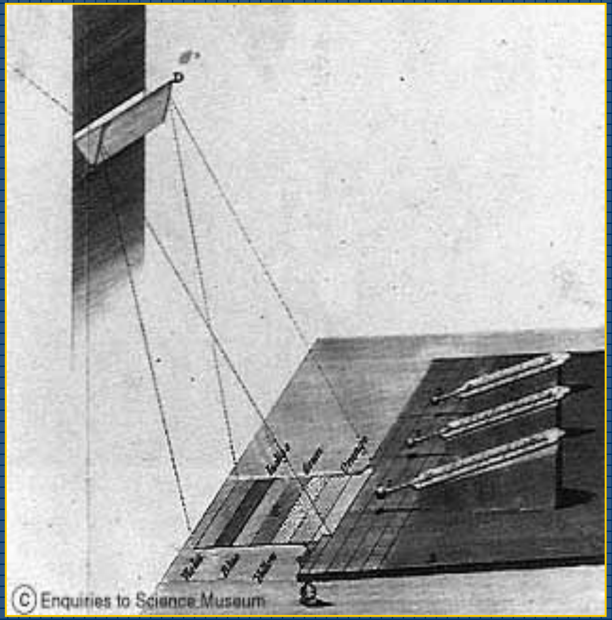
praktická astronomie

IR a UV astronomie,
detektory obecně v optickém, IR a UV oboru
zobrazovací prvky CCD, CCD kamery

cvičení
práce se CCD kamerou

IR astronomie

- 1800 William Herschel – vložení teploměrů za červený konec slunečního spektra
- 1878 Edison, měření IR během zatmění Slunce, tasimeter
- počátek 20. stol. Pettit, Nicholson, M, pl., hvězdy v IR
- 60. léta – InSb, HgCdTe – detektory pro NIR
- FIR – balóny, letadla, družice



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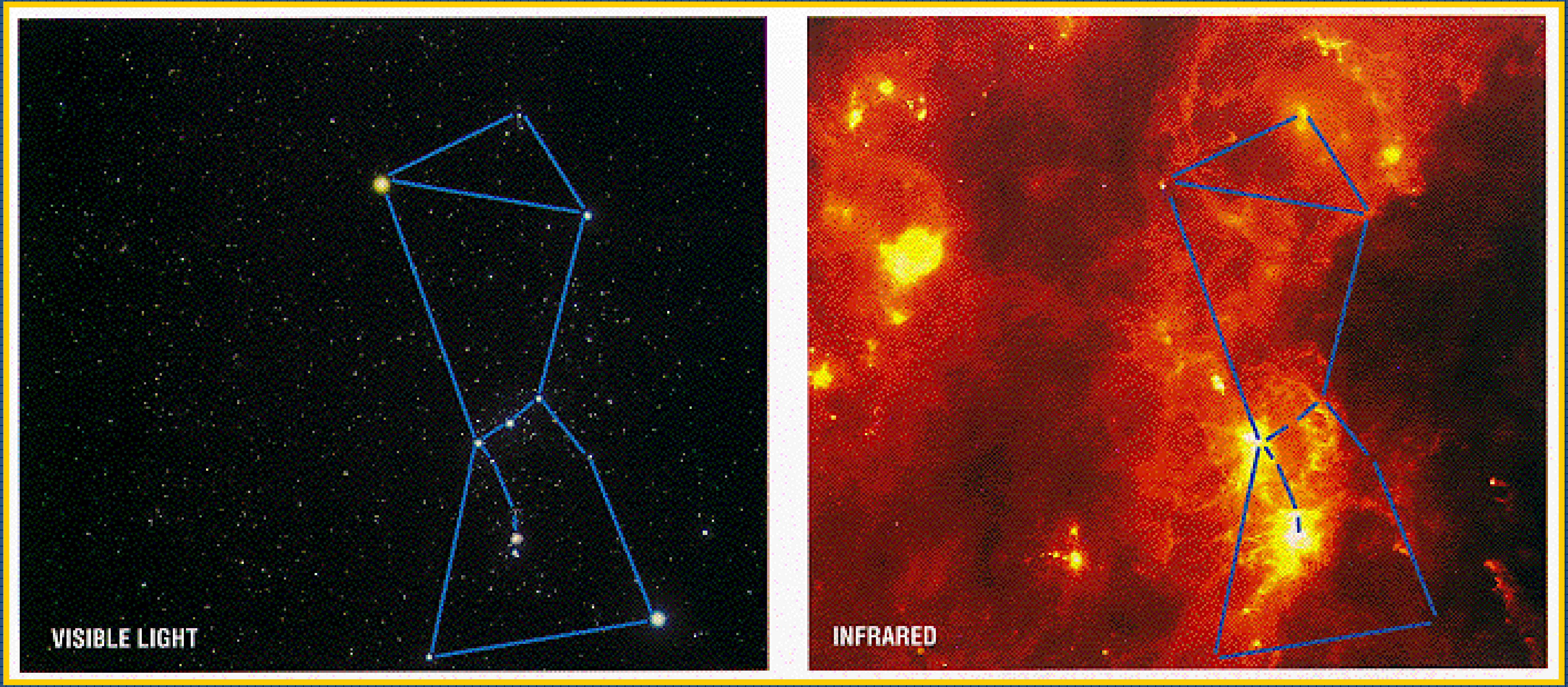
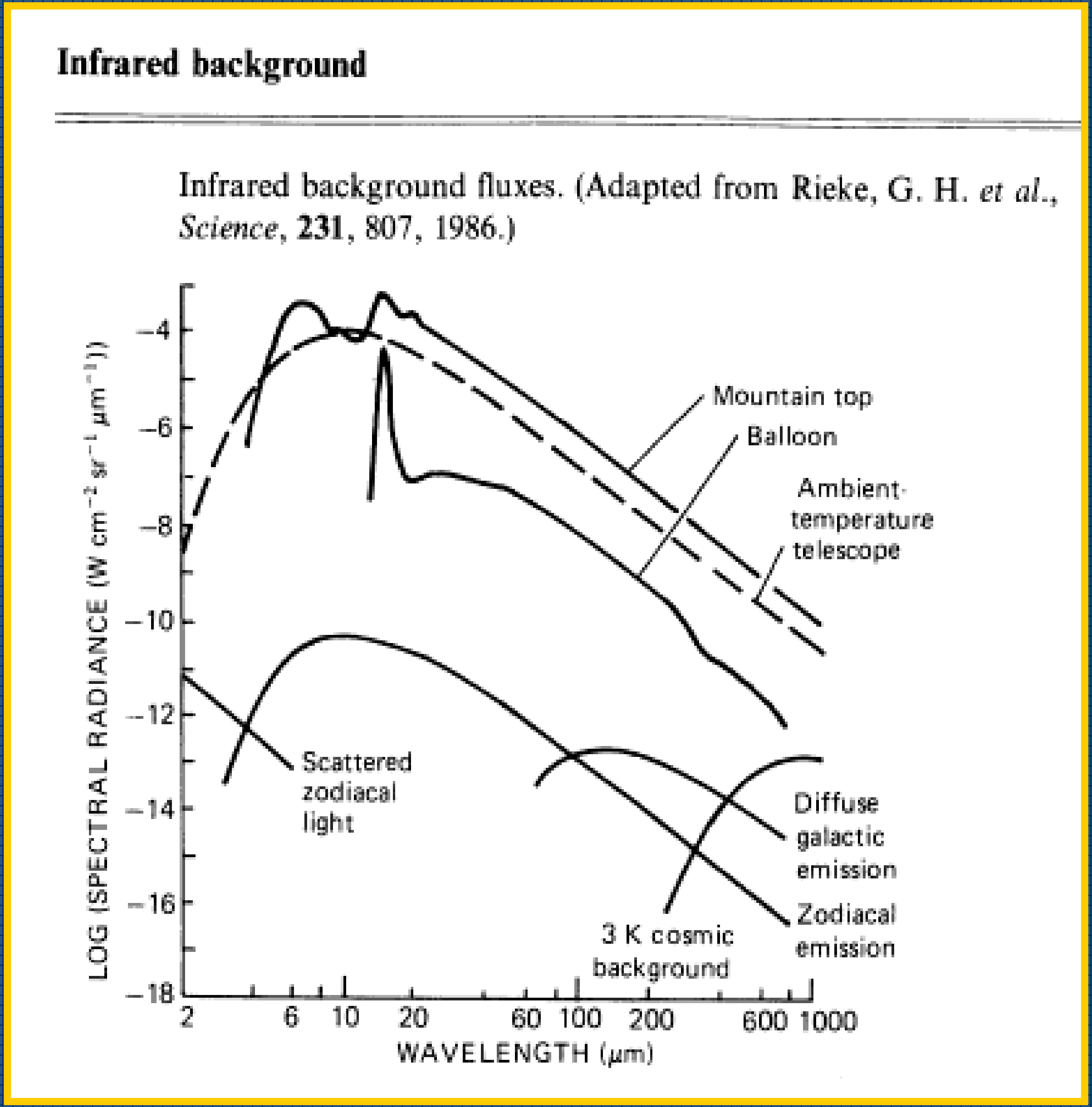
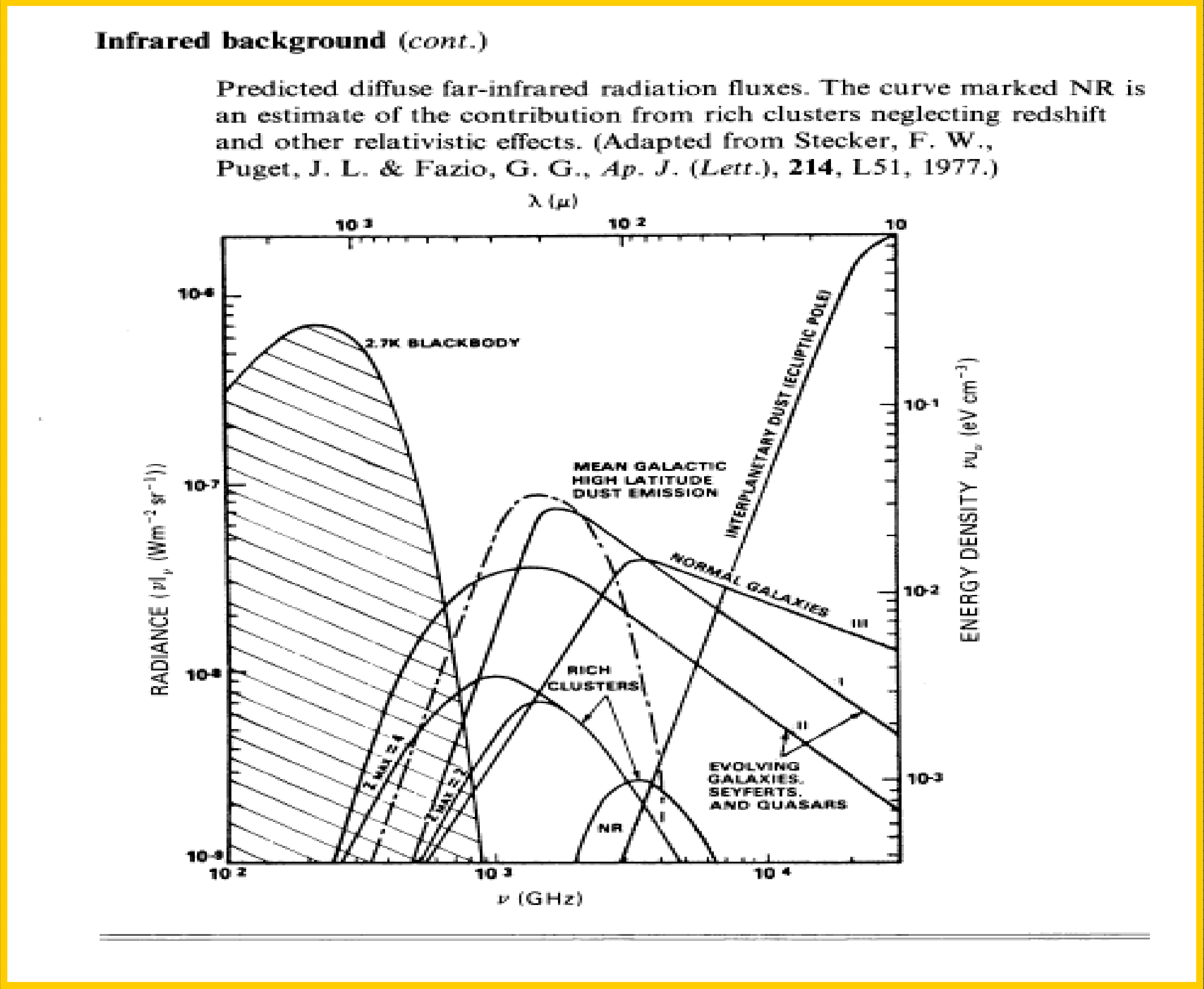
podrobnější časová osa


VISIBLE LIGHT
INFRARED



Infrared background

Infrared background fluxes. (Adapted from Rieke, G. H. *et al.*, *Science*, **231**, 807, 1986.)



Infrared background (*cont.*)

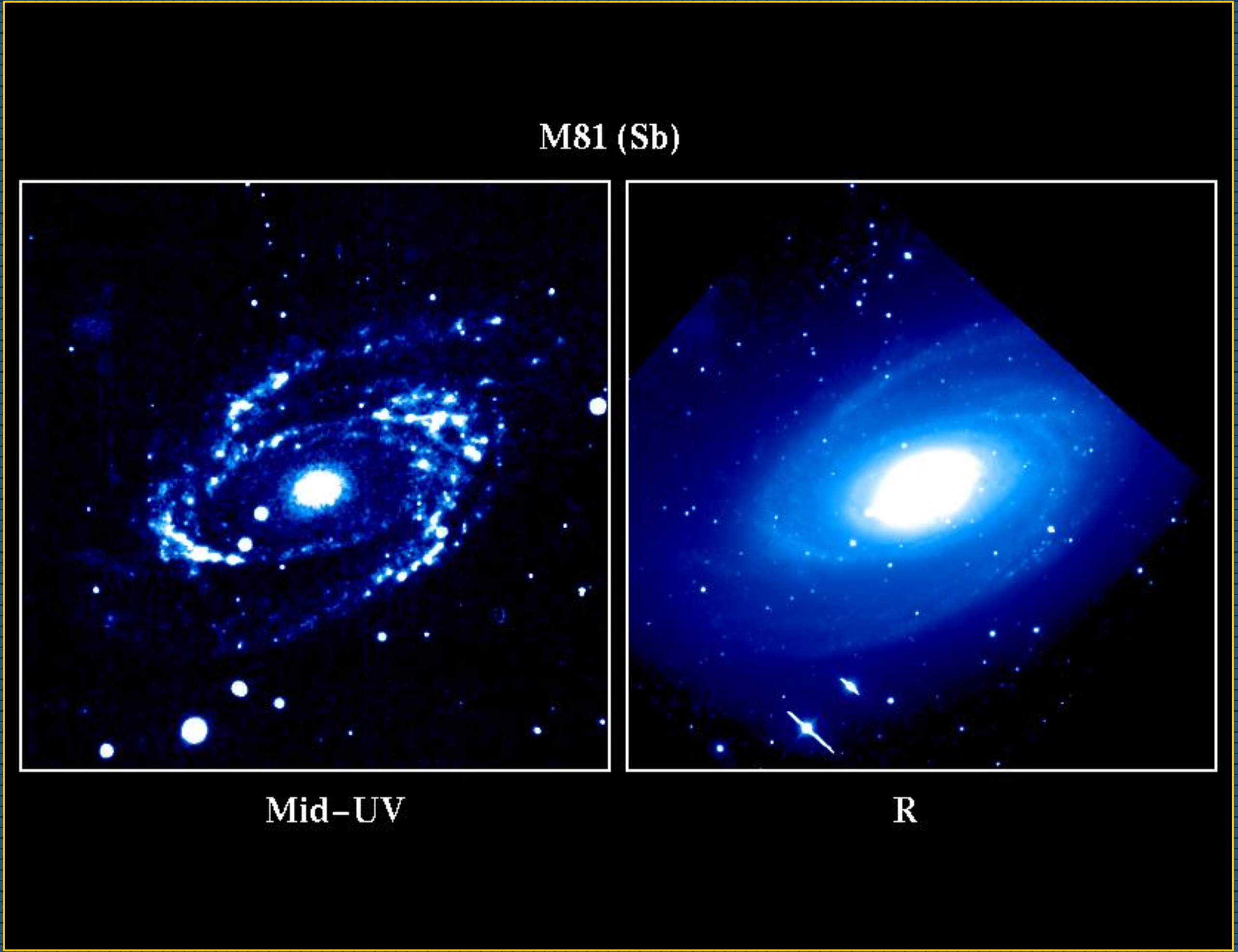
Predicted diffuse far-infrared radiation fluxes. The curve marked NR is an estimate of the contribution from rich clusters neglecting redshift and other relativistic effects. (Adapted from Stecker, F. W., Puget, J. L. & Fazio, G. G., *Ap. J.* (*Lett.*), **214**, L51, 1977.)

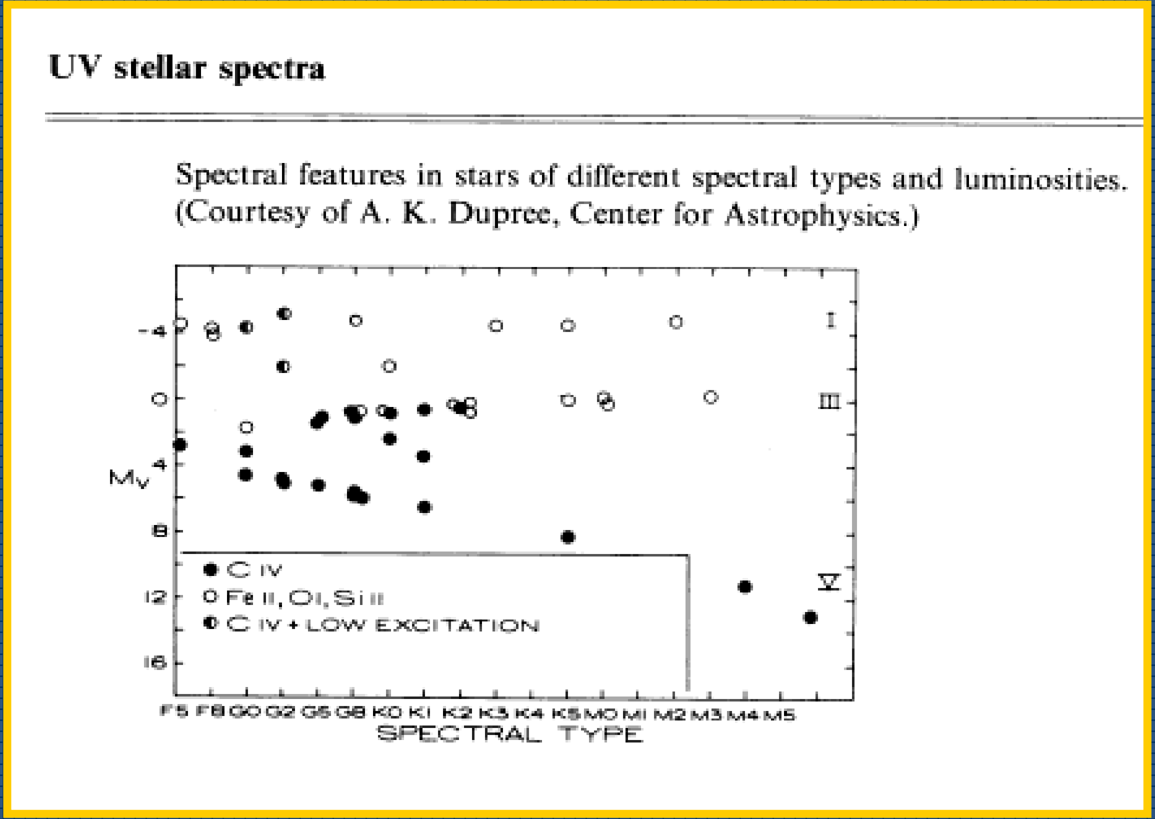
[wikipedia](#)

[Coolcosmos](#) [IR galerie](#)

UV astronomie

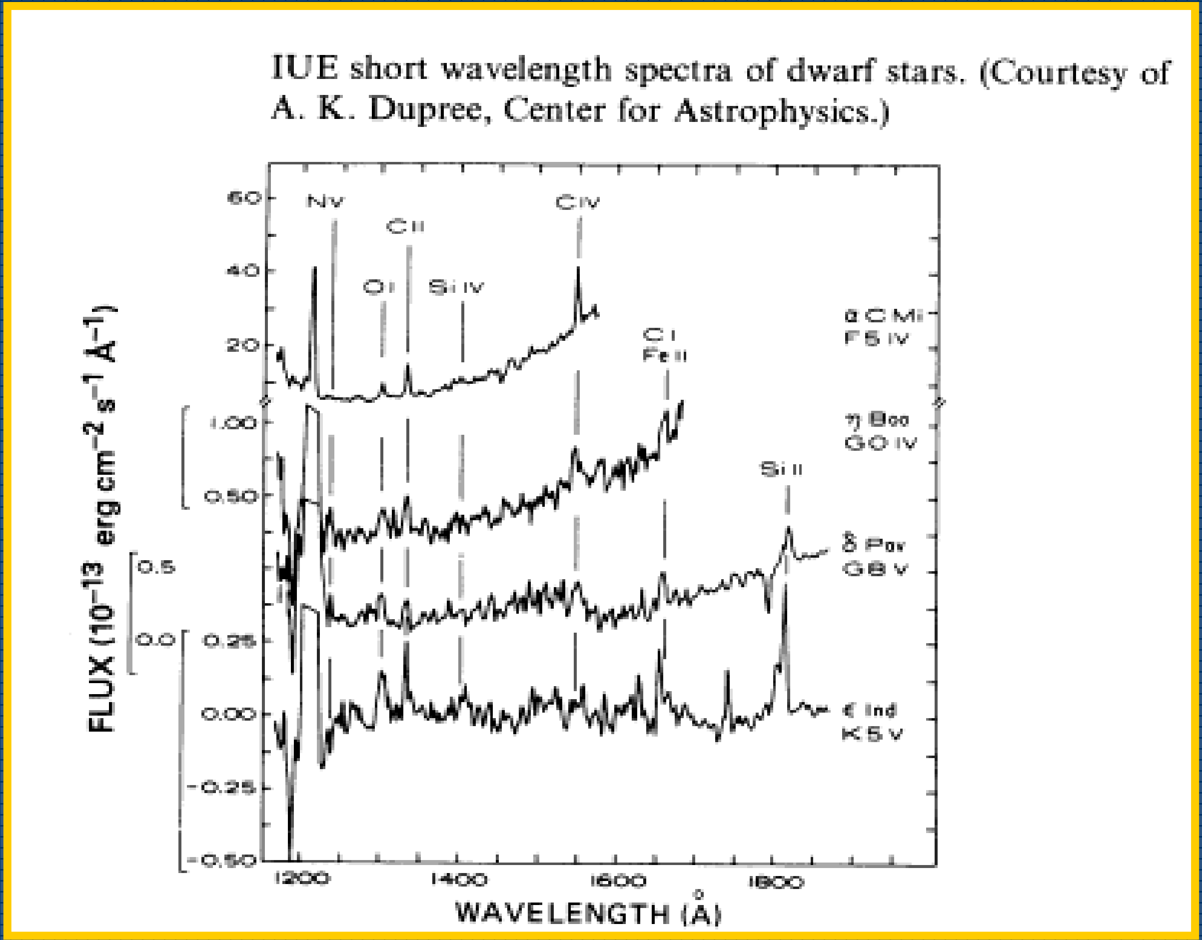
- úvod do UV astronomie
- přehled
- UV Astronomy (wiki)





UV stellar spectra

Spectral features in stars of different spectral types and luminosities. (Courtesy of A. K. Dupree, Center for Astrophysics.)



IUE short wavelength spectra of dwarf stars. (Courtesy of A. K. Dupree, Center for Astrophysics.)

vesmír mnoha vlnových délek

typy detektorů v optické, UV a IR oblasti elmg spektra

- dvě skupiny detektorů
  - kvantové (fotonové) – reagují na přímou interakci fotonů
  - tepelné – reagují na vzestup teploty vlivem absorpce energie záření

- v obou případech jsou nekoherentní, informace o fázi je ztracena

typy detektorů

detektor	princip	spektrální oblast
fotočlánek, fotonásobič	interakce s elektronem	uv, světlo, ir
fotografická emulze	chemická reakce	uv, světlo, ir
charge coupled device (CCD) „nábojově vázaný snímač“	el. náboj	uv, světlo, ir
fotovoltaický článek, termočlánek	el. napětí	uv, světlo, ir
bolometr, fotovodivostní d.	rezistance	ir
Golayova buňka	tlak plynu	ir
lidské oko	chemická reakce	světlo

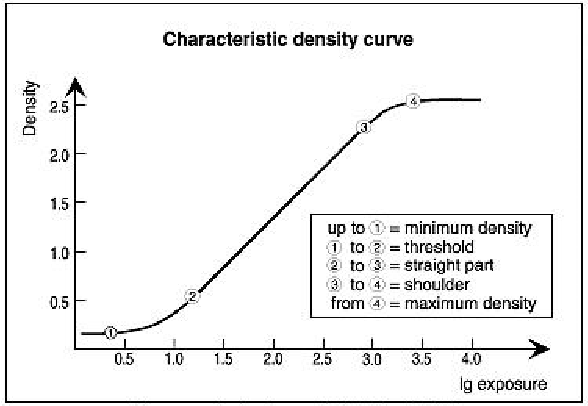
charakteristiky detektorů

- kvantová účinnost (počet detekcí/počet dopadajících fotonů)
- linearita detektoru
- dynamický rozsah
- závislost citlivosti na vlnové délce
- šum
- integrační schopnost
- rozlišovací schopnost (prostorová)
- digitální výstup

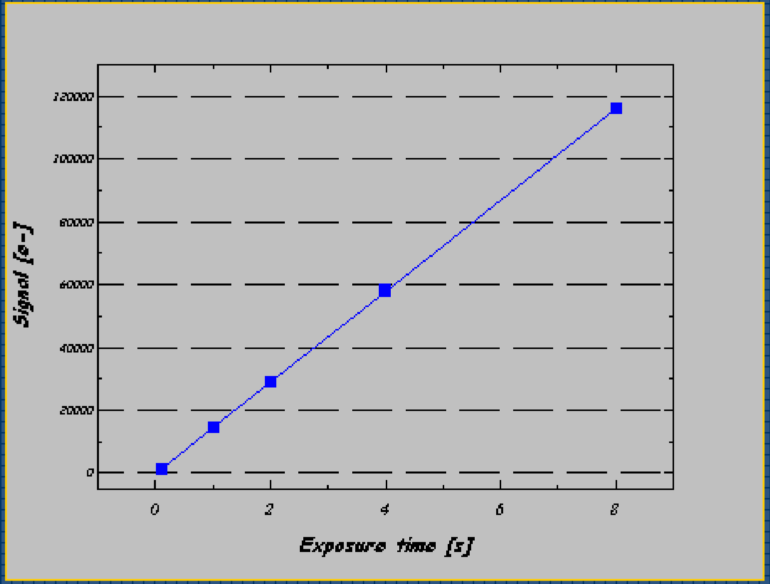
kvantová účinnost

- krystaly fotografické emulze – jen pár %
- elektrony uvolněné fotoelektickým jevem – 5 až 40% ve fotonásobičích
- vznik páru elektron-díra - ~ 50% v CCD

linearita detektoru

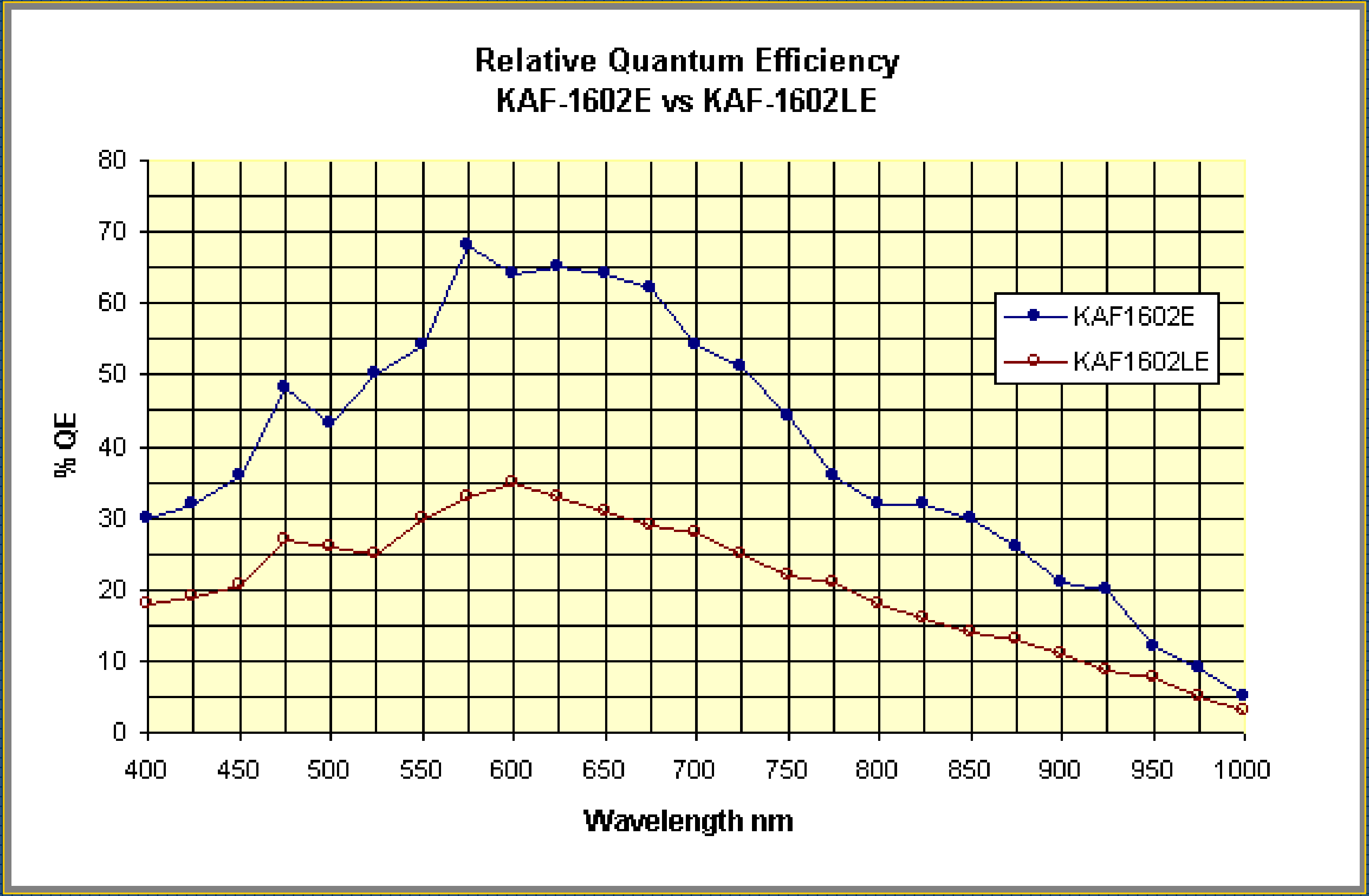


Characteristic Curve ® AGFA (1999)

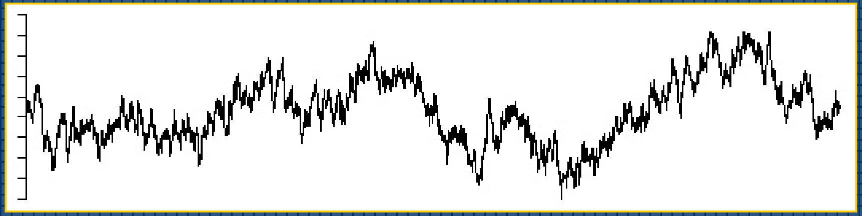


- požadavek na lineární „odezvu" detektoru, aby R = F·t
- fotografická emulze není lineárním detektorem
- CCD a fotonásobiče jsou lineární ve velkém rozsahu

závislost citlivosti na vlnové délce



šum



- šum způsobený kvantovou podstatou záření (Poissonovo rozdělení)
- šum pozadí (oblohy), způsoben změnou průzračnosti, seeingem a scintilací
- Johnsonův šum – elektrony v detektoru vlivem tepelných pohybů, potlačen chlazením
- „vyčítací“ šum
- elektronický šum

$$DQE = \left[\frac{S/N_{out}}{S/N_{in}} \right]^2$$

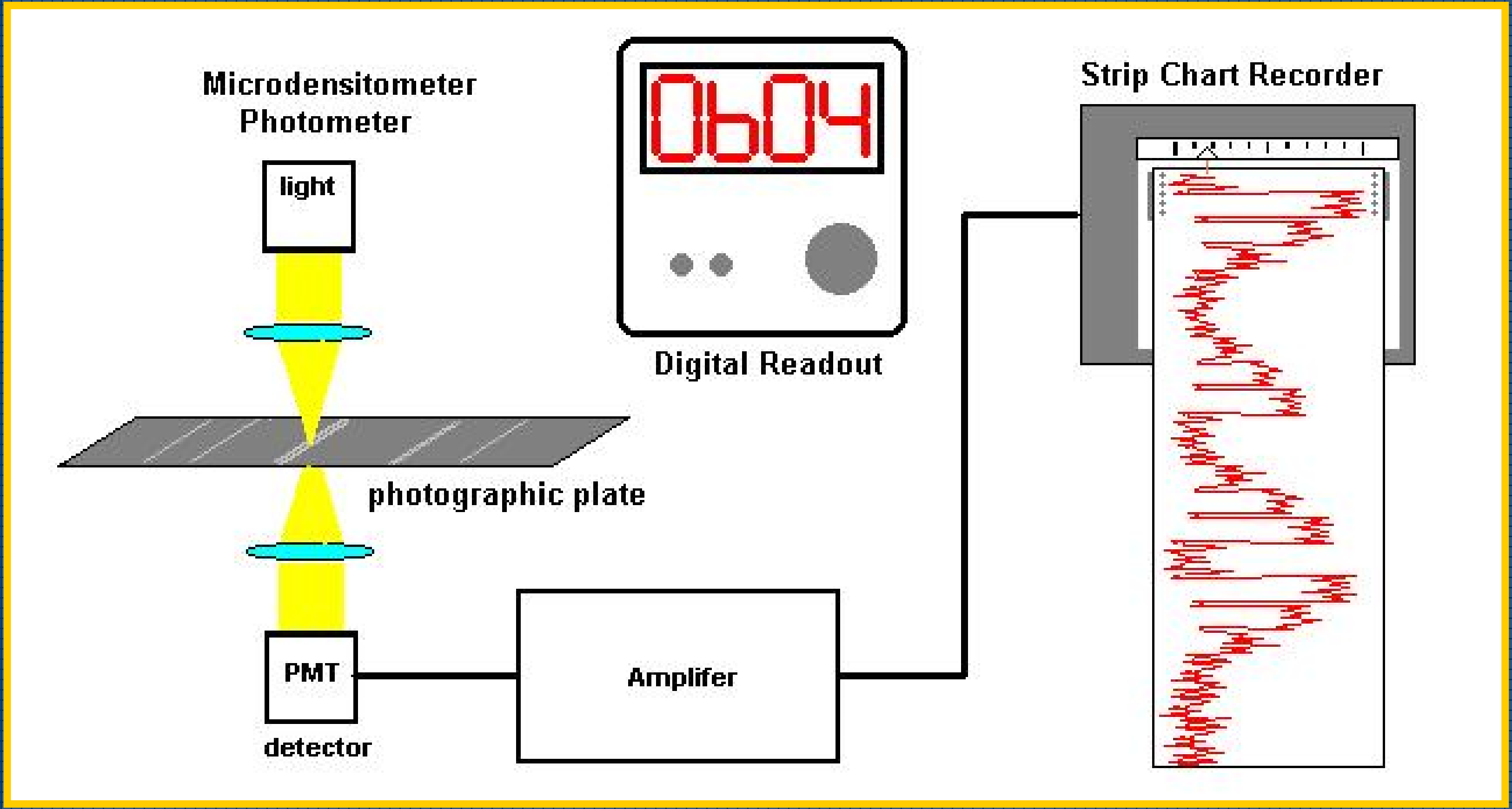
so

$$S/N_{out} = S/N_{in} \bullet DQE^{1/2}$$

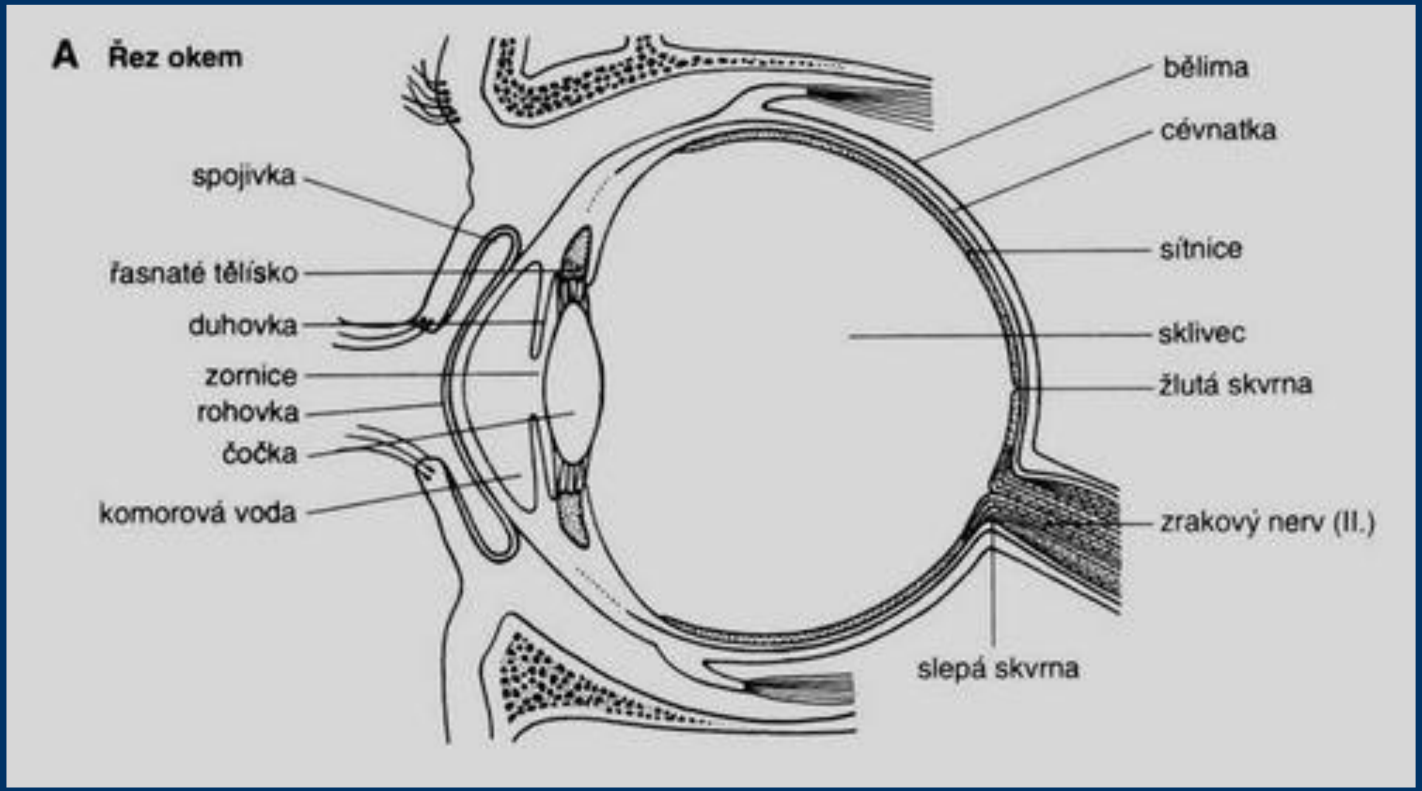
Poisson statistics

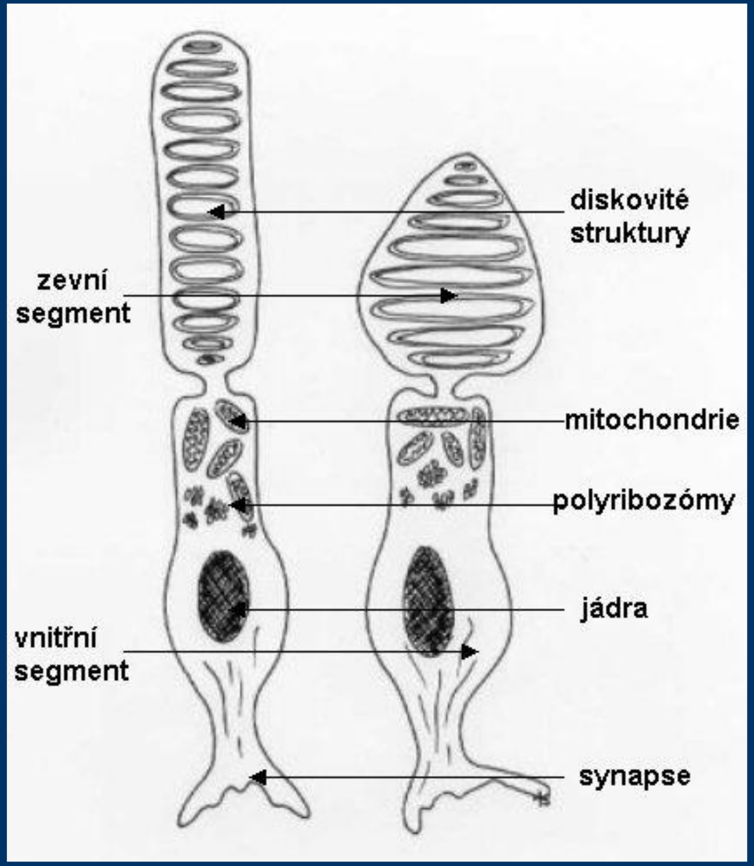
$$S/N_{in} = N^{1/2}$$

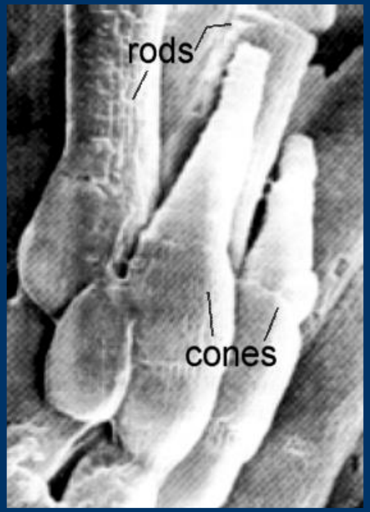
digitalizace




oko

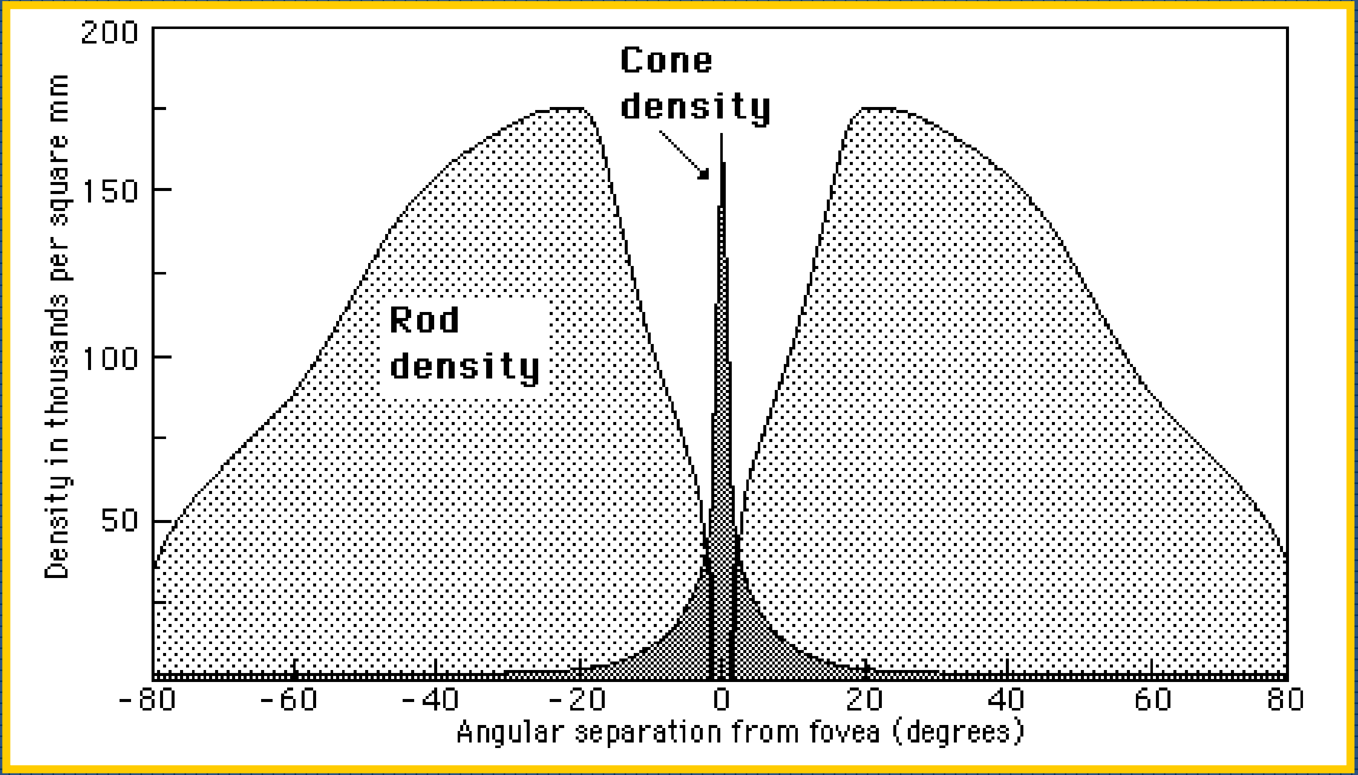

A
Řez okem
spojivka
řasnaté tělísko
duhovka
zornice
rohovka
čočka
komorová voda
bělima
cévnatka
sítnice
sklivec
žlutá skvrna
zrakový nerv (II.)
slepá skvrna


diskovité struktury
zevní segment
mitochondrie
polyribozómy
jádra
vnitřní segment
synapse

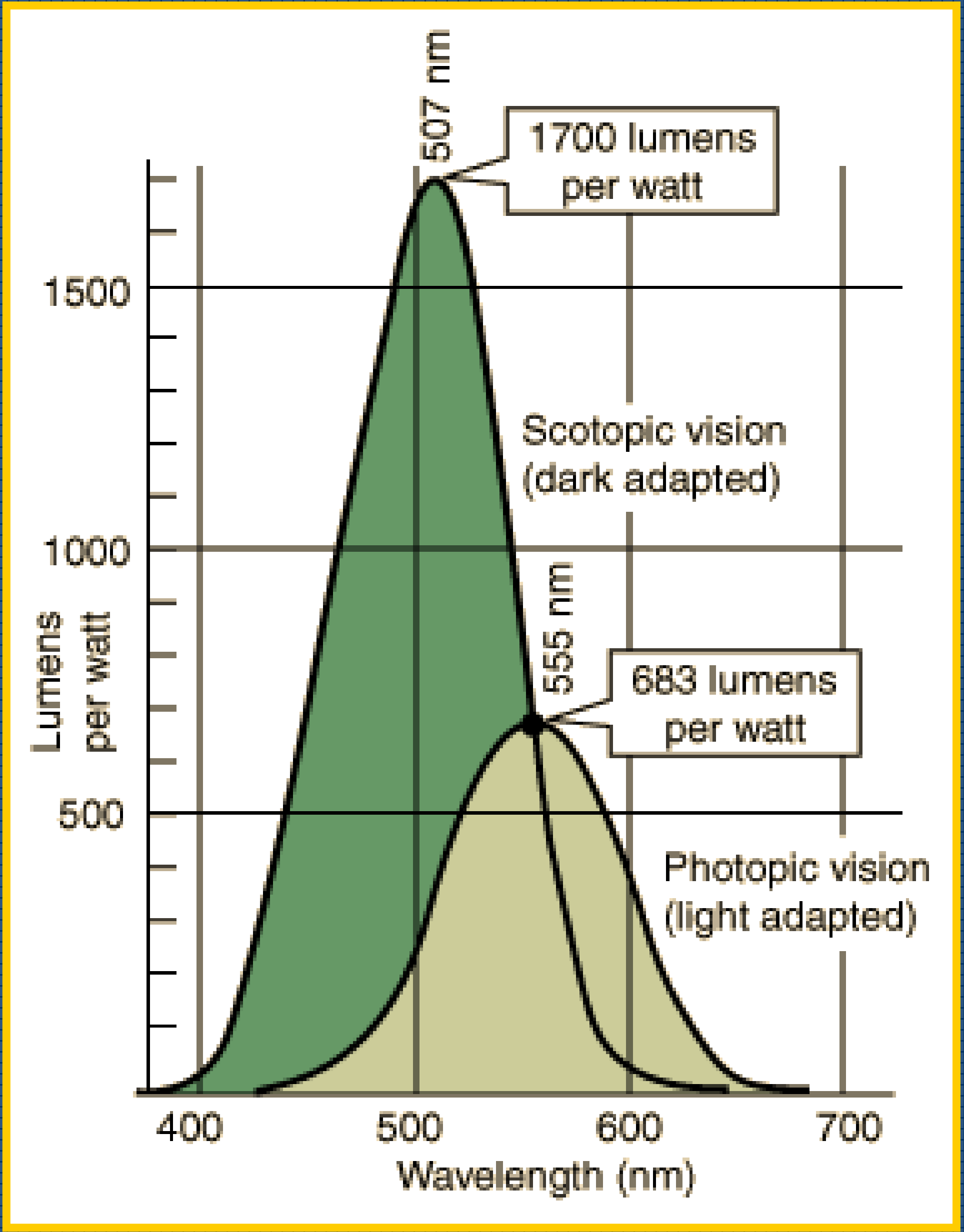

rods
cones

oko - applet

oko

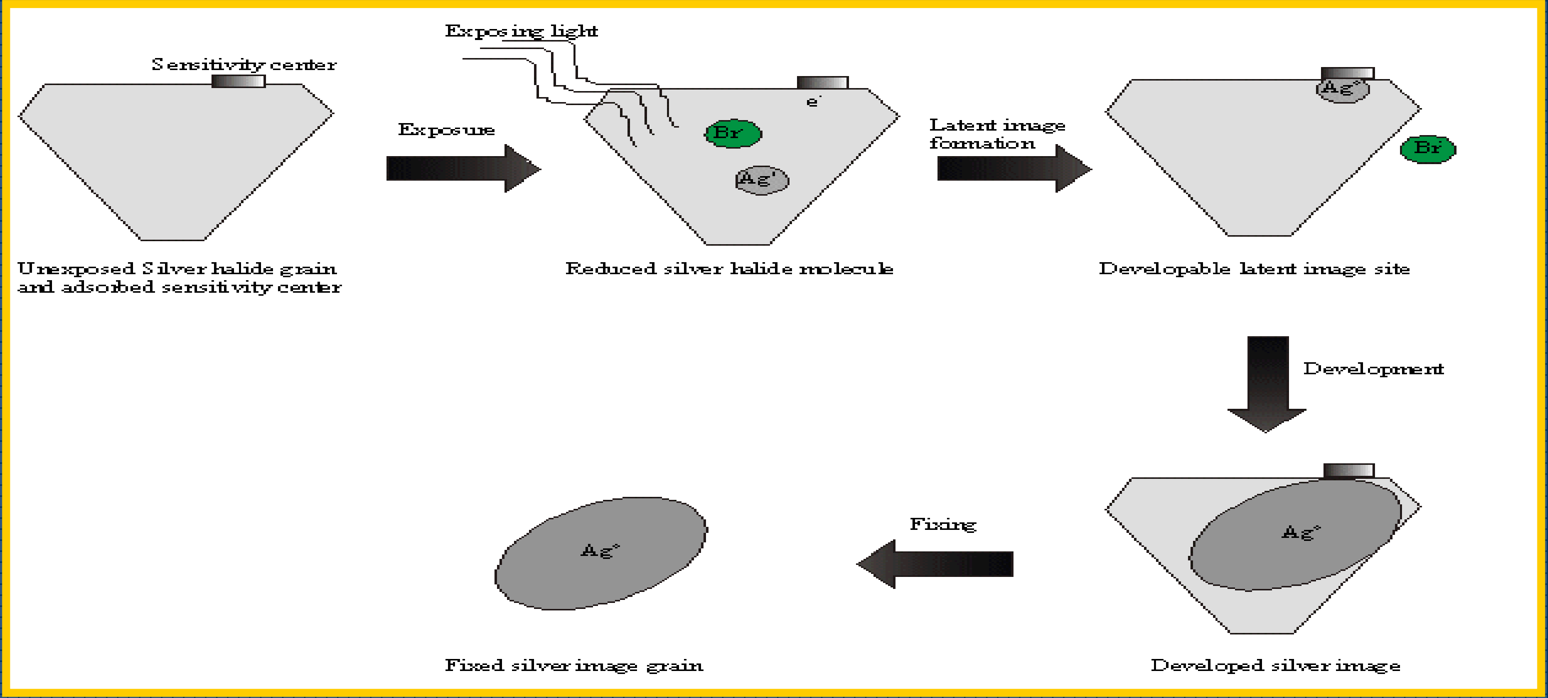


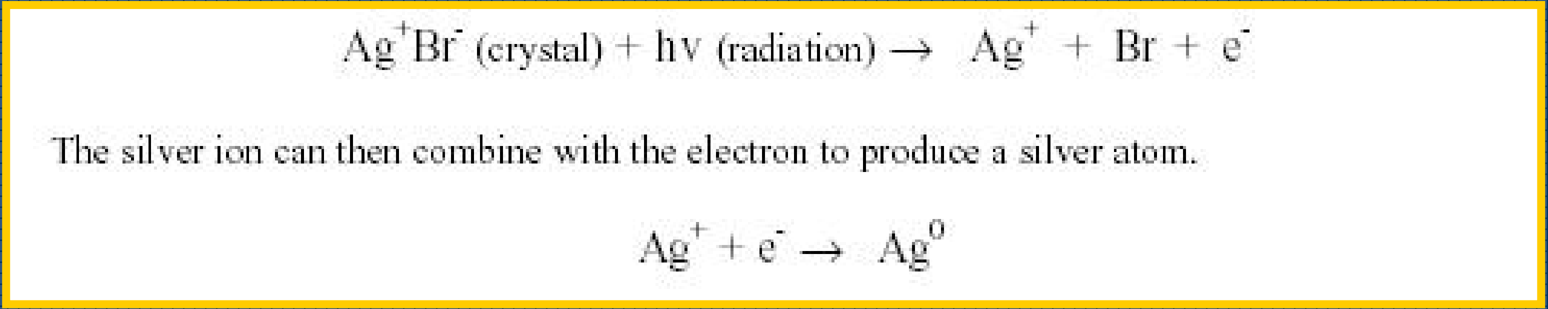
Cone density
Rod density
Density in thousands per square mm
200
150
100
50
-80
-60
-40
-20
0
20
40
60
80
Angular separation from fovea (degrees)



507 nm
1700 lumens per watt
Scotopic vision (dark adapted)
555 nm
683 lumens per watt
Photopic vision (light adapted)
1500
1000
500
Lumens per watt
400
500
600
700
Wavelength (nm)

fotografická emulze



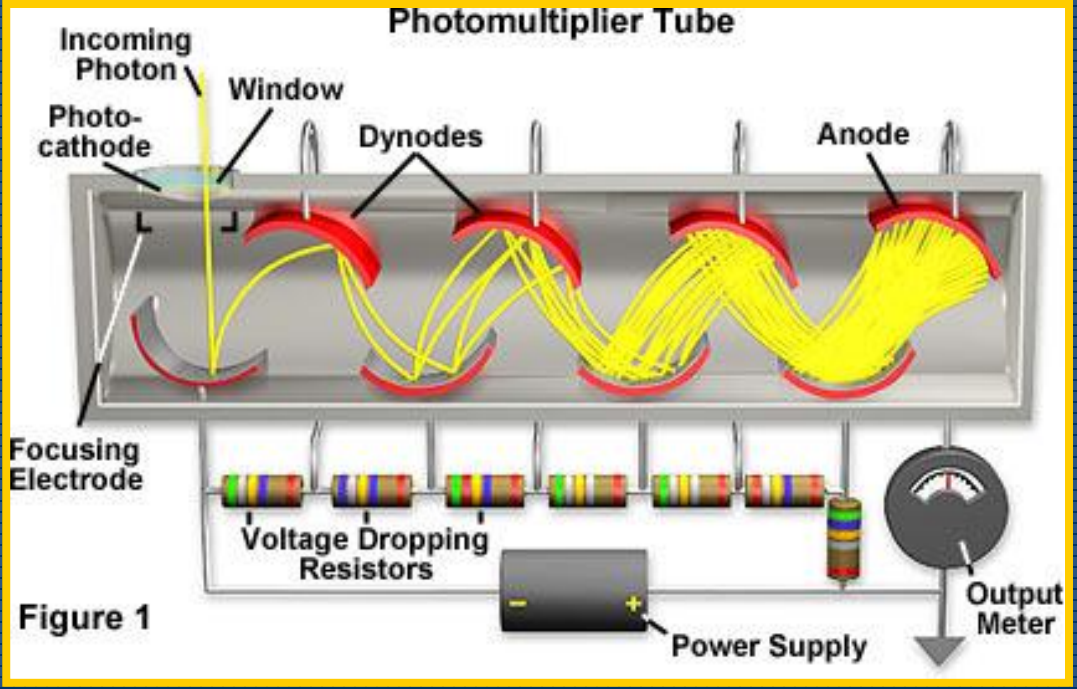


$$Ag^+Br^- \text{ (crystal)} + h\nu \text{ (radiation)} \rightarrow Ag^+ + Br + e^-$$

The silver ion can then combine with the electron to produce a silver atom.

$$Ag^+ + e^- \rightarrow Ag^0$$

fotonásobič



- fotonásobič
- fotoelektrický jev

\+ velmi rychlá odezva (ns)
\+ mohou měřit i velmi slabé signály
\+ povaha výstupu umožňuje použít „pulzní čítače"

\- poměrně malá kvantová účinnost
\- omezený spektrální rozsah

fotonásobič

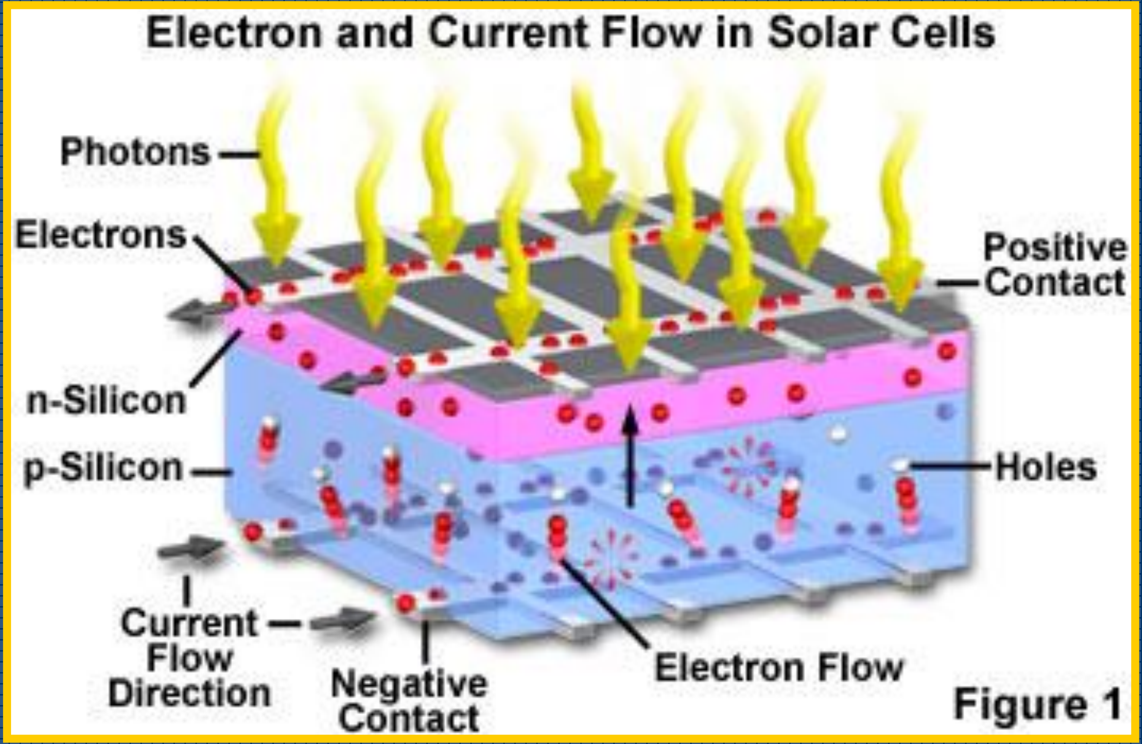
- skleněná „lampa" – obal
- fotokatoda
- dynody
- anoda

charakteristiky

  - citlivost, zesílení, drift (změny v čase)
  - temný proud
  - „mrtvý" čas

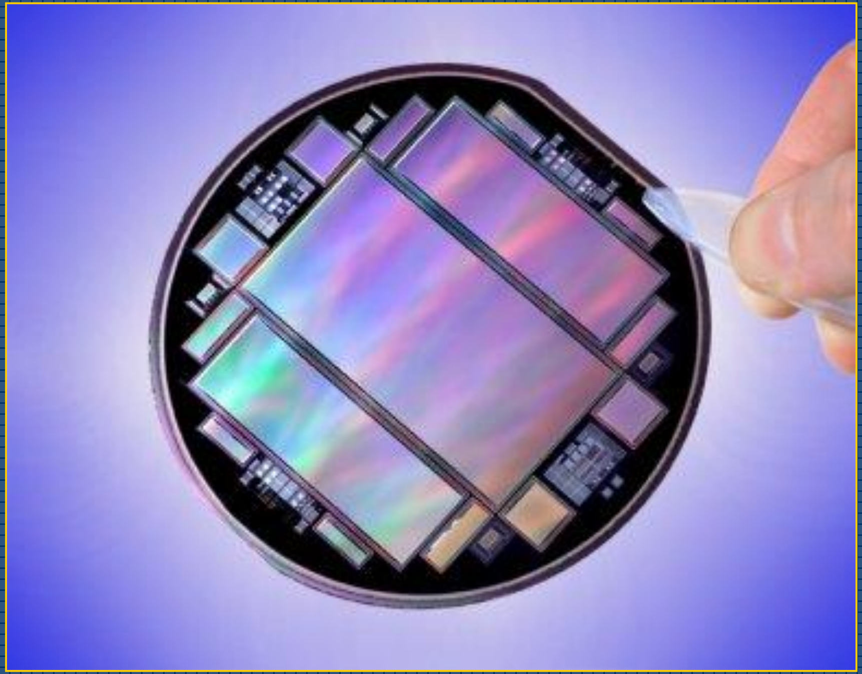
jiné detektory

- detektory STJ (Superconducting tunnel junction detectors)
- fotovoltaický článek
- termočlánek
- fototranzistor
- CID
- TV trubice
- IR detektory
  - fotovodivostní detektor
  - bolometr



CCD

- CCD aplety
- CCD v astronomii
- AAVSO CCD manuál
- přednáška ing. Cagaše



obsah

- prezentace obsahuje:
  - co je to CCD
  - výhody CCD (ve srovnání s fotografií);
  - jak funguje CCD
  - možné problémy a jejich řešení

What is a CCD?

The acronym **CCD** stands for Charge Coupled Device.

CCDs were invented at Bell Laboratories in the early 1970s.

They were originally designed as computer memory but it quickly became apparent that there were other uses for them. Their primary use today is as a solid-state imaging device.

It is this application which has revolutionised astronomy and which we will study further in these Activities.

Astronomical use of CCDs

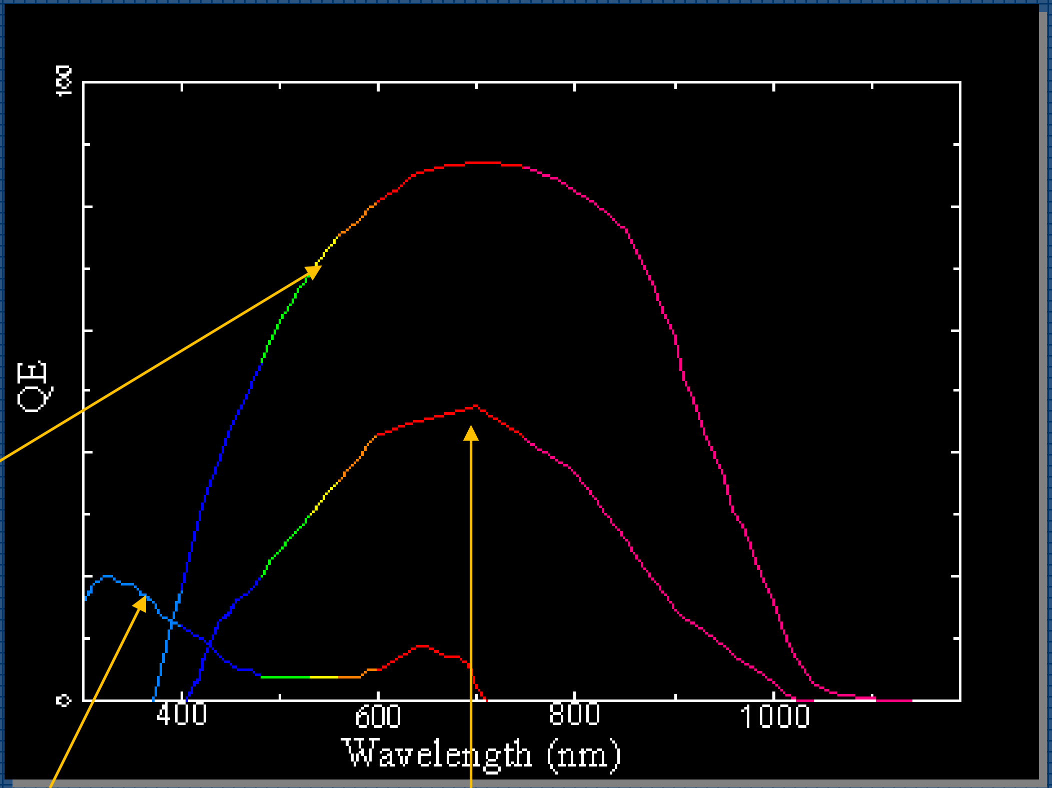
In this discussion of CCDs we will only consider their astronomical use. CCDs are in widespread use today in all manner of devices (video and still cameras, scanners *etc.*) but none of these applications are as demanding as astronomy.

Most CCDs are used in places where there is plenty of light available and so concerns of efficiency are not relevant. Exposures are brief and so noise sources are unimportant. The subject matter is forgiving and so cosmetic blemishes are not noticed. Alas, this is not so when trying to detect a distant galaxy.

Advantages of CCDs over film

CCDs have a higher quantum efficiency (QE) than film. QE is a measure of how efficient a device is in turning input energy (in this case light) into a measurable signal.

Greater efficiency means that more data can be gathered in a shorter time, or that in the same time you can measure a fainter signal.



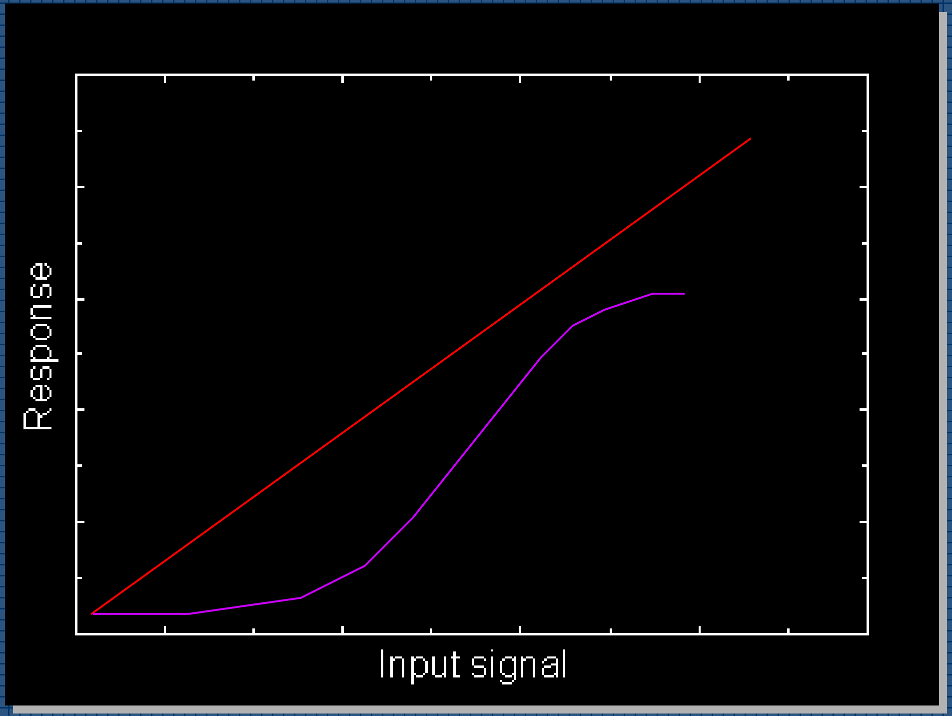
Professional CCD

Best film

Amateur CCD

CCDs have a linear response to light, i.e. the measured signal is directly proportional to the amount of light which was received. This is not true for film.

A linear response means that if the exposure is doubled, then the measurable signal will double. Also, twice the signal means the source is twice as bright.



CCD linear response **Film non-linear response**

More Advantages of CCDs over film

CCDs have a wide dynamic range. Coupled with their linearity they can measure both very faint targets and very bright ones.

- CCDs are dimensionally stable. The sensing elements (pixels – or picture elements) are laid out in a regular grid formed on the silicon substrate. This makes them excellent for most forms of positional measurement.

- CCDs are digital and so modern computers can be put to use in processing the images. No more messing about with photographic chemicals or working in the dark.

Advantages of CCDs

- This all adds up to a revolution in

The increase in QE over film is like making your telescope into a much bigger one - effectively allowing a 1-m telescope to perform like a 4-m.

The accuracy of CCDs in both linearity and stability means the measurements made are of the highest quality, and a wider band of the spectrum is utilised.

The digital nature of CCDs allows new techniques to be devised, both in taking the data and extracting the most from it.

How do CCDs work?

There are 4 basic stages to CCD operation.

- Light (photons) is converted to a charge (electrons) by the photoelectric effect in a layer of silicon.
- The charge is accumulated in “wells” during the exposure.
- At the end of the exposure the CCD is “read out” - the charge is shifted to the readout register.
- Finally, the charge in each pixel is measured.

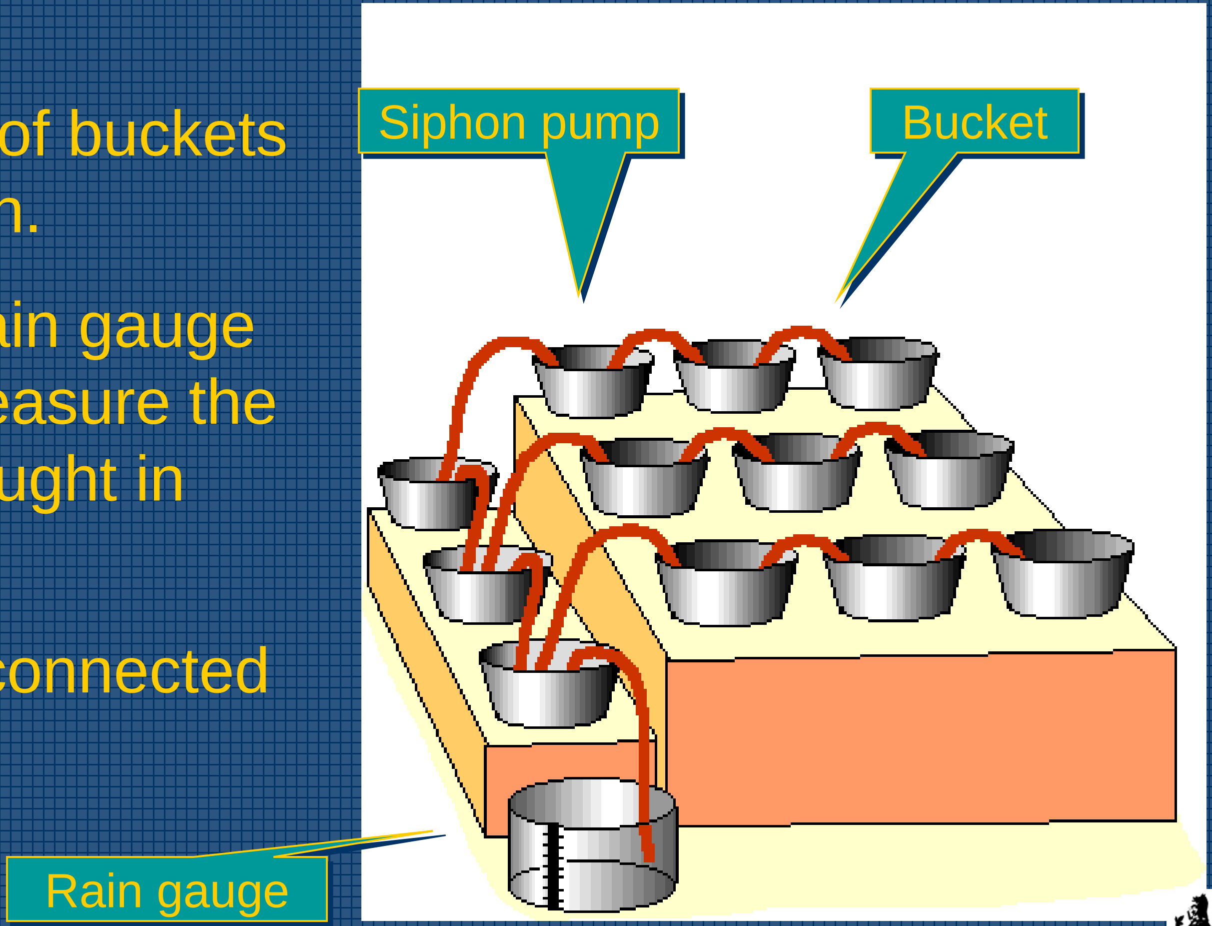
How do CCDs work?

An analogy is useful to picture the mechanisms involved in how CCDs collect, transfer and count charge.

Imagine an array of buckets ready to catch rain.

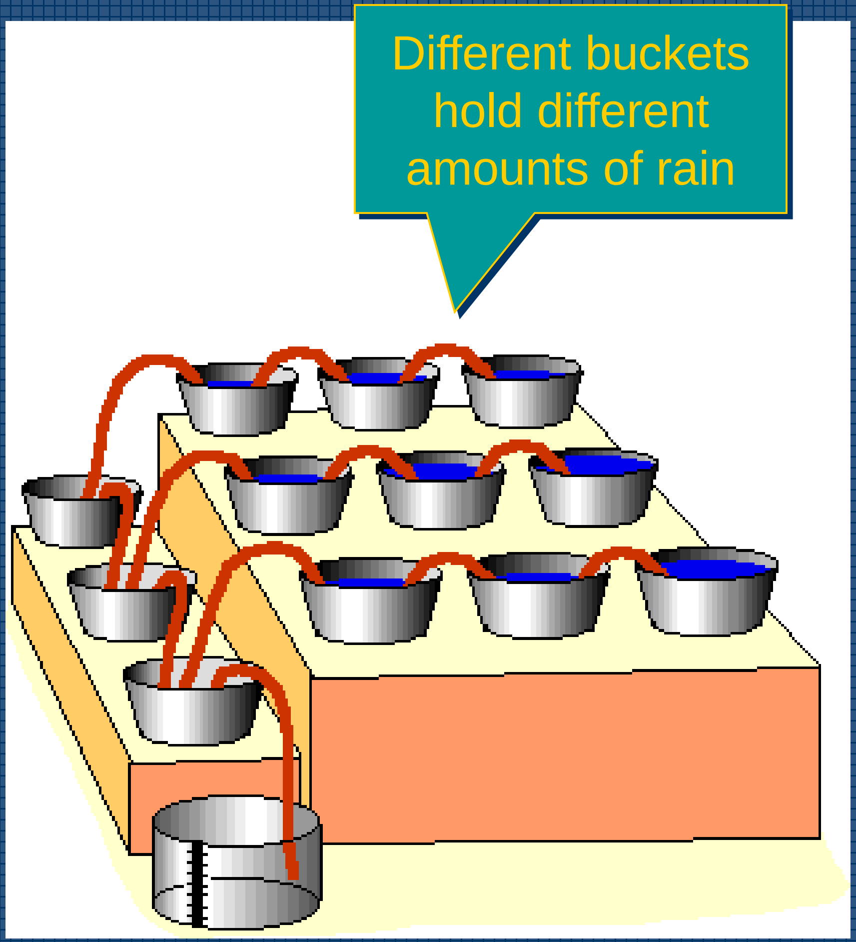
A single master rain gauge will be used to measure the amount of rain caught in each bucket.

The buckets are connected by siphon pumps.



How do CCDs work? – charge transfer

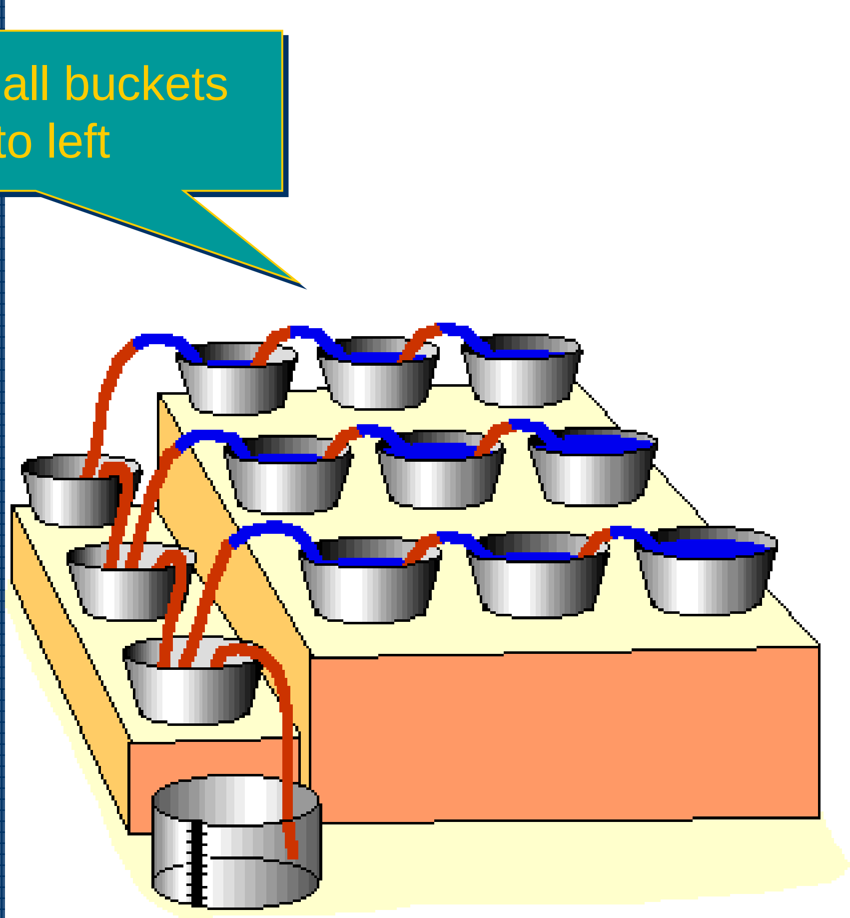
To measure the rain in each bucket (after the rain has stopped), the siphon pumps are used to move the accumulated rain towards the master rain gauge.



Different buckets hold different amounts of rain

How do CCDs work? – charge transfer

First, the end line of buckets are emptied into the empty row lined up with the master gauge.

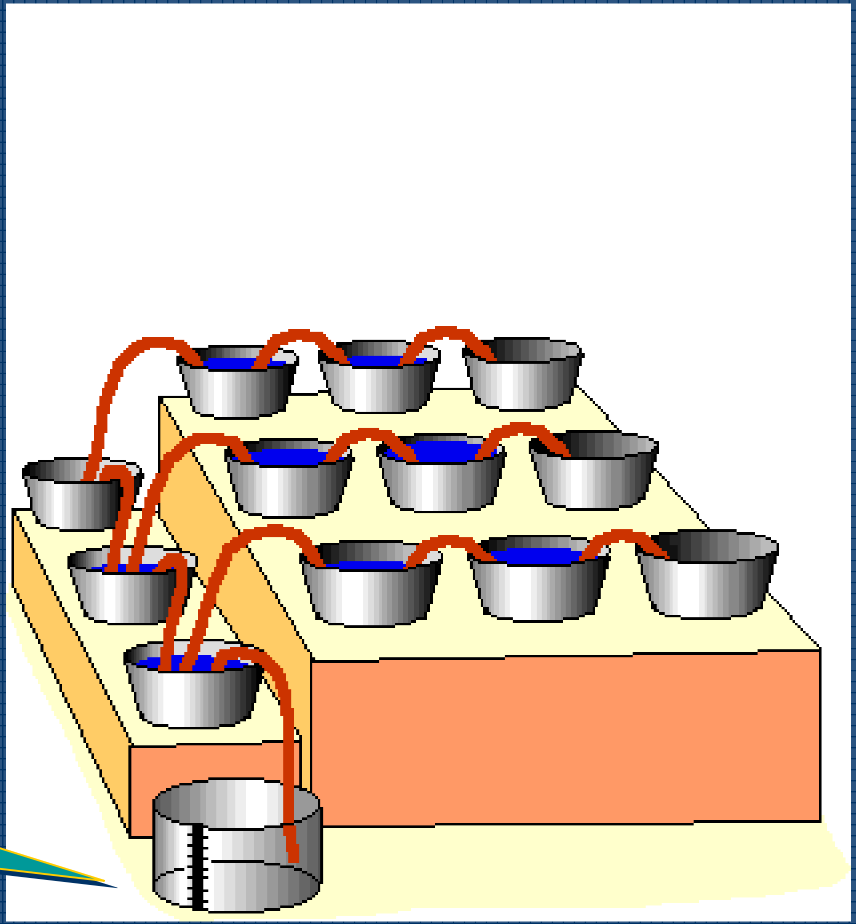


Contents of all buckets move to left

How do CCDs work? – charge counting

Then each bucket in turn is siphoned into the master gauge for measuring.

After each measurement, the master gauge must be emptied before a new measure can be taken.



Rain gauge is emptied

How do CCDs work? – charge counting

Then each bucket in turn is siphoned into the master gauge for measuring.

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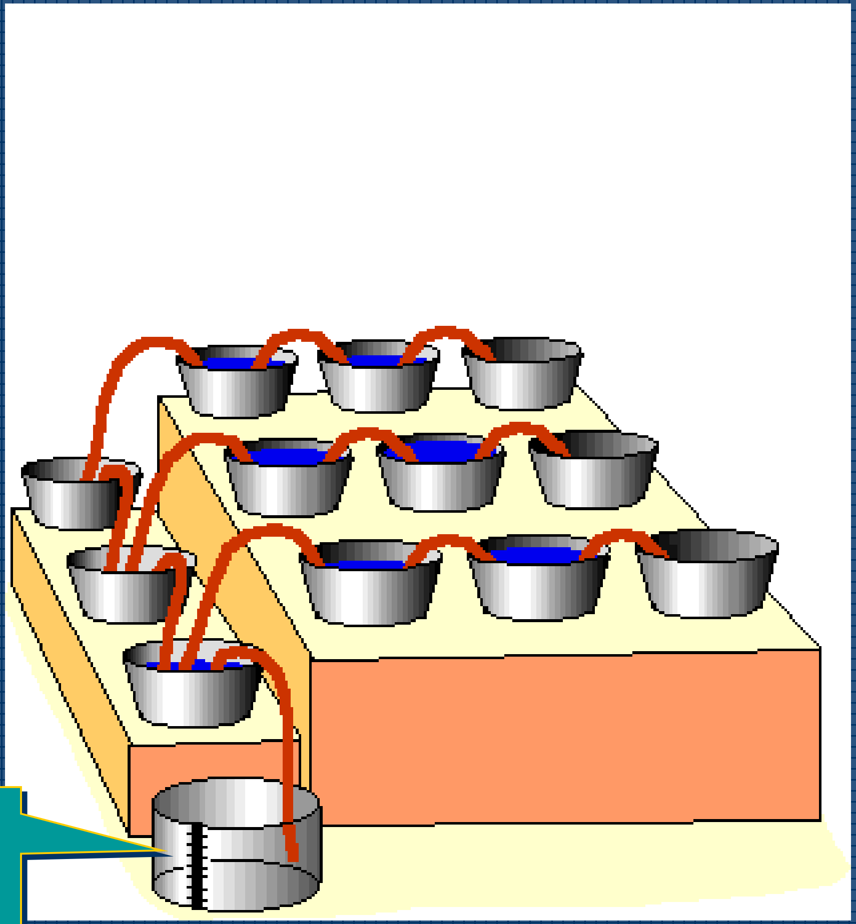

Rain gauge is emptied

How do CCDs work? – charge counting

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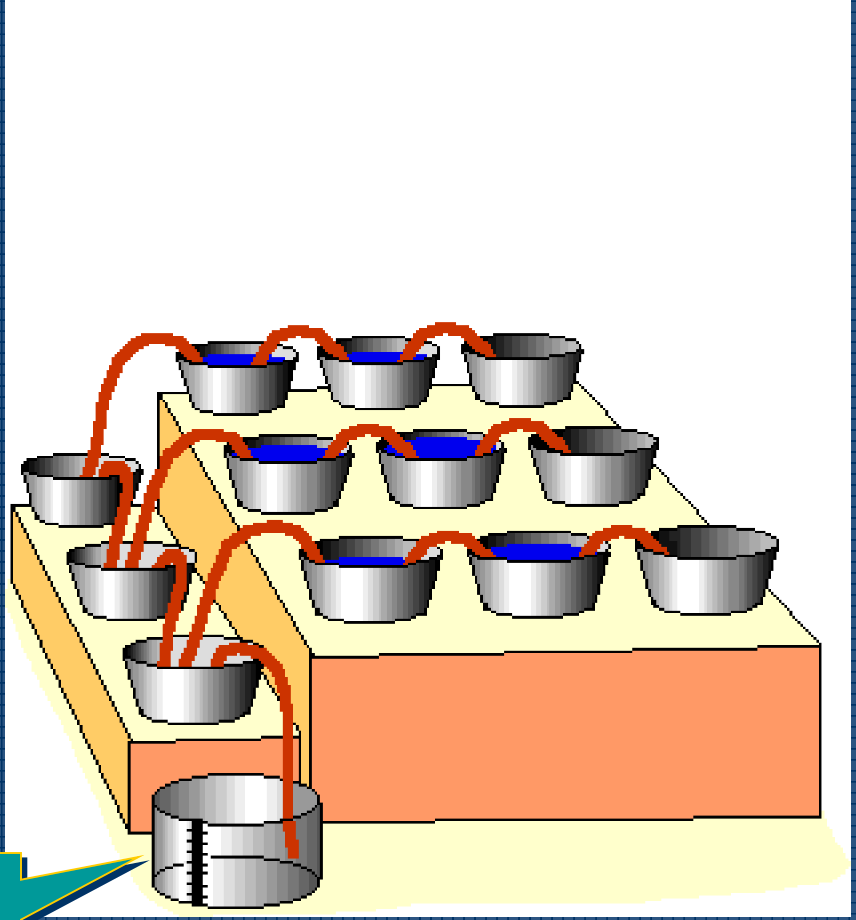
After each measurement, the master gauge must be emptied before a new measure can be taken.

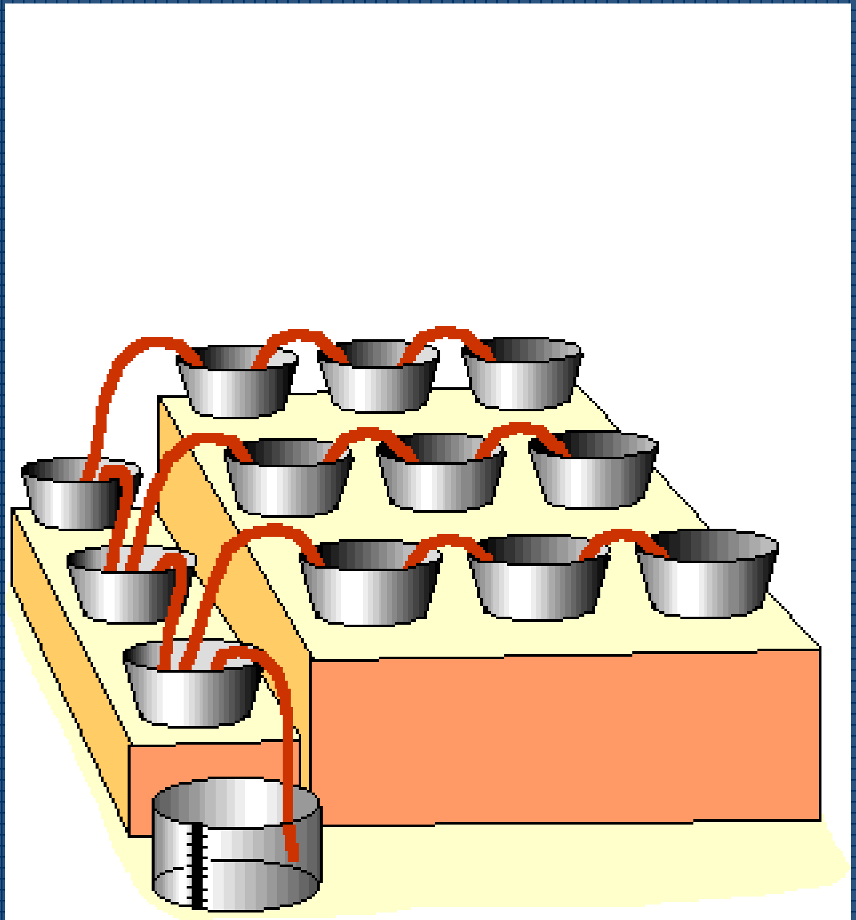


Rain gauge is emptied

How do CCDs work?

This shift-and-measure is carried on until all the water along the "readout register" has been measured.

The remaining water to be measured is siphoned along into the now empty buckets (the readout register) and the process of shifting-and-measuring is repeated.



How do CCDs work?

In the previous analogy, the raindrops represent photons

The accumulated water represents the charge detected by the CCD.

The buckets represent pixels on the CCD (and their depth represents the well depth, or how much charge each pixel can hold).

The siphon pumps represent the CCD shift registers.

The master gauge is the sense capacitor (and the fineness of the graduations represents the measurement accuracy).

How do CCDs work?

Of course CCDs are not quite so simple, but the underlying electronics does a good job at mimicking the analogy. CCDs are actually the most complex electronic circuits fabricated today, mainly because of their size and need for perfection over large areas of silicon. This makes them expensive, too!

You should have been able to spot from the analogy some of the potential problems associated with CCDs. By examining these areas we will get a better understanding of how they work.

Lets start by looking at the individual pixels.

Problems with CCDs – Pixels

The physics of turning photons into electrons is well understood and causes of efficiency loss can be controlled – up to a point. The practical problems associated with the design of CCDs is a limitation, however.

CCDs are 3-dimensional circuitry fabricated on a base of silicon (which is the light sensitive layer). It isn’t possible for 100% of the front surface of a CCD to be free for light to enter as there is nowhere for the circuitry which connects the pixels to go. Therefore, the light has to go through the circuitry which causes obvious losses. This is called “front-side illumination” and is what is used for most commercial CCDs.

An obvious solution is to turn the CCD over and let the light fall on the back side ("Back-side illumination"), but this has its own problem – there is then nothing to support the silicon.

The thickness of the silicon also means that the charge can't be held in the right position and can drift – this is called "charge diffusion". The silicon must be thinned to a few tens of microns to avoid this, and supported in a special way.

However, thinned and back-illuminated CCDs are the norm in professional astronomy today as they offer significant benefits, like 90% or greater QE.

This is the first major difference between professional and amateur CCDs.

Another improvement in not losing light is to apply an anti-reflection coating to the CCD surface. Again, normal in professional CCDs.

In front-side illuminated devices, the loss of light is most apparent in the blue end of the spectrum. One solution found was to coat the chip with “lumigen” – an organic substance similar to the “glow” in highlighter markers.

Lumigen works by converting any photons short of 420nm to 520nm, thus keeping the QE constant in the blue-UV part of the spectrum. Lumigen is cheap compared to thinning and is available for some amateur CCDs.

Problems with CCDs – Charge transfer

How efficient are the siphons in moving the water between buckets? Will every drop be moved or will some be lost? This is called “Charge Transfer Efficiency” (CTE).

The earliest CCDs had a CTE of only ~98 %. Today CTE is typically better than 99,995 % in commercial devices and much higher in scientific devices (99,9999 %).

Poor CTE means that not all of the photons which arrived on the CCD will be counted, and the further from the readout register the worse the effect.

Problems with CCDs – saturation

What happens when the buckets fill? This is a problem of both pixels and charge transfer. The physical size of the pixel determines how much charge it can hold. Larger pixels can hold more charge.

When the pixels are full, they are said to be saturated. What then happens depends very much on the electronic design of the CCD. During readout, not all the charge can be shifted – some is left behind. This leads to streaks (blooming or bleeding) forming behind saturated pixels.

This can be minimised somewhat by the inclusion of electronic “drains” in the CCD, called an Anti-Blooming Gate (ABG). Unfortunately, this also drains off wanted charge and so reduces the QE of the device.

Problems with CCDs – Accuracy

How accurately can we measure the number of rain drops? How finely graduated is the master gauge?

A CCD has an analogue output. Photons are converted to a charge and finally to a voltage for measurement. An on-chip amplifier boost the signal to a useful level. Is it possible to measure exactly how many photons fell on each pixel?

So far, the answer is not exactly. There are many reasons why it isn't possible to count electrons (e^-) – the closest that can be achieved at the moment is an RMS error of ~2e^-. That's close enough for most applications, but not all. Amateur CCDs manage around 20-30 e^- RMS*****.

**Click here to find out more about RMS*

Problems with CCDs – Noise

We’ve just seen “readout noise” – how accurately the number of electrons can be measured. Unfortunately, there are other sources of noise in a CCD.

There’s thermal noise. Astronomical exposures tend to be long – from a few seconds to many minutes – and many thermally induced electrons appear in that time. There is no way to distinguish these from the photo-electrons which we wish to measure.

The solution is to cool the CCD enough so that thermal noise isn’t a problem. This is the next major difference between amateur and professional CCDs. Professional CCD systems are in evacuated chambers and cooled to around 170°K (-100°C); amateur CCDs barely manage -30°C. The difference is very noticeable.

This thermal – or “dark” noise – grows linearly with time and is a function of the temperature of the CCD. Fortunately, because it is fairly repeatable this “dark current” can mostly be removed by careful calibration.

“Bias structure” is another source of noise but can also be calibrated out. The electronics as well as the physical make-up of a CCD will imprint a certain background structure to all images.

Finally, there is the problem that each pixel responds to light slightly differently to its neighbour. Again this is an effect which we can calibrate and remove.

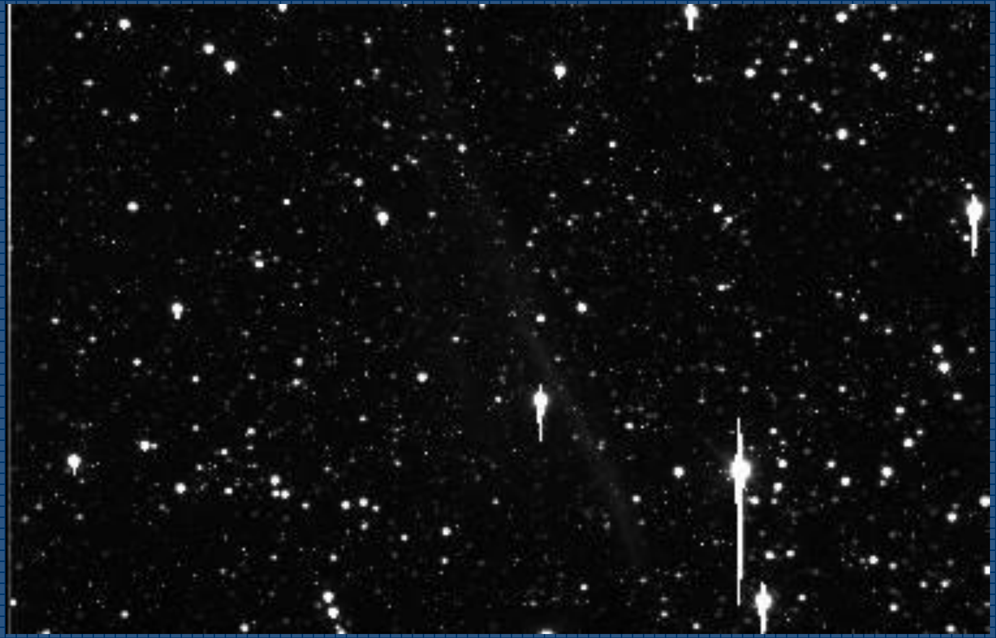
Problems with CCDs – Summary

There are other problems which we’ve not mentioned – such as how the amplifier in some CCDs glows! Defects in the silicon wafer causing non-fatal cosmetic problems etc. Even the Universe is out to get you, sending cosmic rays which zap new stars into existence on your exposure.

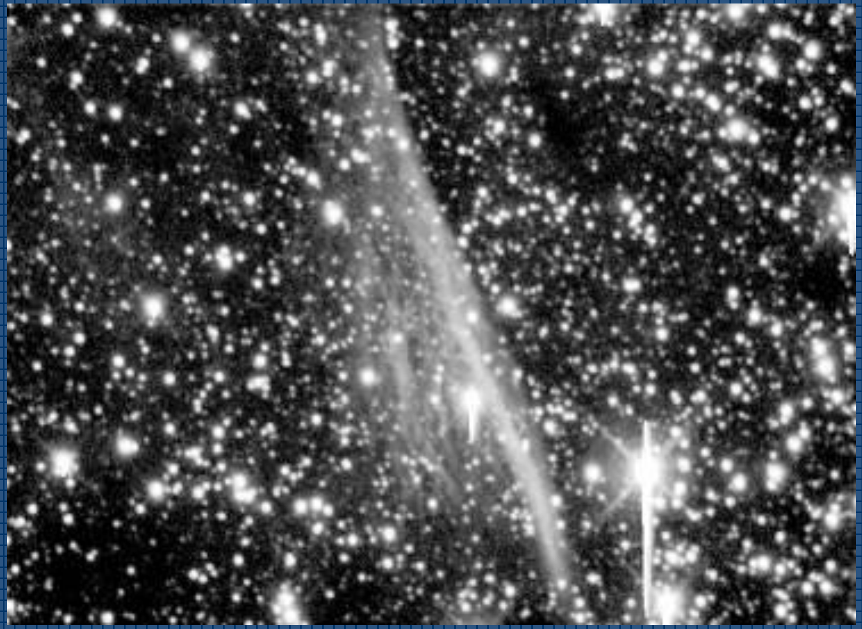
It might seem that there is a lot more to using a CCD than taking a photograph, but some of the problems discussed also affect film – but aren’t possible to control. With CCDs there is greater control and so it is possible to get so much more from them. The benefits far outweigh the problems.

CCD Calibrations

How do we turn
this raw image...



into this...



NGC 2736, part of the Vela SN remnant.

Imaged with 20cm f/4·5 Newtonian and Cookbook 245 CCD camera.

CCD Characterisation

Engineers characterise their CCDs in a laboratory before they are put on a telescope. This allows any problems to be corrected (or bypassed!) and then allows astronomers to use them to their full potential.

The parameters which are needed are:

- The amplifier gain – how many electrons per count.
- The linearity of the amplifier and electronics – there will always be some slight variation from perfection.
- QE and CTE – how good is the CCD.
- Any cosmetic or electronic blemishes (“trapping sites”, *etc.*) – every CCD is unique!

CCD Calibrations

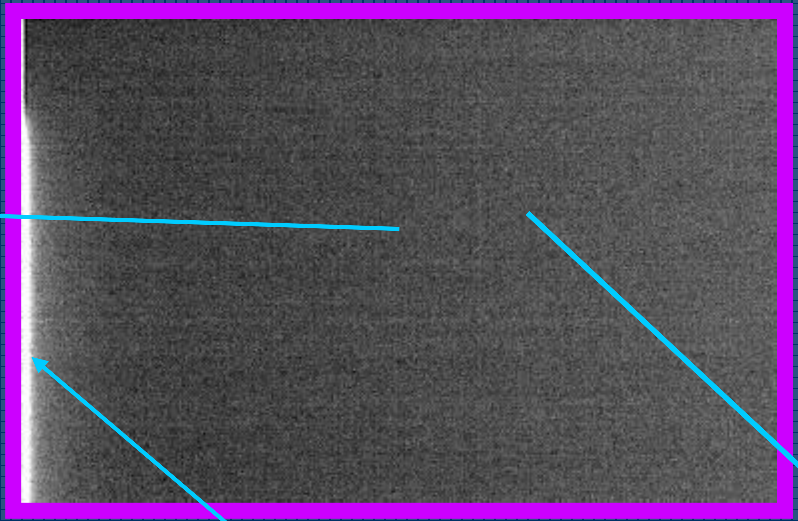
Amateurs don’t usually bother with such characterisation tests, nor can they do much about them if present. Calibrations that can (and should) be done by everybody are BIAS, DARK and FLAT FIELD.

Let’s start with the BIAS, which is a zero-length exposure designed to show what, if any, underlying structure there is on the CCD and electronics.

The bias actually consist of two components; a non-varying level which is the electronic zero-point, plus any structure present. Professional systems usually produce an overscan region to allow the zero-point for each exposure to be seen.

CCD Calibrations – bias

Here is a bias frame from a typical amateur CCD.



Little other structure is evident; statistical variation is only 0·4 ADU so can be considered quite a clean bias.

The image is scaled with only 6 ADU from black to white

The most obvious structure is this bright stripe on the left

The mean level is 100·8 ADU

CCD Calibrations – bias

The bias structure is a constant and may simply be subtracted from each image.

As the readout noise is a significant part of the variation in each image, it is better to average several (say 10–20) bias frames and create a master bias.

The bias should not change in the short term and so once a master bias has been created it can be re-used until such time as the electronics are changed.

Removing the bias is the first stage in image processing.

CCD Calibrations - dark

To remove the thermal content of an exposure, take a DARK frame. A dark frame is the same length as a normal exposure but with the shutter closed so no light falls on the CCD.

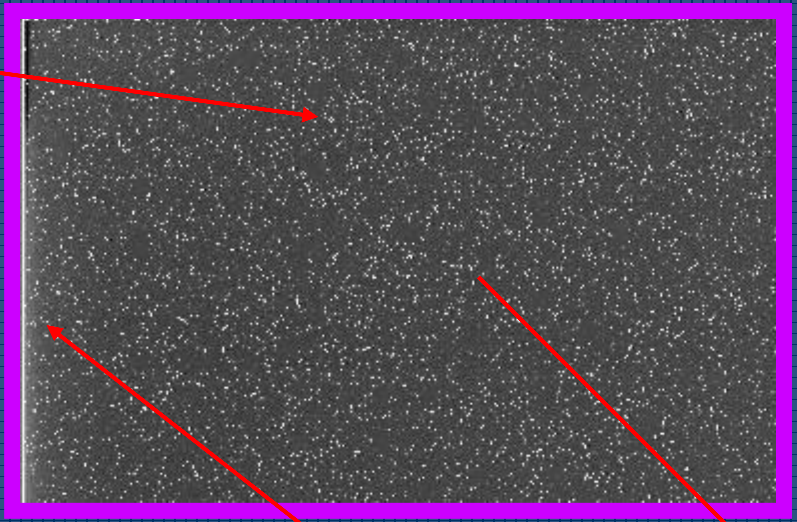
It is subtracted from a normal image, provided they are of the same duration. (After the bias has been removed, of course.)

Again, statistical variations can be minimised if you average several dark frames together.

All images, including darks, contain the bias. A shortcut often used is to not separate out the bias but subtract the dark+bias. This works well enough.

CCD Calibrations

Here is a 4 minute dark frame from a typical amateur CCD.



The statistical variation is now 20 ADU and the whole CCD is covered in bright spots

The image is scaled with 20 ADU from black to white

The mean level is 102.9 ADU (little more than the bias), but the maximum is now 709 ADU

The bright stripe is now insignificant

Removing the dark is the second step in image processing.

CCD Calibrations – flat field

The next stage is to remove the pixel-to-pixel variations. This is done with a flat field – an image of a featureless, uniform source (twilight sky is a good source for this).

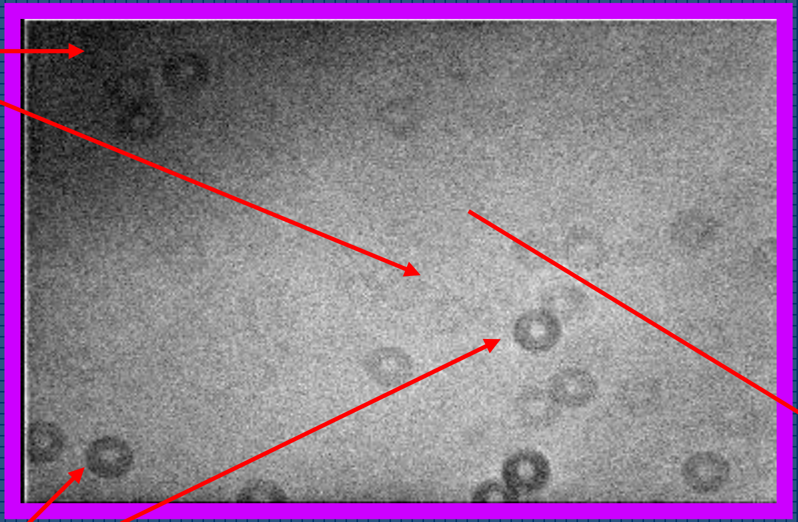
What a flat field shows is not only the minor pixel variations, but all the defects in the optical train such as vignetting and dust spots which cause sensitivity to vary across the frame.

The de-biased, dark subtracted image is divided by the normalised (image mean reduced to 1) flat field. This enhances areas of low sensitivity and reduces areas of higher sensitivity, creating a field with apparent uniform response.

Dividing by a flat field is the third step in image processing.

CCD Calibrations – flat field

Here is a flat field from a typical amateur CCD.



The variation in intensity from centre to edge represents a change of only 1.7%

The image is scaled with 50 ADU from black to white

The "dust donuts" here look bad, but represent a variation of only 1% in the most extreme case. (Dust donuts are an inverse "pinhole camera" image of the telescope – with a central obstruction in this case.)

The mean level is 1800 ADU with only 9 ADU variation, so is actually quite uniform

Summary

This Activity has concentrated on understanding the basics of CCDs. It has shown both the advantages and some of the problems of electronic imaging.

Once the quirks of CCDs are understood, the necessary calibrations become a simple exercise (which can be carried out automatically under some software).

In the next Activity we shall see how to put all this knowledge to use and take some CCD images.

Appendices

Some terms used when discussing CCDs:

ABG	Anti-Blooming Gate. An electronic “drain” on pixels to try to minimise bleeding due to over-saturation. Has unwanted side effects like lowering QE.
ADC	Analogue-to-Digital Converter; it converts an analogue voltage to a digital count.
ADU	Analogue-to-Digital Unit; one “count” out of a CCD
Bias	The background level of the CCD
Bias Frame	A zero length exposure to show the bias structure of the CCD

Bleed or Bloom	When a pixel is over-filled the charge has to go somewhere, usually into ugly streaks.
Calibration frame	An auxiliary image taken to help calibrate a science exposure.
CCD	Charge Coupled Device
Channel Stop	An electronic structure on a CCD to stop the charge in a pixel from migrating.
Clocks, clocking etc.	The charge on a CCD is moved around by stepping (or clocking) voltages. There are various electronic signals which control this.
CTE	Charge Transfer Efficiency; how good the electronics are at shifting the accumulated charge around.

Dark current	The rate of build-up due to thermal noise
Dark Frame	An exposure to measure the dark current
Exposure	The time the CCD is exposed to light
Flat Field	An image of a blank target designed to show imperfections in the CCD and imaging system
Full-frame Device	A CCD which has its entire area exposed to light. It needs an external shutter to stop it from being exposed to light during read out.
Frame Transfer Device	A CCD which has only half its area exposed to light, and the other half covered. The exposure is transferred first to the covered area before being read out.

Gain The number of e^- per ADU

Interline Transfer Device A CCD which has adjacent active and readout columns. Not widely used in astronomy.

Image processing The art and science of calibrating a digital image (not necessarily CCD) to extract the most information from it.

Lumigen A fluorescent coating which can be applied to a CCD to improve its UV/blue response.

Overscan By reading out more pixels that actually exist on the CCD, you create an overscan strip. This gives the bias level on an exposure.

Pixel	Picture element; the resolution element of the CCD approximately 6 to 30µm in size (not always square).
QE	Quantum Efficiency; how well the device responds to light of different wavelengths
Saturation	When a pixel well is full. If it continues to receive light it may bleed (or bloom). See ABG.
Shift Register	The mechanism by which charge is shifted around on the CCD.
Readout Noise	The accuracy to which the charge in a pixel can be measured. Usually given as e^- RMS
Readout Register	The place on a CCD where the charge is measured

Trapping site	A defect on a CCD which impedes the flow of electrons
Well depth	How many electrons a pixel can hold before saturating

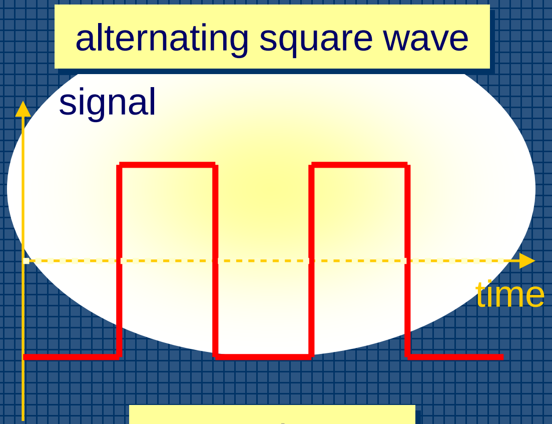
Return to Activity

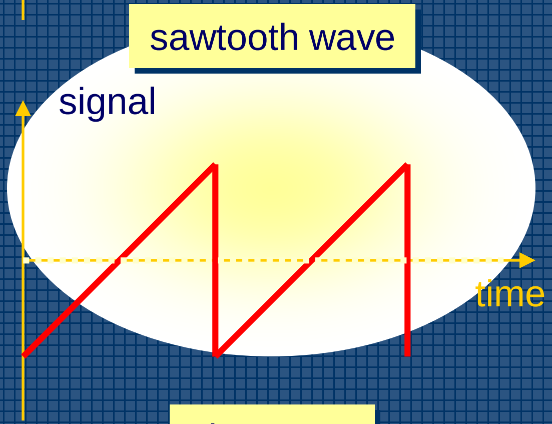
Average value versus RMS

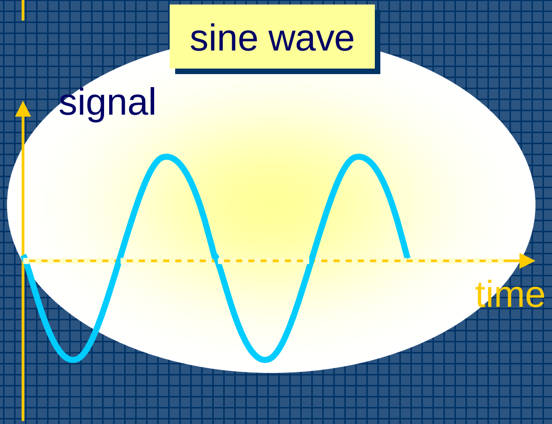
- In engineering and physics, sets of data often "alternate": they vary from positive to negative and spend equal amounts of time in each state.
- If you found the **average value** of the data in the normal way, you would obtain zero.
- The average values are shown on the graphs in blue.

Because of this, the usual type of average gives very little information when information or energy is obviously being transmitted and work is being done (as in the use of alternating electric current).

In situations like that, scientists and engineers tend to use the **RMS value** instead.


alternating square wave


sawtooth wave


sine wave

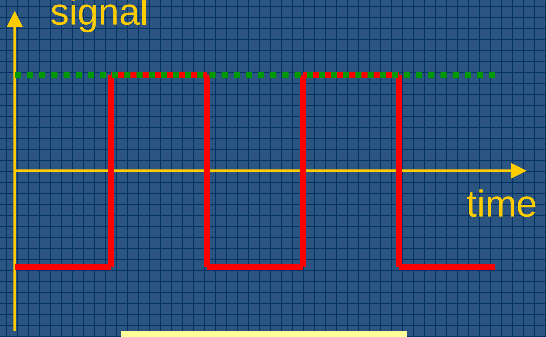
RMS

- RMS stands for **R**oot **M**ean **S**quare.
- To find the RMS value for a series of data,
  - the data are all **s**quared
  - the **m**ean (or average) of the squares is found
  - the square **r**oot of this mean is taken.
- The rms values are shown in **green**.

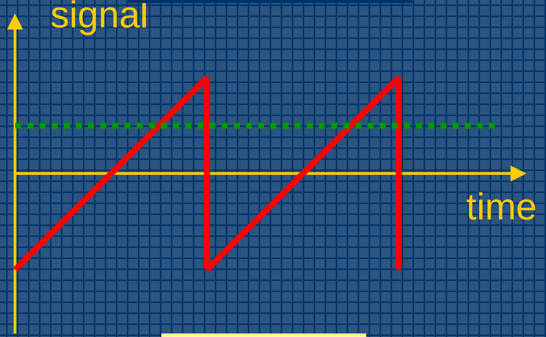
The power of a signal, or its intensity, are very often related not to the signal’s amplitude, but instead, to the ***square*** of the signal’s amplitude.

For that reason, the RMS value usually gives a very useful indication of the average **power** or **intensity** of a signal, and is a standard measure used in many branches of physics and engineering.

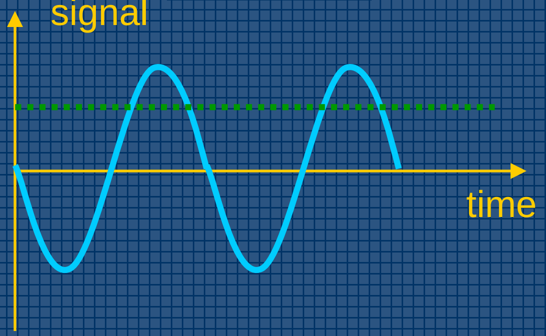
alternating square wave



sawtooth wave



sine wave



cvičení
práce se CCD kamerou

příklady CCD a CMOS kamer MI (ing. Cagaš)

… the end …