = N e^{-N\rho} = \frac{N}{e^{N\rho}}$$

If $N\rho$ is small (which it is – so that squared and higher terms are safely negligible) we can approximate $e^{-N\rho}$ with a McLaurin expansion terminated after the first order so

$$n = \frac{N}{1 + N\rho}$$

or, rearranging,

$$N = \frac{n}{1 - n\rho}$$

We can make use of this practically by, for example, selecting a large (L) and small (S) aperture and making repeated measurements of the (uniformly illuminated) twilight sky. These need to be fairly rapid as the sky brightness will be changing (but one can interpolate). Since the size of the apertures is unchanging:

$$\frac{N_L}{N_S} = \alpha = \frac{n_L(1 - n_S\rho)}{n_S(1 - n_L\rho)}$$

and with some tedious substitution and approximation (eg. losing terms in ρ^2) one can derive:

$$\frac{n_L}{n_S} \simeq \alpha + \rho(1 - \alpha)n_L$$

and the zero point and gradient of a linear plot of n_L/n_S against n_L give the “dead time” or “pulse-coincidence loss”, ρ .

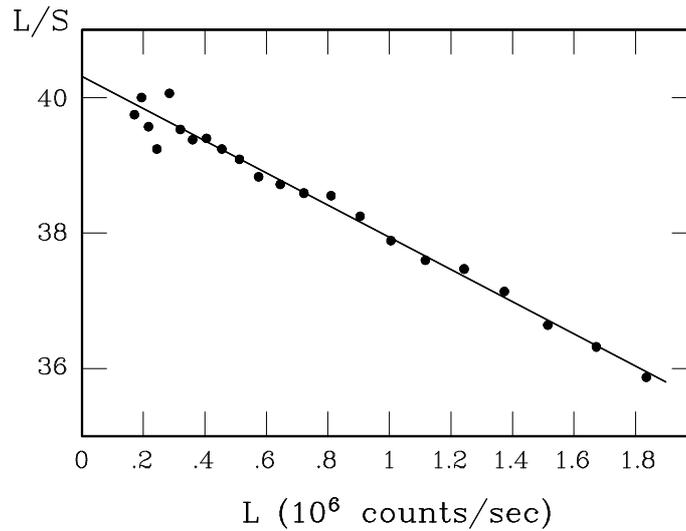


Figure 10: “Dead-time” plot for an EMI 6256 (S-11) photomultiplier

In the example shown in the figure, apertures of 9 (S) and 60 (L) arcseconds were used, so the ratio of areas – or photon counts – is $(60/9)^2$ or about 45. From the graph, the y-axis intercept is

$$\alpha = 40.31$$

and the gradient

$$\rho(1 - \alpha) = -2.376 \times 10^{-6}$$

(Note that the abscissa is in millions of counts per second)

So the dead-time

$$\rho = 60 \times 10^{-9} \text{ seconds}$$

Since

$$N = \frac{n}{1 - n\rho}$$

we can write

$$N \simeq n(1 + n\rho) = n + n^2\rho$$

Typical values for the dead-time are a few tens of nanoseconds. Assuming $\rho = 30 \times 10^{-9}$ sec and given that the correction to the observed counts, n , to get actual counts, N , is $n^2\rho$ then

for 10^4 counts/sec, the correction is 3 counts or 0.03%
 for 10^5 counts/sec, the correction is 300 counts or 0.3%
 for 10^6 counts/sec, the correction is 3×10^4 counts or 3%

Advantages of photomultipliers:

- Relatively cheap (not so true any more!) and easy to operate.

- LINEAR and very accurate even at fairly low count rates (but see section on “dead-time”, will also show saturation-type effects at high count rates).
- Can be used for very fast photometry (millisecond or faster, in principle).
- Fair quantum efficiency (up to about 30%) see figure

Disadvantages:

- Can only measure one star at a time.
- Sky has to be measured separately.

Some people will tell you that photomultipliers are no longer useful – having been replaced by high-quantum-efficiency area detectors such as CCDs.

Whilst this is true to some extent, there are certain specialised applications where they are invaluable. These include:

- High speed applications.
- Bright objects.

The High Energy Stereoscopic System (HESS) for the detection of Čerenkov radiation from very high energy cosmic rays is one good example:



Figure 11: Two of the four (Phase 1) $\sim 11\text{m}$ telescopes of the HESS telescopes for detecting Čerenkov radiation from high energy cosmic rays.



Figure 12: Top end detector for the first HESS telescope. Note the array of 960 photomultipliers.

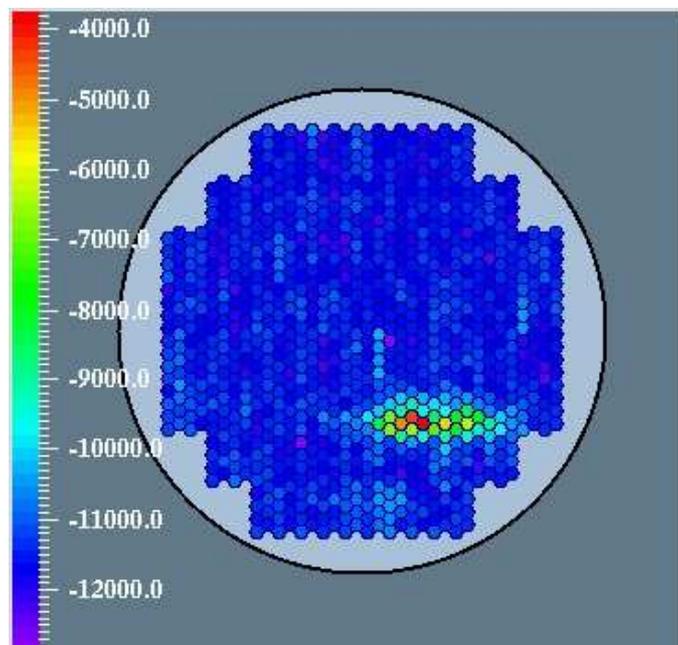


Figure 13: Representation of one of the first detections of Čerenkov radiation from the first operational HESS telescope.

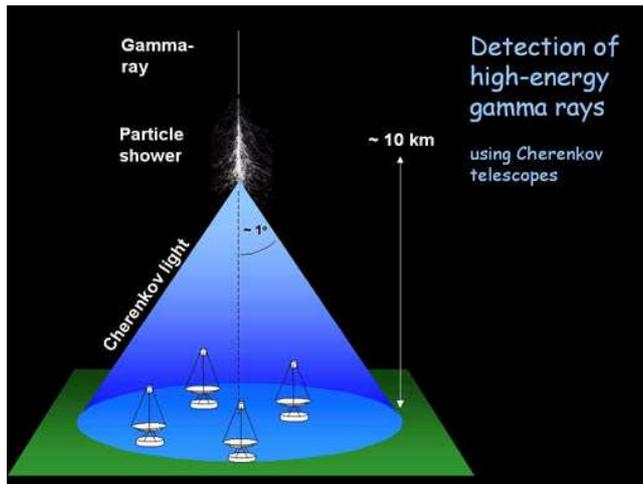


Figure 14: HESS telescope schematic. A high energy γ -ray produces a “burst” of particles travelling faster than light (in air) which produces a cone of Cerenkov radiation detectable by the HESS array.

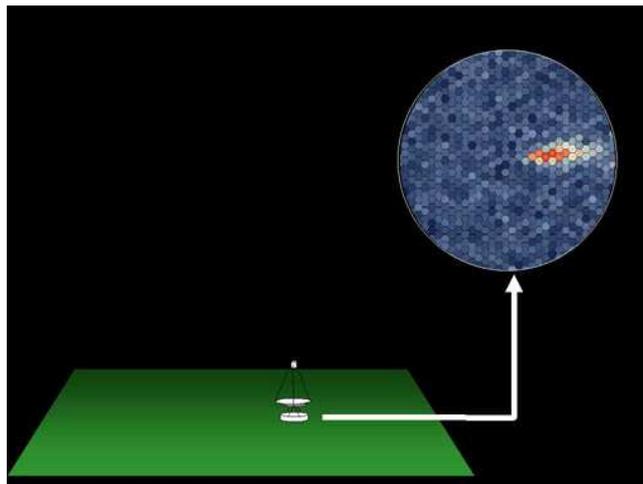


Figure 15: HESS telescope schematic. Each telescope registers a “hit”. For an event to be recorded at least two telescope must detect close to simultaneous events.

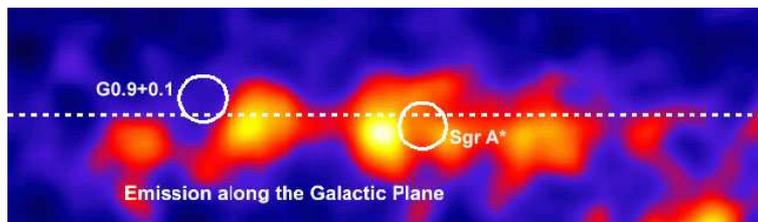


Figure 16: Recent result; HESS detects γ -ray afterglow from Galactic centre gas clouds, indicative of a pre-historic particle accelerator (see *Nature*, 439, 695, 2006 Feb).

And the Kamiokande neutrino detector in Japan is another:

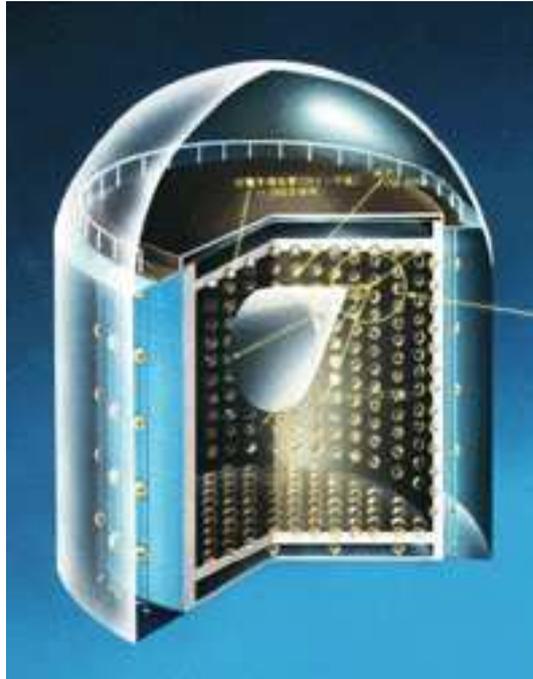


Figure 17: Artists impression of the **Super Kamiokande** neutrino detector – actually located about a kilometre underground. The $\sim 40\text{m}$ high tank holds 50 000 tons of pure water monitored by $\sim 11\,200$ $\times 50$ cm photomultipliers to detect Čerenkov radiation.

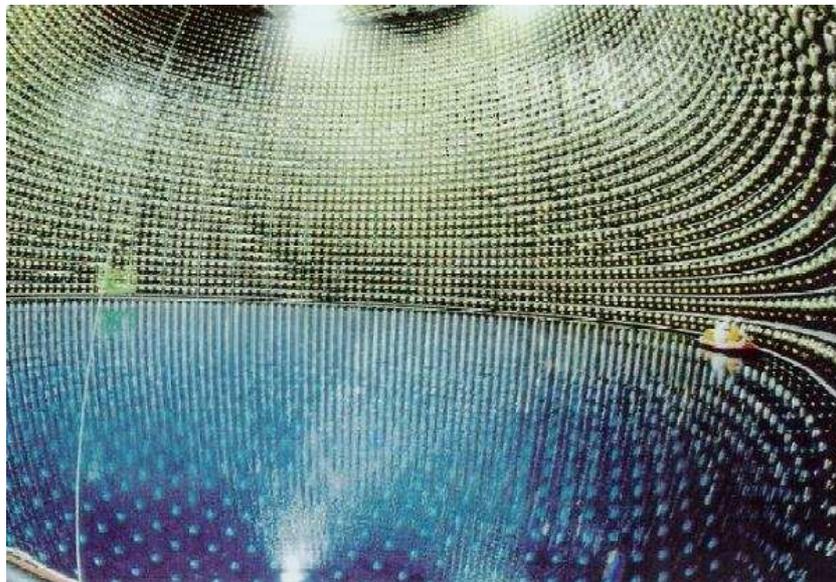


Figure 18: The inside of the Super Kamiokande tank as it was being filled with pure water. The tank is lined with photomultipliers; some idea of scale can be gained from the small dinghy on the right. The photomultipliers are of Venetian-blind type with bialkali (Sb-K-Cs) photocathodes giving a quantum efficiency of about 22% at typical Čerenkov wavelengths ~ 390 nm.

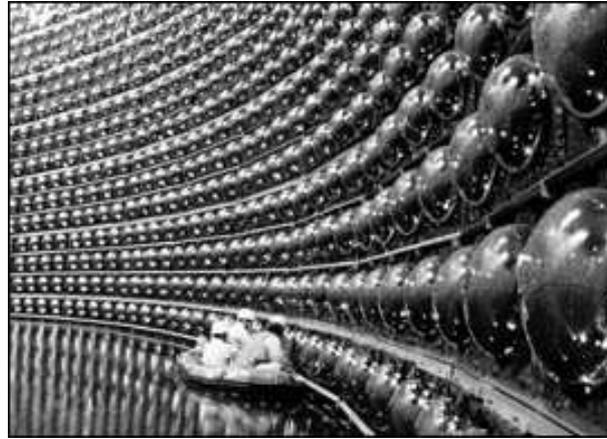


Figure 19: Close up of the interior of Kamiokande.



Figure 20: A real cutie – a Hamamatsu R1449 photomultiplier developed for proton decay and muon detection.

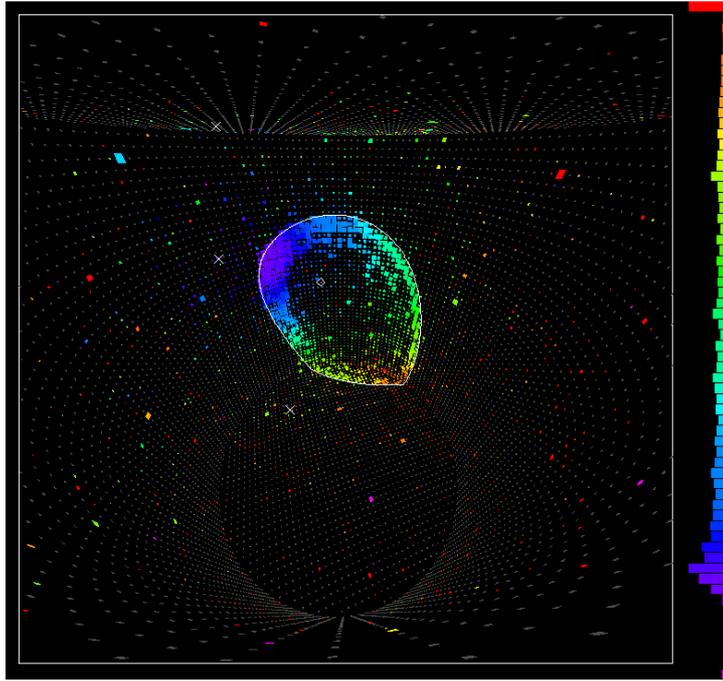


Figure 21: Super Kamiokande: 1063 MeV neutrino strikes a free proton and produces a 1032 Mev muon (see Kamiokande web page).

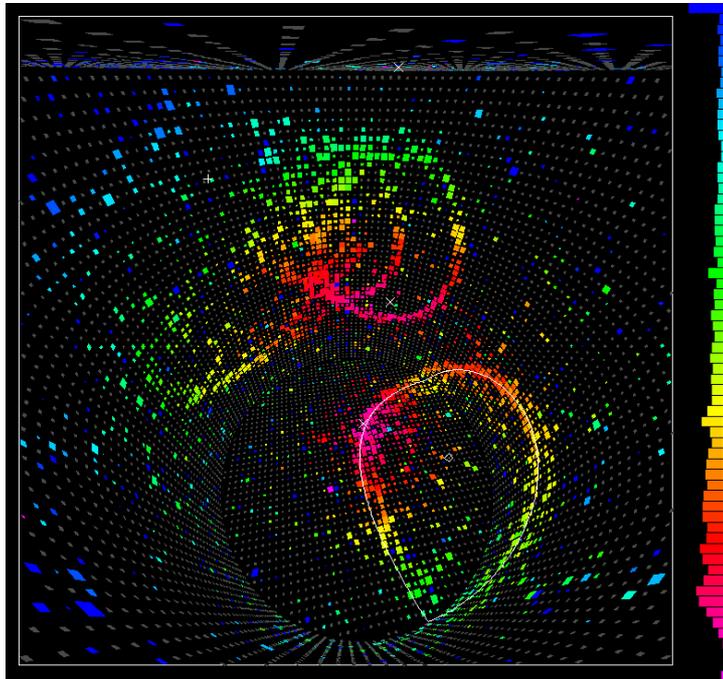


Figure 22: Super Kamiokande: Multiple ring event. A candidate for proton decay into a positron and π_0 . The latter would decay immediately into two γ rays which make overlapping fuzzy rings (see Kamiokande web page).

6 The CCD

(NB These are just introductory notes; a full lecture will be given on CCDs later.)

A charge-coupled device (CCD) is a charge transfer device which is essentially a two-dimensional array of metal oxide semiconductor (MOS) capacitors. These are biased to create potential wells in the bulk silicon which forms the CCD so that photon generated electrons are stored and can be read out at the end of an exposure.

The capacitors are arranged in a matrix of rows and columns. Devices commonly in use nowadays have 1024×1024 (1k \times 1k) up to 2048×4096 pixels (2k \times 4k) are being produced for astronomical use. When an exposure has been made, the CCD is read out by shifting each column towards the readout column (see Fig 2.7) which reads each column sequentially, one pixel at a time.

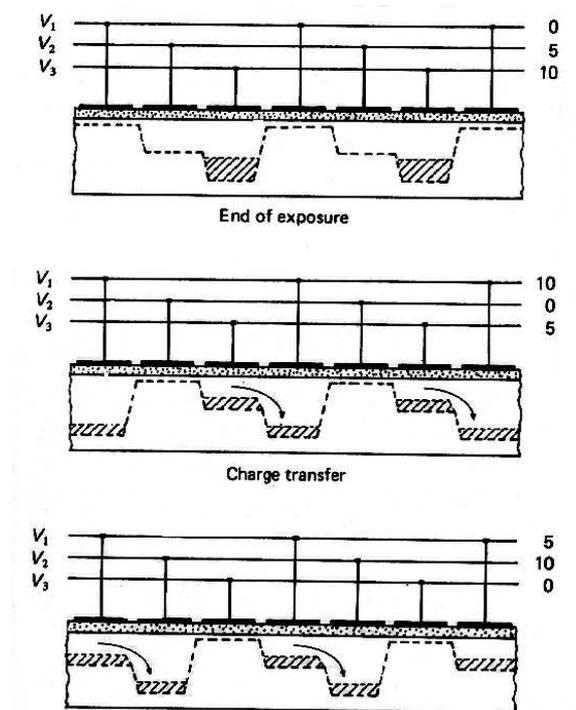


Figure 23: Schematic three-phase CCD readout

In front-illuminated CCDs the incident light actually passes through the electrode structure. In back-illuminated CCDs, the silicon is thinned to about $10 \mu\text{m}$ to allow light directly into the silicon (and to ensure electrons are collected in the potential wells). “Science quality” CCDs are not cheap or trivial to use but have some enormous advantages:

- LINEAR detectors. They can saturate, both the wells (typically at a few $\times 10^5$ electrons) and the readout amplifier, typically at $\sim 10^5$ electrons)
- Can observe many objects at once
- Fairly easy to calibrate (some care must be taken with “flat fields” to get a measure of relative sensitivity of all the pixels. Some care must be taken to avoid “fringing” effects).
- Have very high quantum efficiencies, particularly in the red/near infra-red (usually $> 80\%$ for 500-800 nm).

- Vital in "crowded-field" work
- Background sky measurement is made at the same time
- "Differential photometry" (comparing stars on the same exposure) enables, for example, variable star observations to be made in less-than-perfect conditions.

Disadvantages (minor):

- Small field of view (cf photographic plate) typically a few arc-minutes on a side. CCDs are, however, getting bigger and are being used in arrays themselves to give bigger fields of view.
- Huge amounts of data can be collected, which is good of course, but reduction/analysis time can be long, although "batch processing" eliminates this.
- Read-out times can be a few seconds to a few minutes which tends to make "fast" work difficult. This can be largely circumvented by using the CCD in "frame transfer" mode or reading out more-or-less continuously.

CCDs can be used as "photographic plates" with small fields but QEs over 80% instead of the few percent of photographic emulsion.

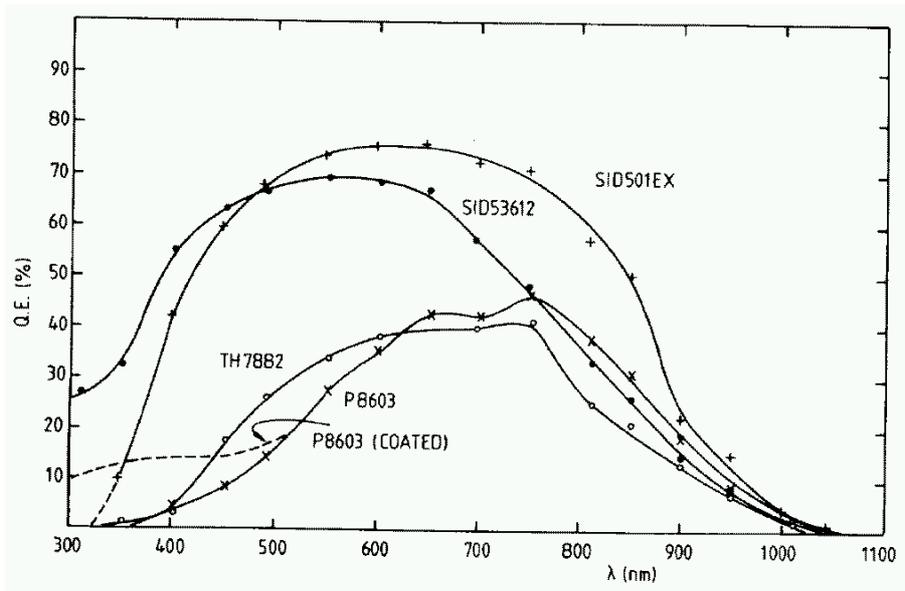


Figure 24: Sample sensitivity plots for some CCD types

They are used for direct imaging with the advantage that crowded fields can be observed and images separated by profile-fitting in the software. Because of the better QE, stars can be observed much fainter than with photomultipliers. The simultaneous measurement of sky, plus the ability to measure many objects at once, makes observing efficiency very high. CCD-type arrays are currently being developed for infra-red photometry ($> 1 \mu\text{m}$) and CCDs have almost completely replaced older detectors for astronomical spectroscopy.

7 The Photometer

Photomultiplier tubes are usually mounted in a photometer (see schematic below):

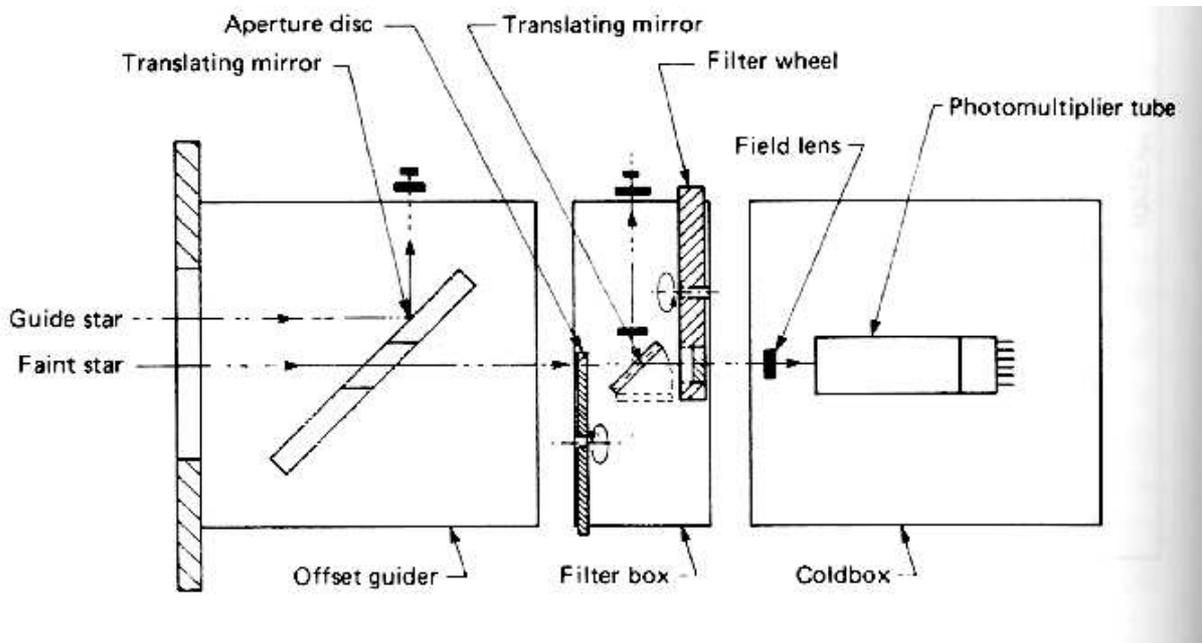


Figure 25: “Exploded” sketch illustrating important components of a photomultiplier photometer.

Important components are:

- A viewing system - to identify stars and possibly “offset guide”
- Aperture wheel - a selection of small holes to allow isolation of a single star
- Filter wheel - optical (glass or interference) filters to isolate various pass-bands in the spectrum
- Field (Fabry) lens - produces an image of the primary mirror on the photocathode (eliminates effects of small movements of star image)
- Photomultiplier
- Amplifier/discriminator - to amplify the pulses somewhat and produce square output pulses suitable for TTL logic. The discriminator removes small pulses (ie. pulses not from the cathode).
- Counting electronics - usually a card in a PC

8 Elements of positional astronomy

Having looked a little at detectors, we now consider what they can be used for

Area detectors (such as the CCD and photographic plate) can immediately be applied to the accurate measurement of position – and more importantly – to *changes* of position. These lead simply to two important fundamental quantities – stellar distance and motion through space.

8.1 Parallax

As the Earth moves around the Sun, stars which are very close to the Sun will appear to shift slightly relative to more distant “background” stars. (see figures 4.1 and 4.2). This effect is known as parallax, or in the context of astronomy, **stellar parallax**.

As seen in Figure 4.1, the total displacement of the nearby star, measured over a 6 month interval, is twice the parallax – p in that figure, but more usually written π .

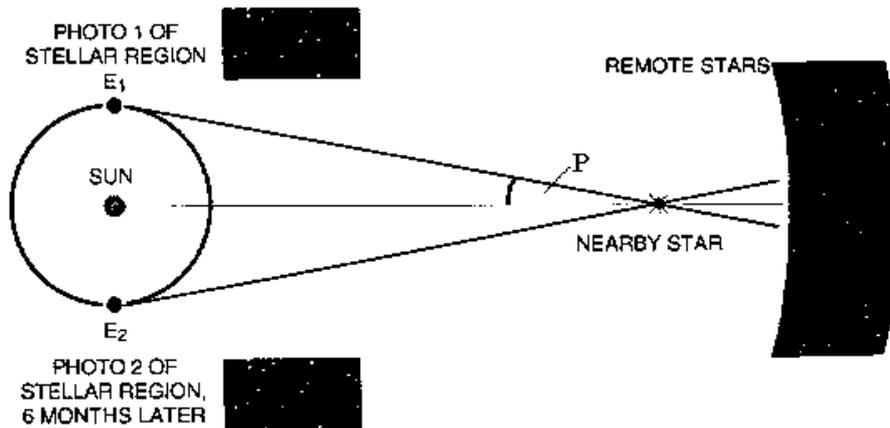
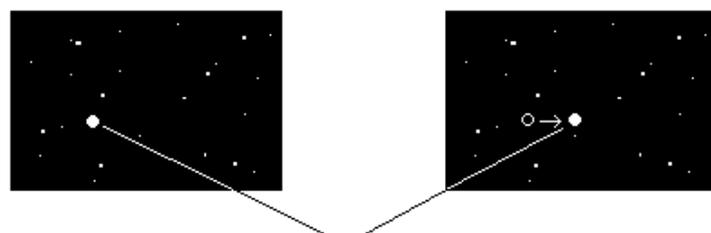


Figure 26: Illustration of annual parallax.



This star has moved 0.5 seconds of arc between photos.

Figure 27: Schematic of the six month difference in position of a nearby star relative to distant stars.

The stellar parallax is defined as the angle subtended at the star by the *radius* of the Earth's orbit (see figure 4.3). The mean Earth-Sun distance, also known as the **astronomical unit (AU)** is

a shade under 150 million kilometres (OK - 149 597 870.691 km).

From Figure 4.3, it is clear that:

$$\frac{a}{r} = \tan \pi = \pi \text{ (radians)}$$

where the approximation $\tan \pi = \pi$ is very good because π is always less than an arcsecond !

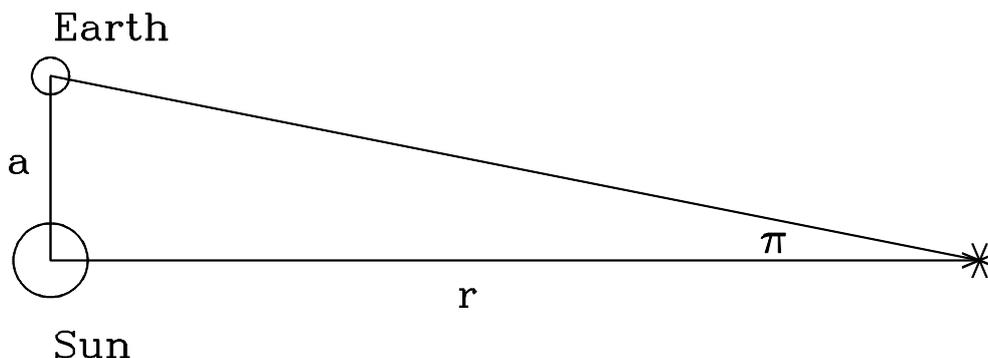


Figure 28: Illustration of annual parallax.

If we now define the **parsec** (pc) as the distance of an object with a parallax of one arcsecond, when the baseline $a = 1$ (AU), then

$$\frac{1}{r(\text{pc})} = \pi(\text{arcsec})$$

and since there are 206 264.806 arcseconds in a radian,

$$1 \text{ pc} = 206\,264.806 \text{ AU} \simeq 206265 \times 150 \times 10^6 \text{ km} = 3.086 \times 10^{13} \text{ km}$$

Since the **light year** is defined as the distance light travels in a year,

$$1 \text{ lightyear} \simeq 299\,792.5 \times 365.25 \times 86400 = 9.46 \times 10^{12} \text{ km}$$

so

$$1 \text{ pc} = 3.26 \text{ lightyears}$$

The table lists some of the nearest stars, arranged in order of increasing distance – but with some omissions (eg. the Sun). The accuracies of these parallaxes – determined by the *Hipparcos* satellite – are about 1 milliarcsecond (mas).

Note that this kind of accuracy means that for a distance of 200 pc, $\pi = 5$ mas, so the error in parallax is already 20 %.

The best ground-based parallaxes are only good to about 0.01" (or 10 mas) which means that errors are of the order of 10% as close as 10 pc and 50% at only 50 pc. *Hipparcos* was, therefore, a great leap forward and you should check out their web page.

Future (possible) space missions include GAIA, FAME and SIM (Space Interferometry Mission) which aim to push this fundamental measure of distance to the 1 – 10 *microarcsecond* level, giving ~ 10% accuracy in the 10 – 100 *kiloparsec* range.

Table 1: Parallaxes for a few of the nearest stars.

Star	Sp. type	V	M_v	π (arcsec)	r (pc)	Notes
α Cen C	M5	11.01	15.45	0.772	1.30	Proxima
α Cen A	G2	-0.01	4.34	0.742	1.35	Henderson
α Cen B	K0	1.35	5.70	0.742	1.35	
Barnard's star	M5	9.54	13.24	0.549	1.82	
Wolf 359	M6	13.45	16.56	0.418	2.39	
BD+36 2147	M2	7.49	10.46	0.392	2.55	
Sirius A	A1	-1.44	1.45	0.379	2.64	
Sirius B	DA	8.44	11.33	0.379	2.64	
L726-8 A	M5.5	12.41	15.27	0.374	2.67	
L726-8 B	M5.5	13.25	16.11	0.374	2.67	
Ross 154	M4.5	10.37	13.00	0.336	2.98	
Ross 248	M6	12.29	14.79	0.316	3.16	
ϵ Eri	K2	3.72	6.18	0.311	3.22	planet(s)
:	:	:	:	:	:	
:	:	:	:	:	:	
Procyon A	F5	0.40	2.68	0.286	3.50	
Procyon B	DA	10.7	13.0	0.286	3.50	
61 Cygni A	K5	5.20	7.49	0.285	3.51	Bessell
61 Cygni B	K7	6.05	8.33	0.285	3.51	
:	:	:	:	:	:	
:	:	:	:	:	:	

8.2 Proper motion

The proper motion, μ , of a star is its angular rate of change in position, perpendicular to the line-of-sight. It is sometimes given as a total angular motion (per annum) and a “position angle”, θ (the angle between the proper motion vector and the great circle direction of north), but is more usually resolved into components in RA and Dec :

$$\mu_{\delta} = \mu \cos \theta$$

$$\mu_{\alpha} \cos \delta = \mu \sin \theta$$

where the $\cos \delta$ term corrects for the small circle effect – and you have to make sure whether this has been applied or not ...

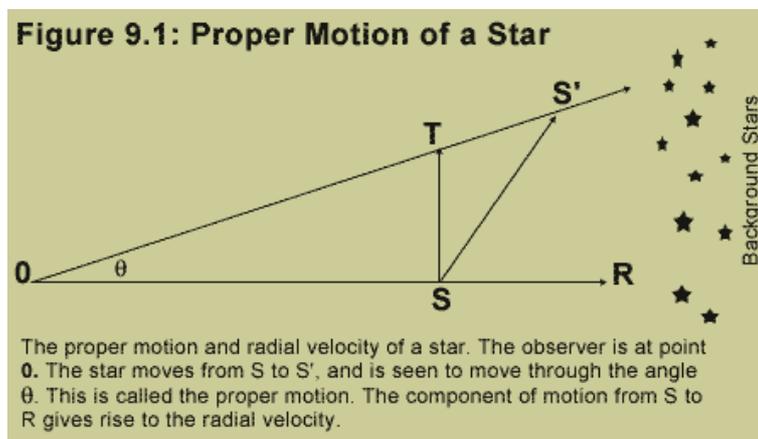


Figure 29: Illustration of stellar proper motion.

The proper motion is clearly directly proportional to the linear velocity perpendicular to the line-of-sight, the **transverse velocity**, v_t .

Since we can write the proper motion per annum in terms of the distance of the star, r , and the distance travelled in a year, a , as:

$$\mu(\text{radians}) = \frac{a(\text{pc})}{r(\text{pc})}$$

then, turning radians into arcseconds on the left and parsec/year into km/sec on the right, we have :

$$\mu(\text{arcsec/yr}) \times 206265 = \frac{v_t \times 3.086 \times 10^{13}}{r(\text{pc}) \times 365.25 \times 86400}$$

so,

$$\mu(\text{arcsec/yr}) = \frac{v_t(\text{km/s})}{4.74r(\text{pc})}$$

Of course, for nearby stars it might well happen that both parallax and proper motion are significant. It will then take several or many measurements to disentangle the two effects. The figure shows results for Barnard’s star – the star with the largest known proper motion, as well as being one of the nearest stars.

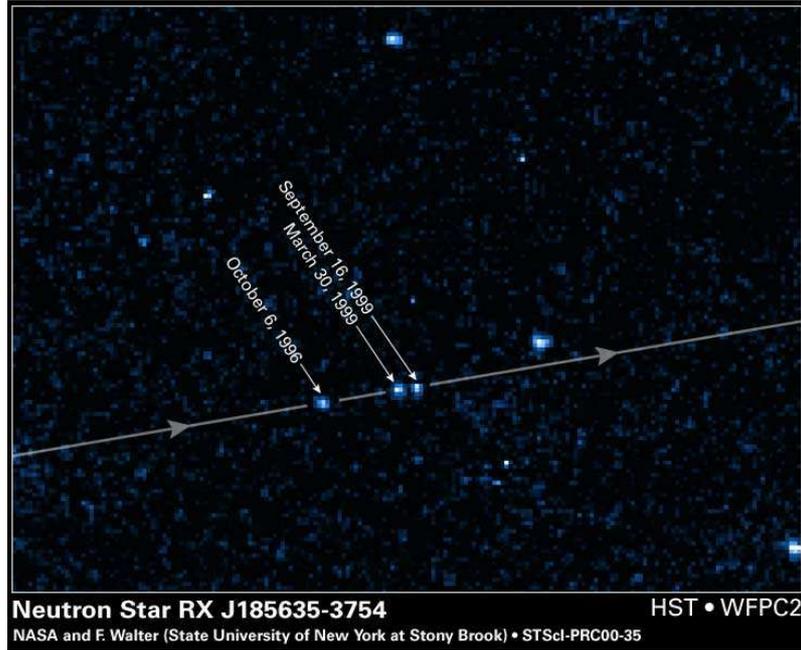


Figure 30: A composite formed from three different epoch Hubble Space Telescope (Wide Field Planetary Camera) images. The field is 8.8×6.6 arcseconds. The three images superimpose exactly except for the neutron star, which is clearly moving – at about 0.3 arcseconds/year. The parallax “wobble” is not visible but is about $0.016''$ - giving the star a distance of about 60 pc.

Table 2: Some of the highest proper motion stars.

HIP	Star	Sp. type	V	μ (arcsec/yr)	pos. angle (deg)	Notes
87937	Barnard's star	M5	9.54	10.358	355.6	
24186	Kapteyn's star	M1	8.86	8.671	131.4	
57939	Groombridge 1830	G8Vp	6.42	7.058	145.4	
114046	Lacaille 9352	M0.5	7.35	6.896	78.9	
439	CD-37°15492	M1.5	8.56	6.100	112.5	
67593			13.31	5.834	23.0	
104214	61 Cygni A	K5	5.20	5.281	51.9	
104217	61 Cygni B	K7	6.05	5.172	52.6	
	:	:	:	:	:	
70850	α Cen C	M5	11.01	3.853	281.5	Proxima
	:	:	:	:	:	
71681	α Cen B	K0	1.35	3.724	284.8	
71683	α Cen A	G2	-0.01	3.710	277.5	
	:	:	:	:	:	

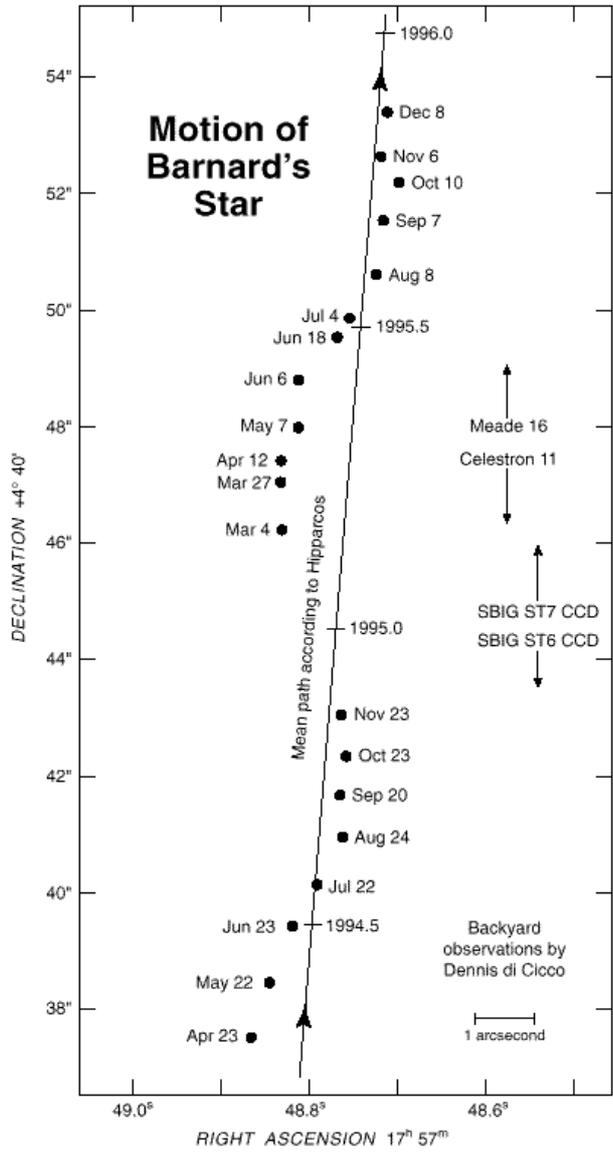


Figure 31: Schematic illustration of the motion of the star with the largest known proper motion – Barnard’s star. The annual proper motion is a little more than 10 arcseconds/year and the superposed wave is due to the annual parallax.

8.3 Radial Velocity



Figure 32: Stellar radial velocity – measured by the Doppler shift of spectral lines.

The proper motion components give two components of the total space motion; the **radial velocity**, v_r , is the third component – along the line-of-sight and is found by measuring the Doppler shift of features in the spectrum of the object under investigation:

$$\frac{\Delta\lambda}{\lambda_{rest}} = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{v_r}{c}$$

with the obvious convention that velocities towards the observer (“blue shifts”) are negative and velocities away from the observer (“red shifts”) are positive.

Note that

- Whereas the errors in proper motion (and parallax) increase rapidly with distance, the errors in radial velocity are much less distance dependent (being related to the strength and sharpness of the spectral features, as well as the signal/noise in the spectrum). As we have seen, even with the best satellite data currently available, errors are typically 1 mas, so that proper motions are usable only up to distances of the order of kiloparsecs, whereas radial velocities are usable on megaparsec scales.
- **But**, if long baselines in time are available, this can substantially improve the accuracy of proper motions. This is one valuable aspect of “early epoch” photographic survey material.
- Because the Earth has an orbital velocity of ~ 30 km/s, the *measured* radial velocity of an object can vary by up to 60 km/s (maximum for an object near the ecliptic plane) during the year. The Earth also introduces a diurnal variation off up to 0.45 km/s (maximum at the equator) due to its rotation. It is therefore usual to correct radial velocities for the Earth’s motion, producing **heliocentric radial velocities**.