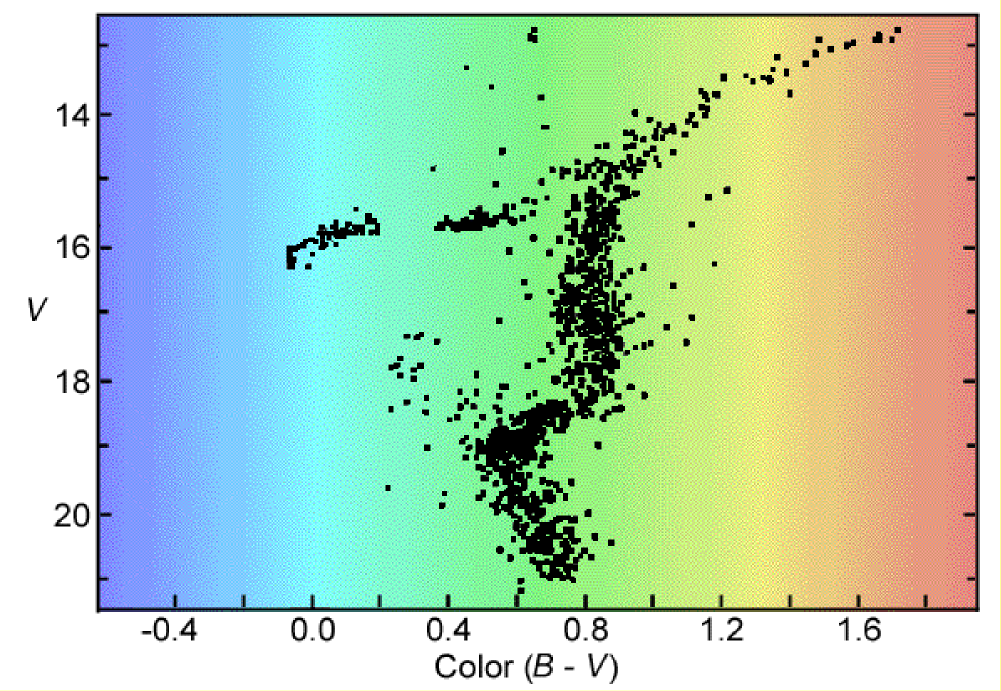
Photometry



Gerald Handler

Nicolaus Copernicus Astronomical Center, Warsaw

Photometry measures the light output of (astronomical) objects

- Photometry measures the energy from a source using a narrow range of wavelengths.
- The observed brightness is related to the energy received.
- In astronomy, the unit of magnitudes is used.
- The magnitude scale was originally six classes, is effectively logarithmic, and lower numbers correspond to brighter objects.
- 6^m is at the limit of human vision.
- The magnitude (*m*) was formally defined in 1856 (Pogson).

Photometry measures the light output of (astronomical) objects

$$m - n = 2.5 \log \left(E_n / E_m \right)$$

For one unit of magnitude: $$\frac{E_n}{E_m} = 10^{1/2.5} = 2.512$$

Astronomical definition of colour:

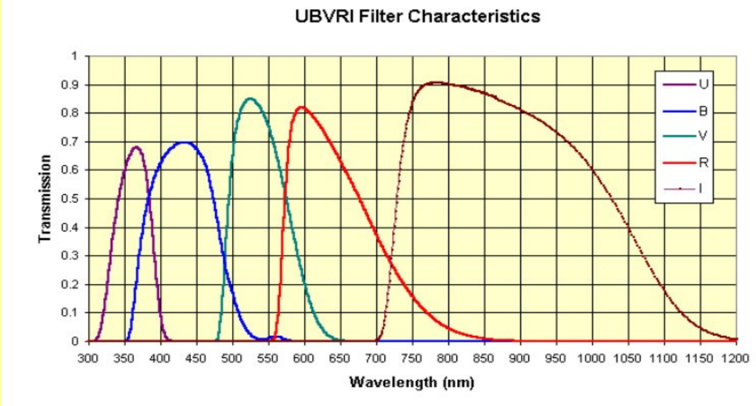
$$m(\lambda_1) - m(\lambda_2) = -2.5[\log I(\lambda_1) - \log I(\lambda_2)]$$

$$U - B = m_U - m_B, \quad B - V = m_B - m_V$$

$$V - R = m_V - m_R, \quad R - I = m_R - m_I$$

Photometry measures the light output of (astronomical) objects

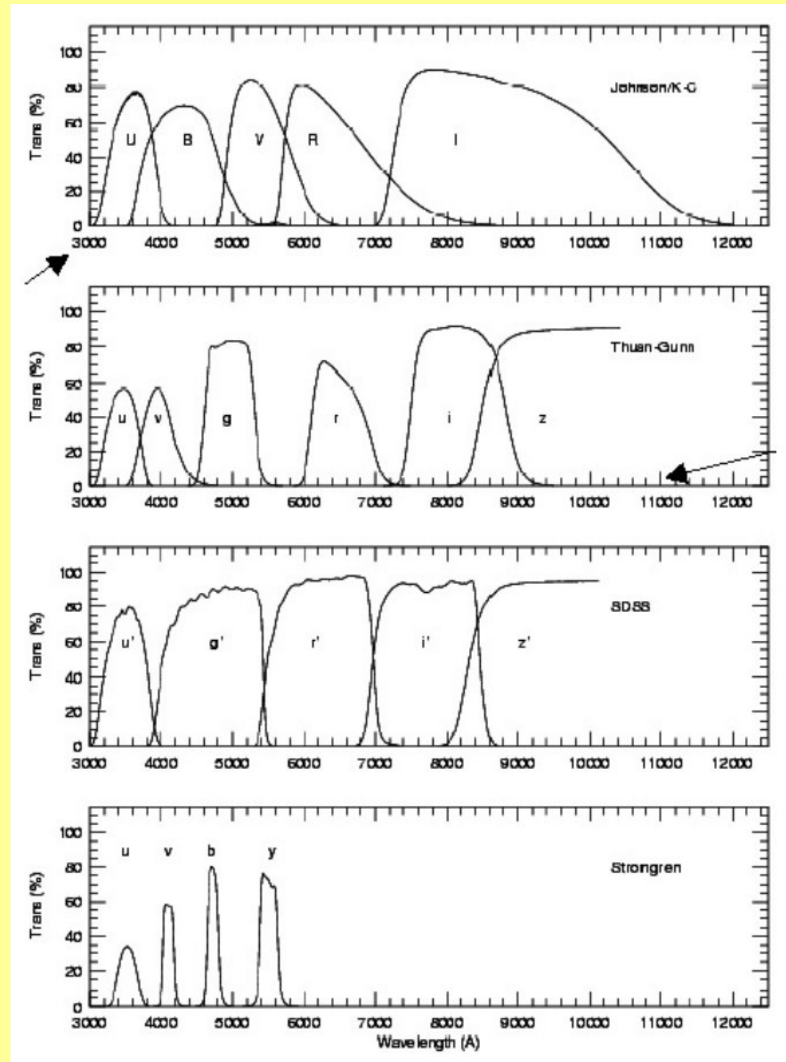
- Photometry uses filters to select wavelengths.



Photometry measures the light output of (astronomical) objects

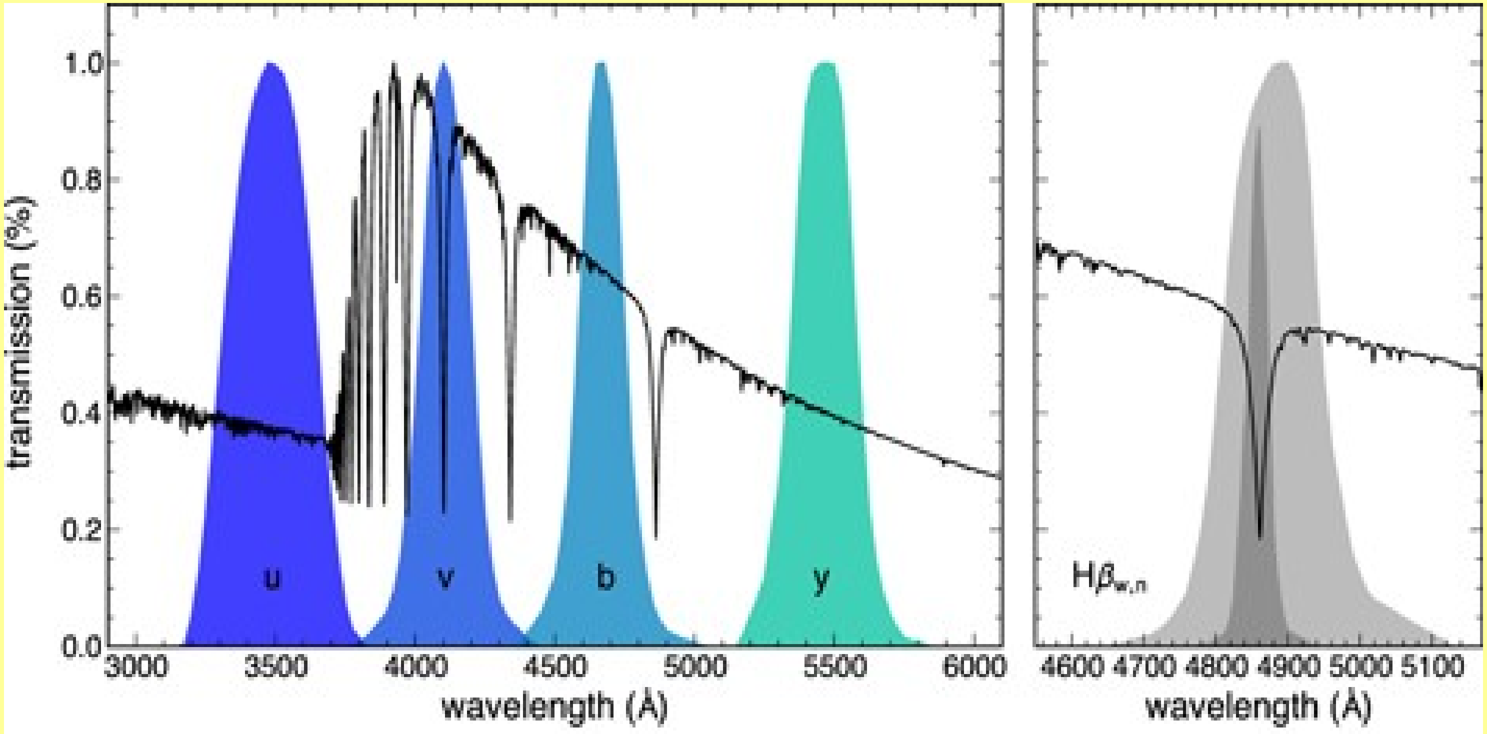
- ...and there are lots
  of filter systems!

- This has partly historical,
  but mostly scientific reasons.



Photometry measures the light output of (astronomical) objects

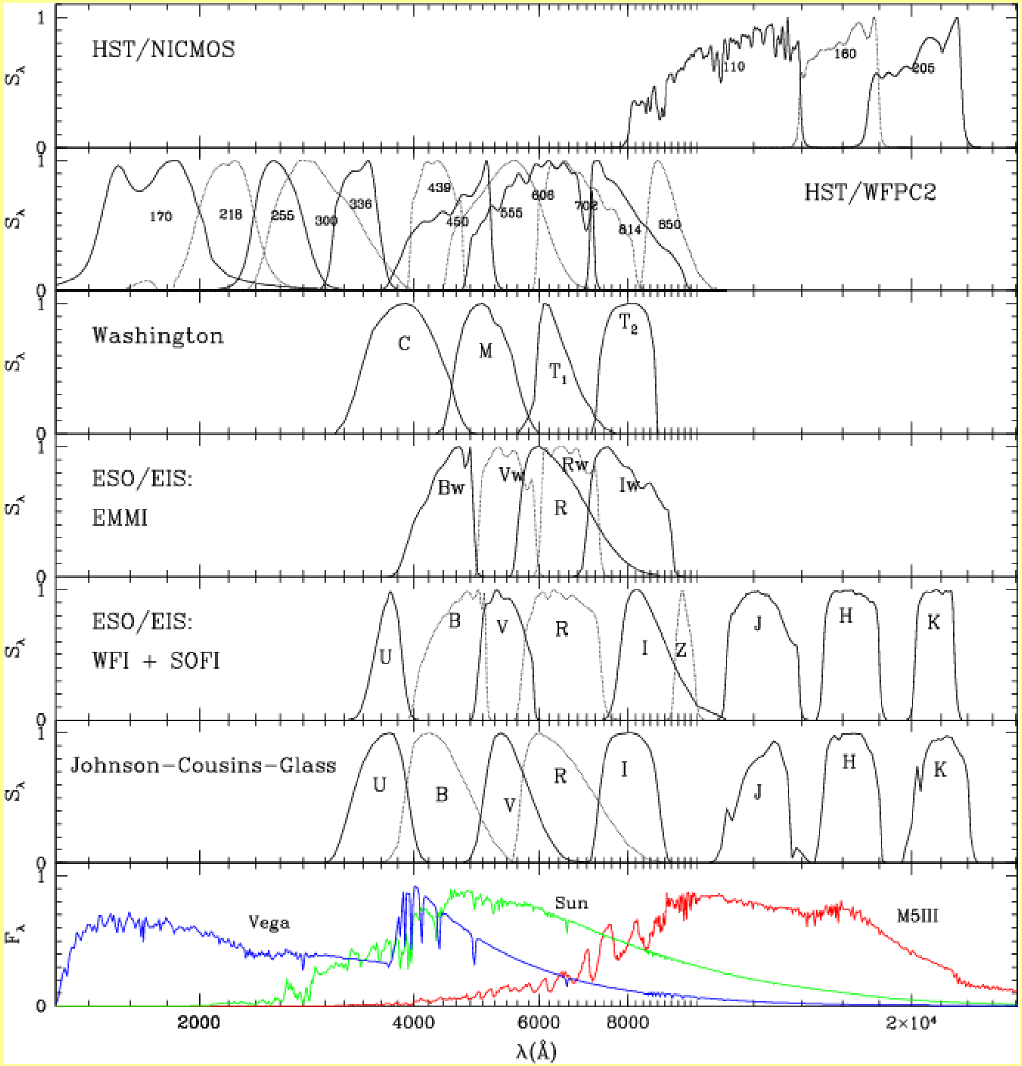
Example: the Stromgren system



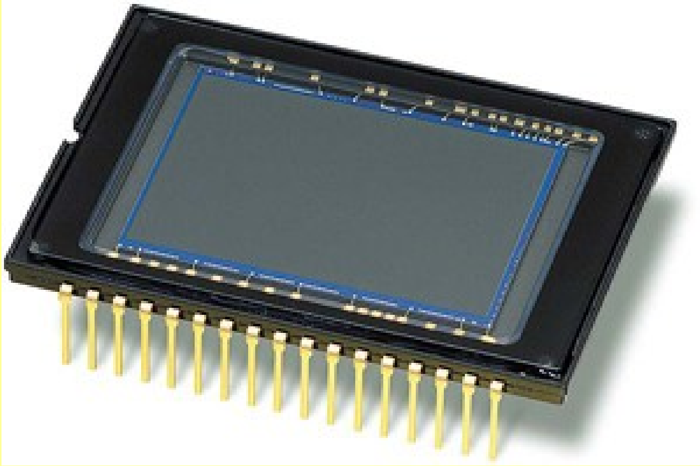
Photometry measures the light output of (astronomical) objects

Filter systems are usually chosen to derive some physical properties of the target objects.

Smaller telescopes needed than for spectroscopy!

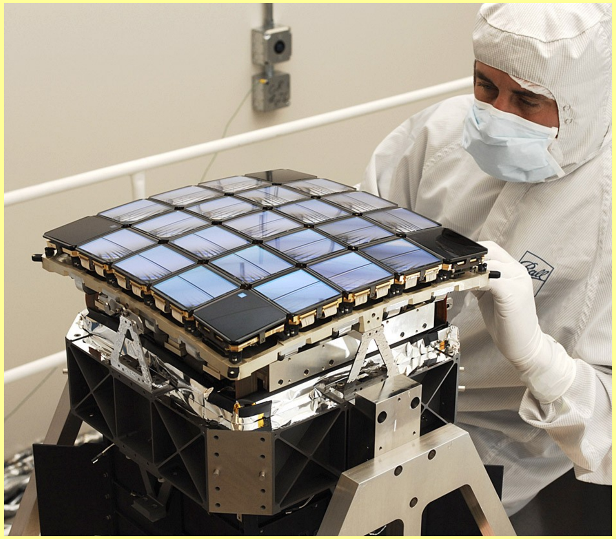


Some words about detectors:
Charge Coupled Devices (CCDs)

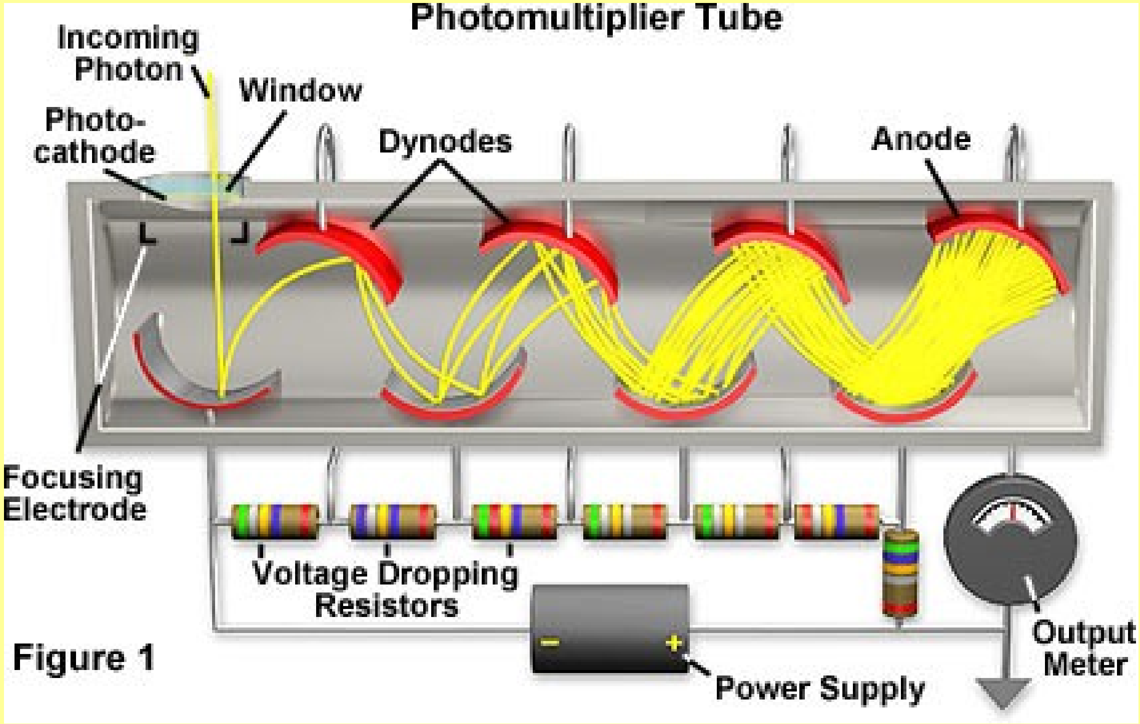


The two dimensional format makes these ideal detectors for photometry over a wide field.

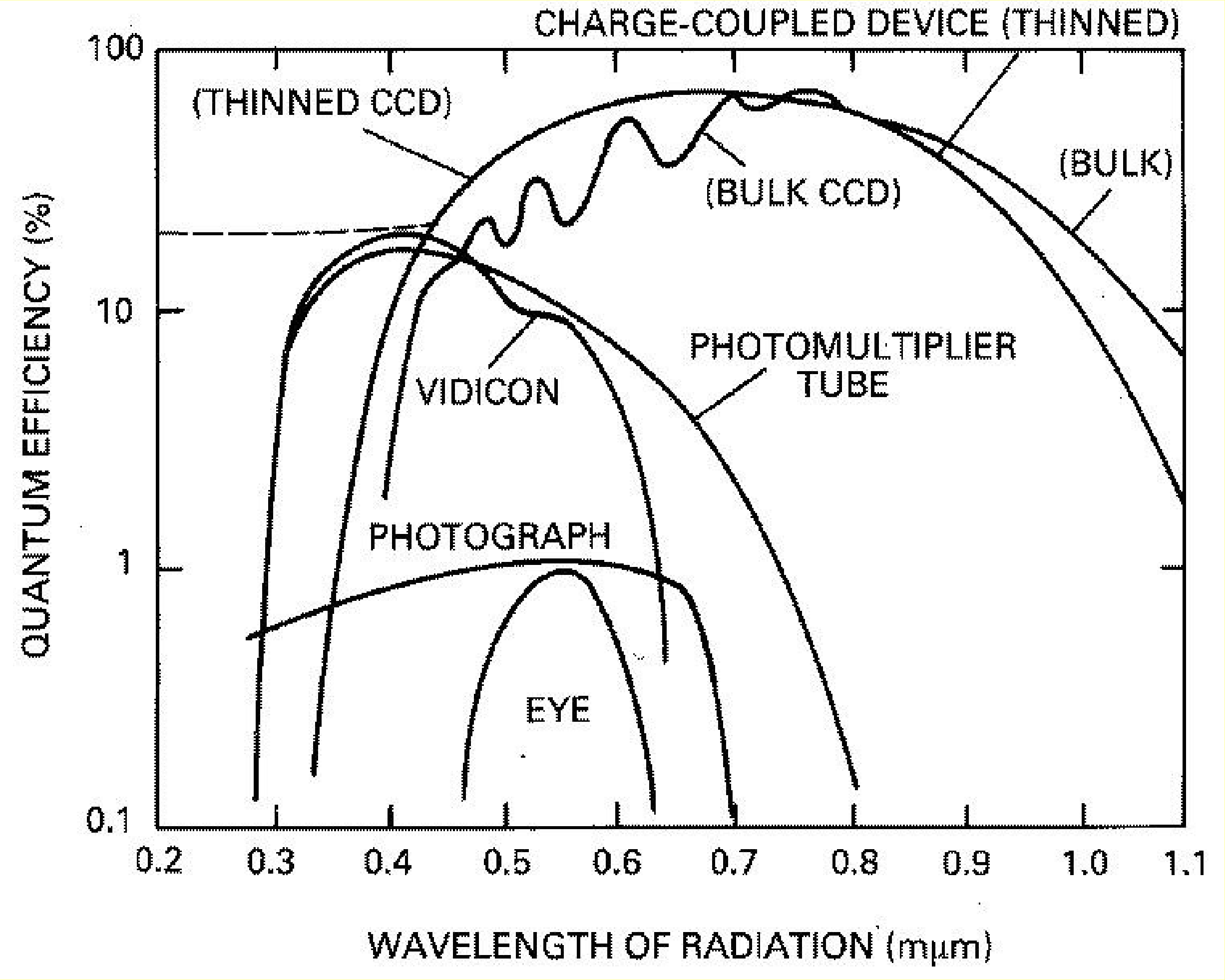
Kepler's 42 CCDs



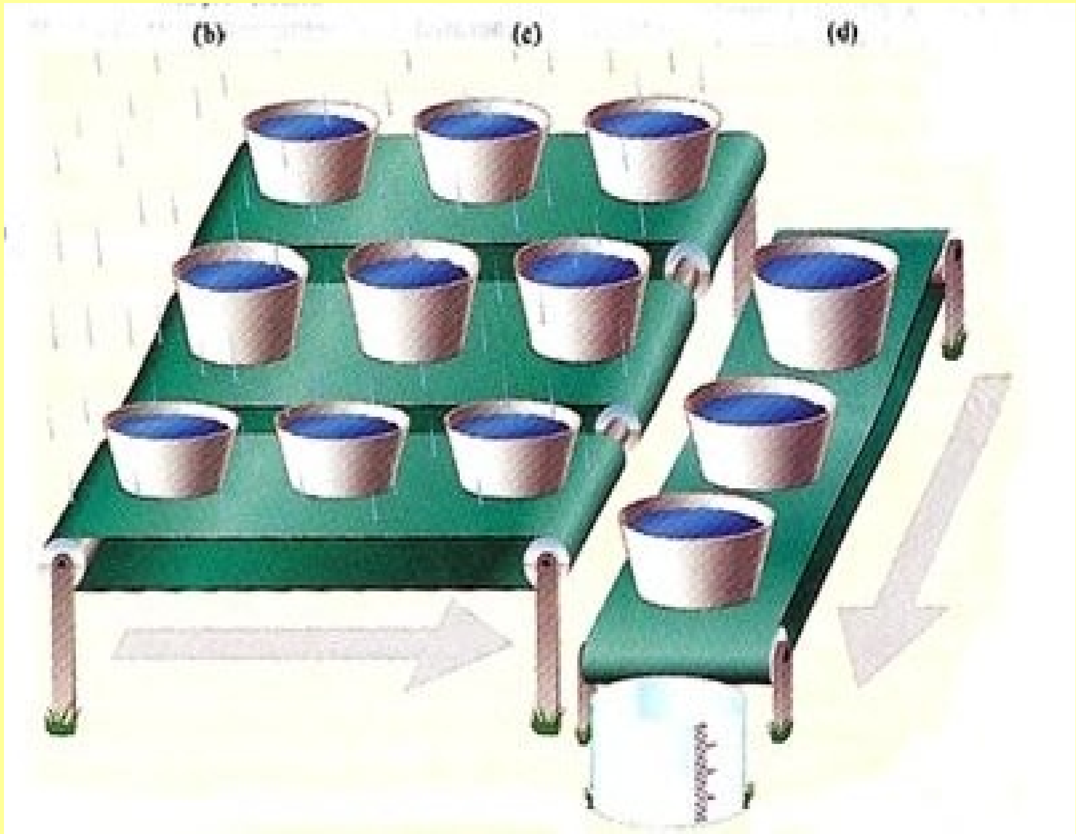
Photometric detectors of the past: photomultipliers



CCDs took over due to higher quantum efficiency (=sensitivity)



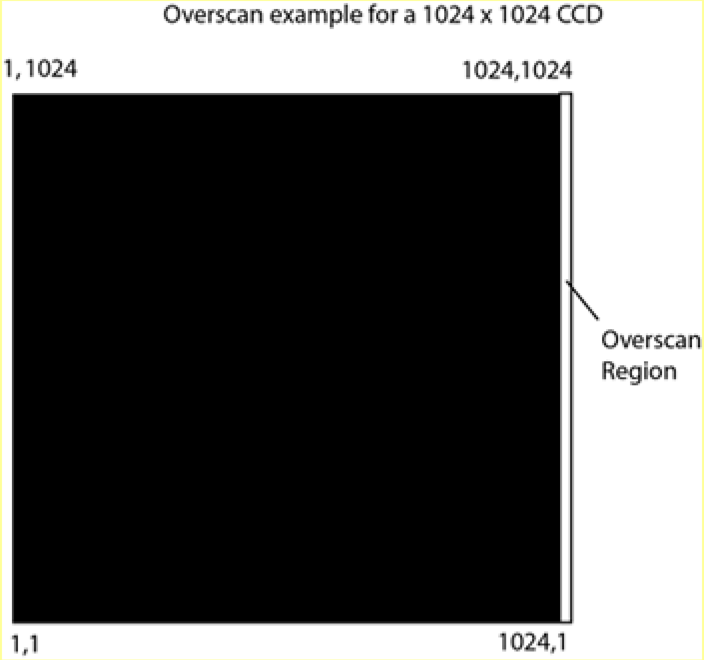
How does a CCD work?



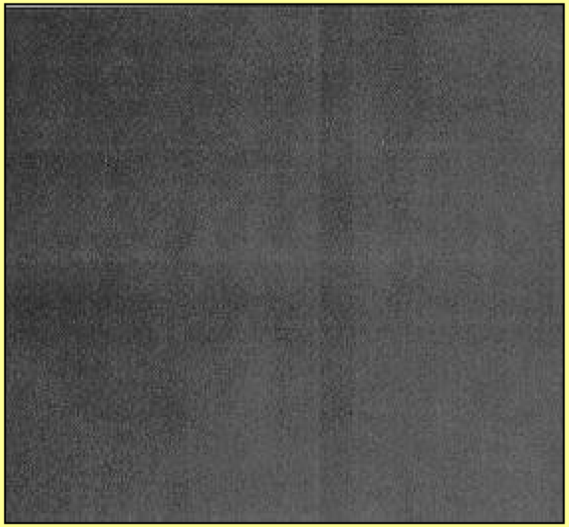
- Rain = Photons
- Water = Charge (photon strikes silicon semiconductor surface and knocks an electron loose by the photoelectric effect)
- Buckets = pixels (electrons accumulate in “potential wells”; depth represents how much charge each pixel can hold)
- The charge in each line of pixels is shifted to the readout register
- The charge in each pixel is counted

Basic CCD image reduction steps

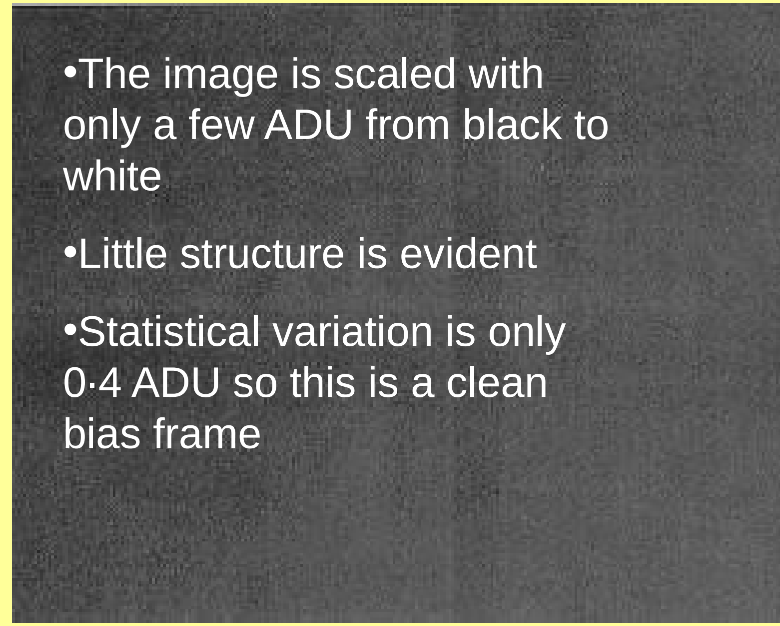
The electric charge in each CCD pixel is transferred into digital numbers. To ensure positive values, a so-called bias value is added that needs to be subtracted. For that, an overscan region is very useful.



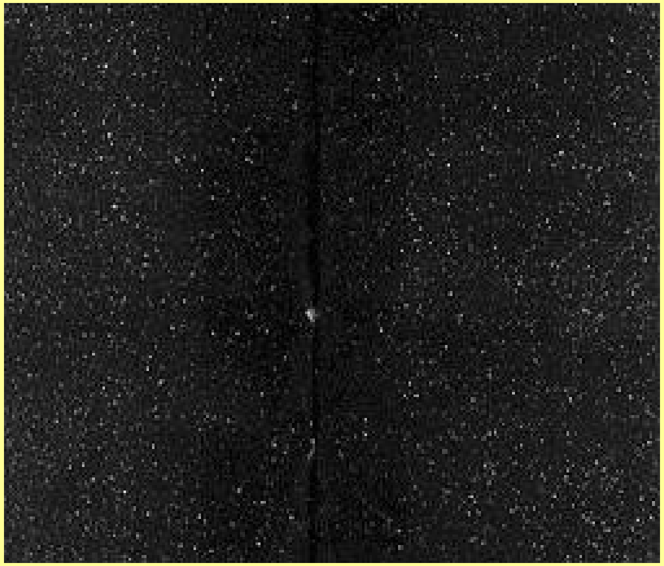
Subtract overscan -->



CCD Calibrations - Bias



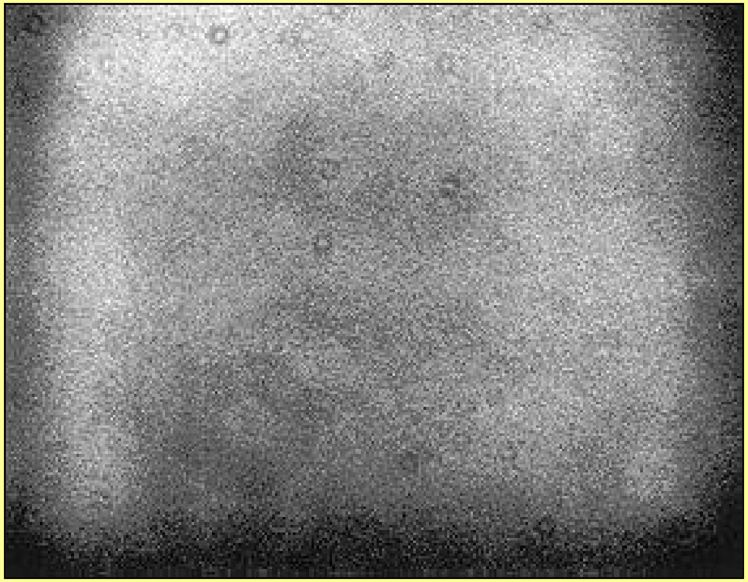
- A BIAS frame is a zero-length exposure to show any underlying structure in the image from the CCD or electronics
- The bias consists of two components
    - » a non-varying electronic zero-point level
    - » plus any structure present
- CCD systems usually produce an overscan region to allow the zero-point for each exposure to be measured
- The bias structure is a constant and may simply be subtracted from each image
- Because of readout noise (the noise created by reading out the device), average several (say, 10–20) bias frames to create a master bias frame



CCD Calibrations - Dark

- To remove dark current, take a series of DARK frames
- A dark frame is the same length as a normal exposure but with the shutter closed so no light falls on the CCD
- Since CCDs also detect cosmic rays, take several darks and combine them with a median filter to remove cosmic rays from the combined dark frame. Combining several dark frames also minimizes statistical variations.
- Subtract the combined dark frame from a normal image, provided they are of the same duration. (After the bias has been removed, of course.)
- All images, including darks, contain the bias. A shortcut often used is to not separate out the bias but subtract the dark+bias.
- Most research CCDs have very low dark current, so dark frames may not be necessary. But better always take dark frames and check in hindsight instead of regretting you don't have enough!

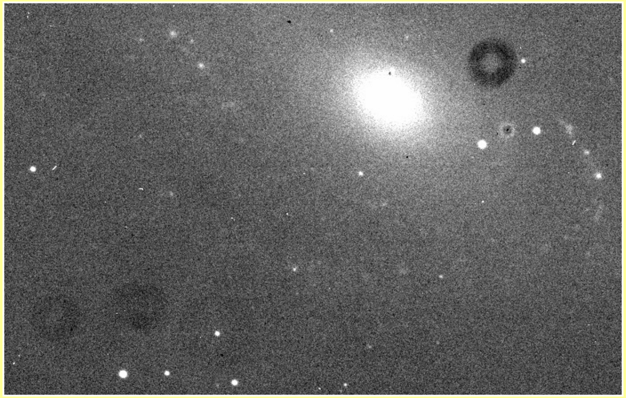
Center to edge variations and
donuts are both are about 1%



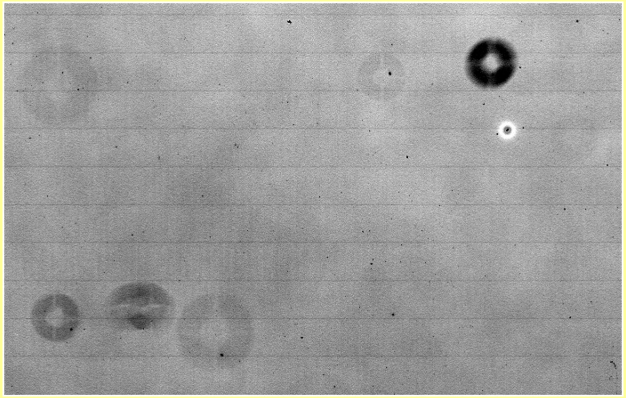
CCD Calibrations – flat field

- Pixel-to-pixel variations are removed with a “flat field” image
- A flat field is an image of a featureless, uniform source (such as the twilight sky or a dome projector screen)
- A flat field shows the minor pixel variations, as well as all the defects in the optical train (e.g. vignetting and dust spots)
- After bias and dark subtraction, divide the image by the “normalized” (image mean reduced to 1.0) flat field
- Dividing by the flat field image corrects for variations in sensitivity on the detector and throughput of the telescope and instrument

CCD Calibrations – flat field



Raw Frame



Flat Field

Raw divided by Flat

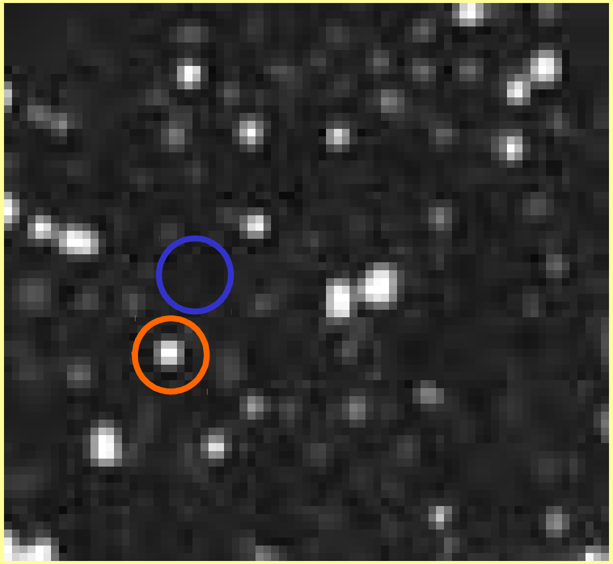
Now we can finally do photometry!

How to measure a magnitude?

The “simplest” way:
aperture photometry

Get data (star) counts

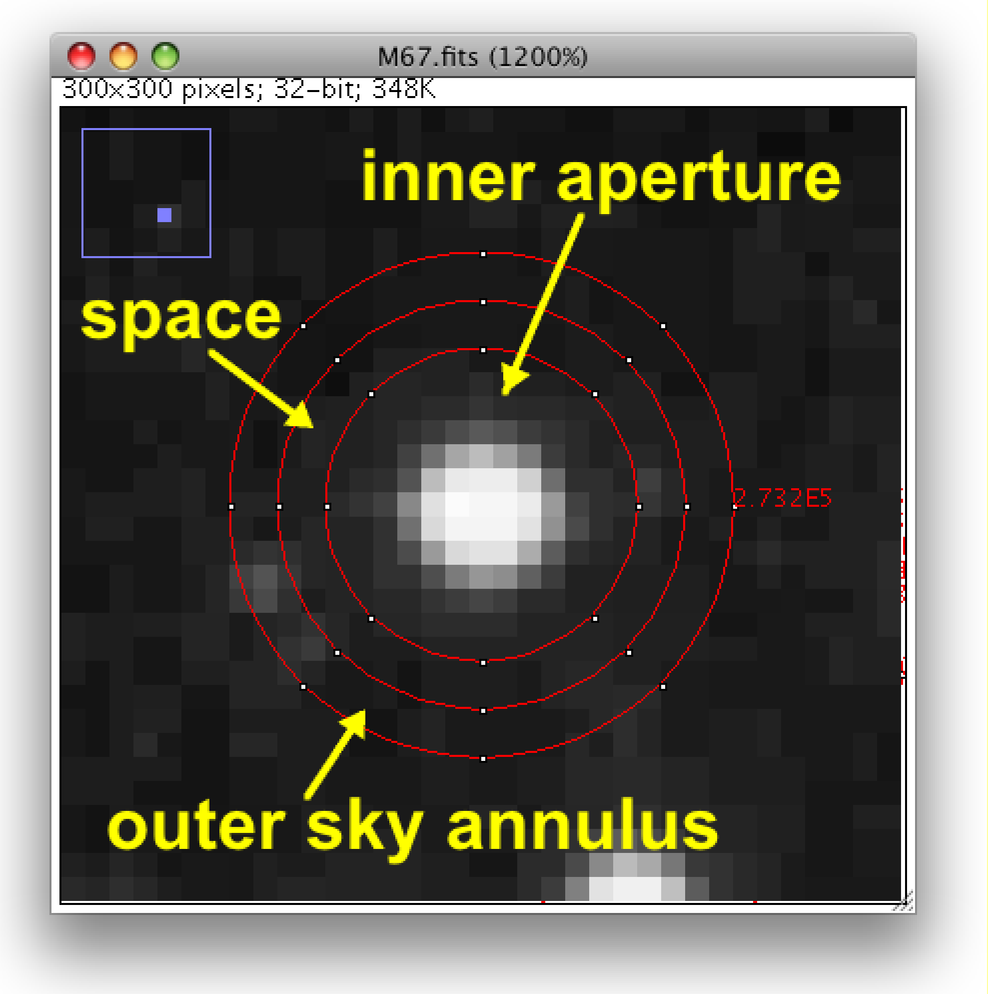
Get sky counts



Magnitude = constant –2.5 x log [Σ(data – sky)/(exposure time)]

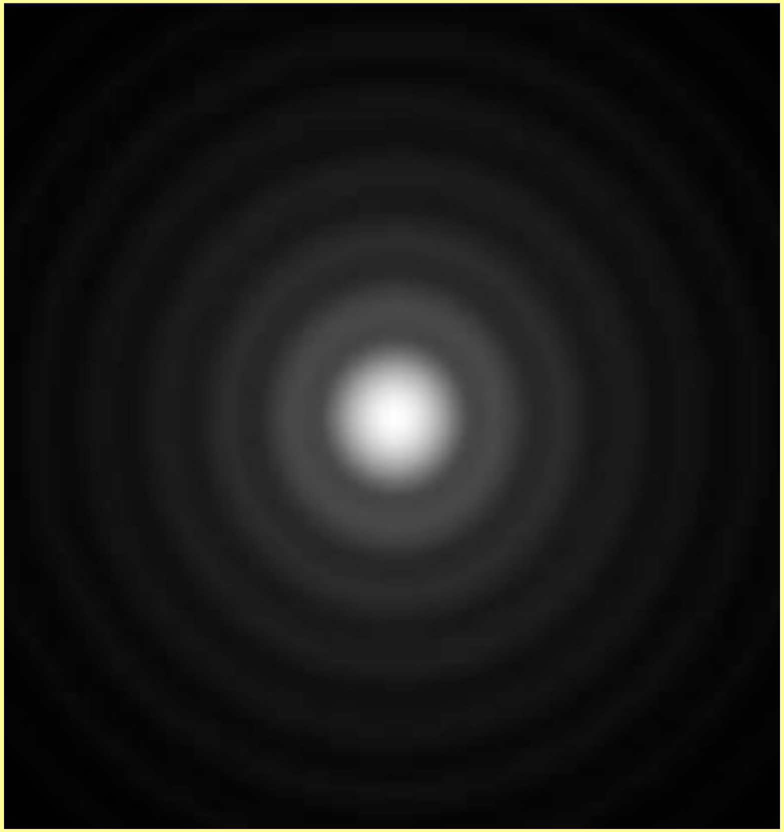
Aperture Photometry

But how to choose the apertures for star and sky background?

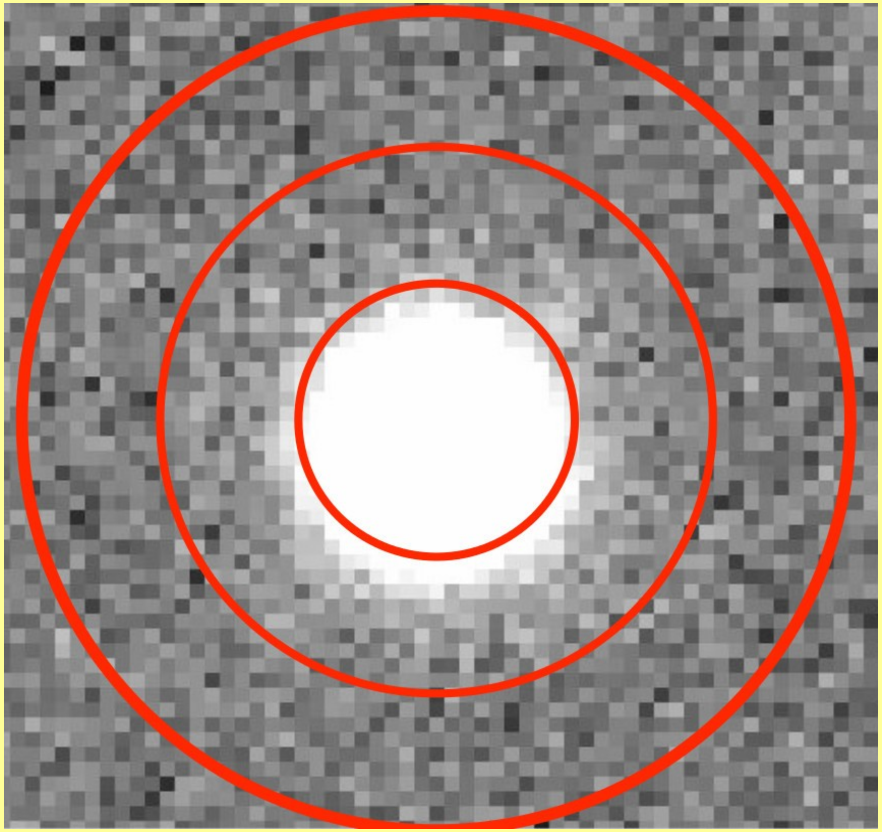


Aperture Photometry

Theoretical stellar image

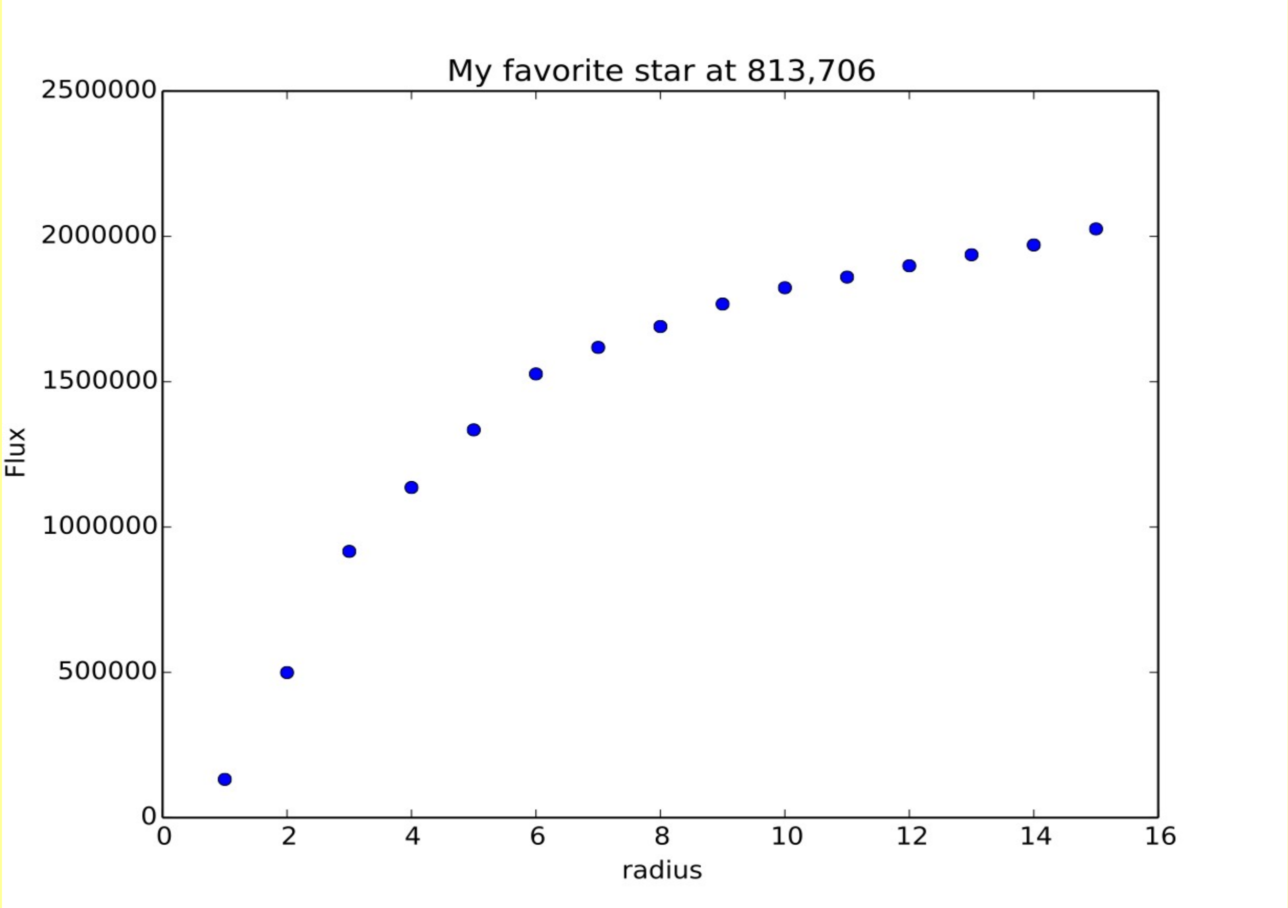


And how it looks in practice



Aperture Photometry

Curve of growth:



Aperture Photometry

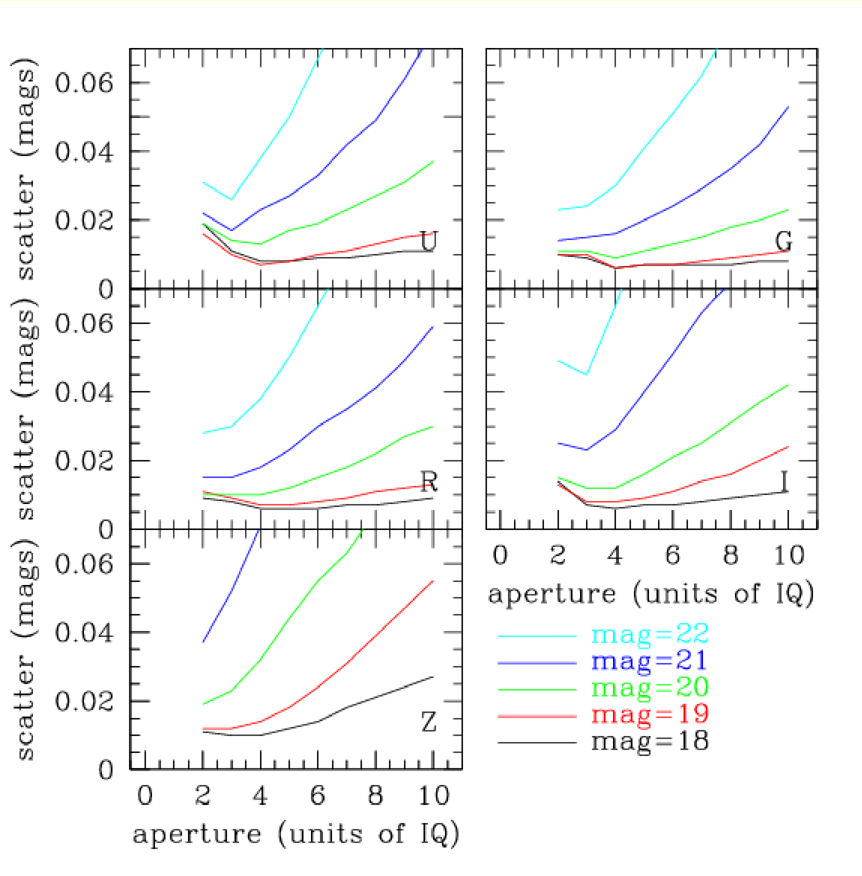
But there is sky noise:

$$\sigma_{(*+sky)} = N_{(*+sky)}^{-1/2}$$

$$\sigma_{sky} = N_{sky}^{-1/2}$$

$$\sigma_* = \sqrt{(N_{(*+sky)} + N_{sky})}$$

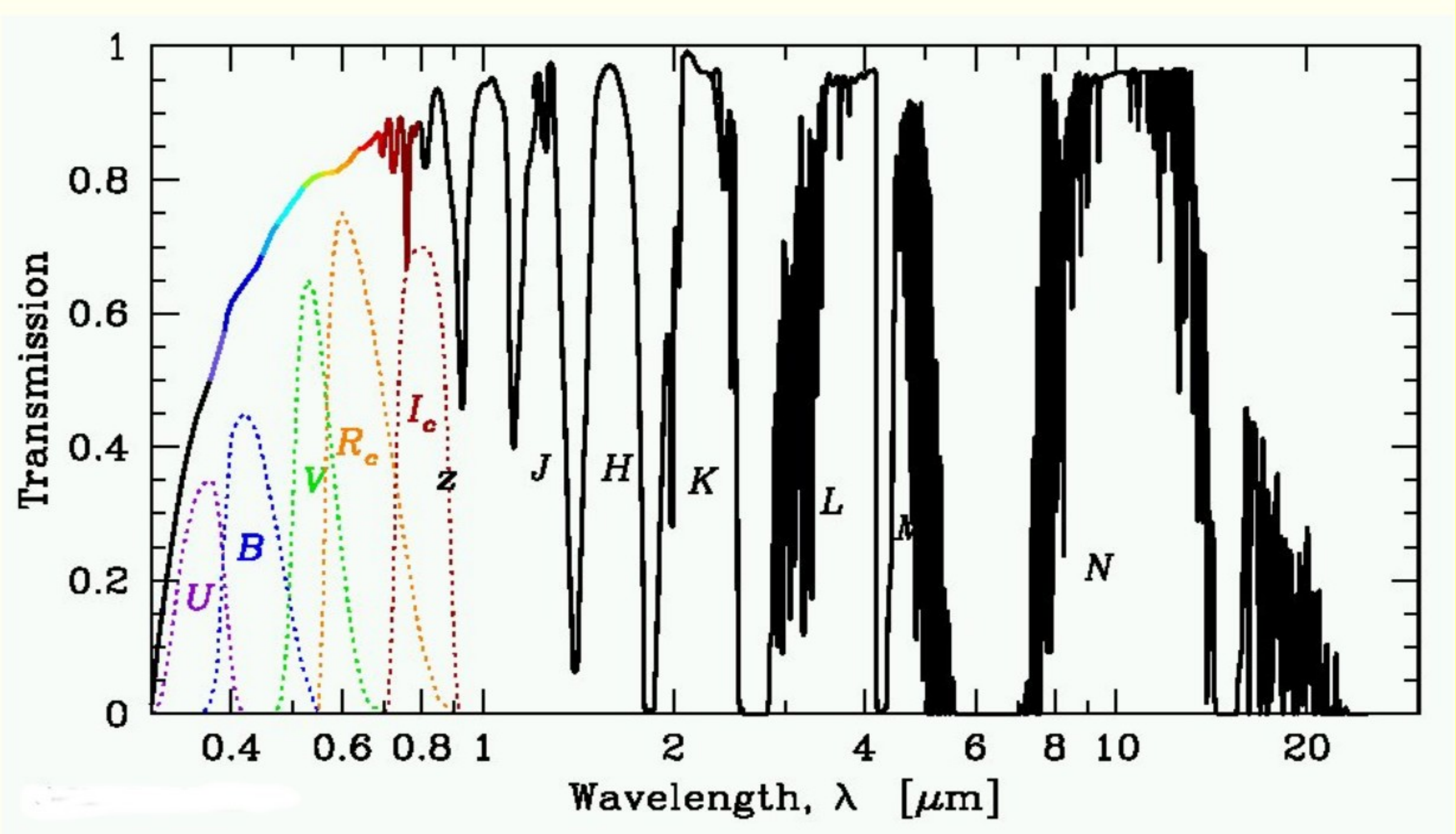
Hence:



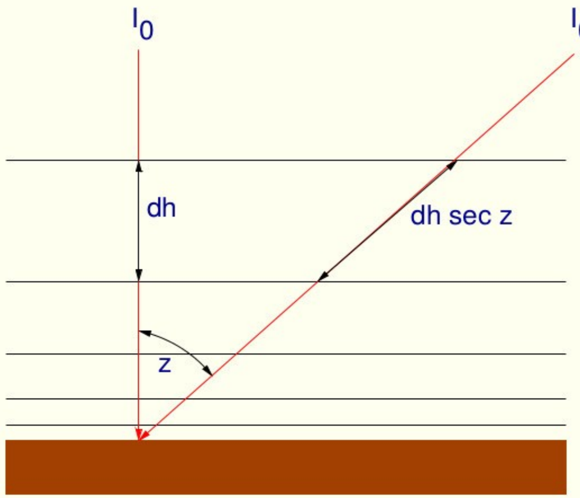
Check which aperture yields the highest-quality photometry!

Further reduction steps

The Earth's atmosphere is not perfectly transparent



Extinction and air mass



$$\mathrm{d}I = -I\kappa\,\mathrm{d}h$$

$$\ln I = \int_0^{\infty} \kappa(h)\,\mathrm{d}h + \mathrm{const}$$

We denote the extinction coefficient for one airmass by K. With a zenith distance z we then have

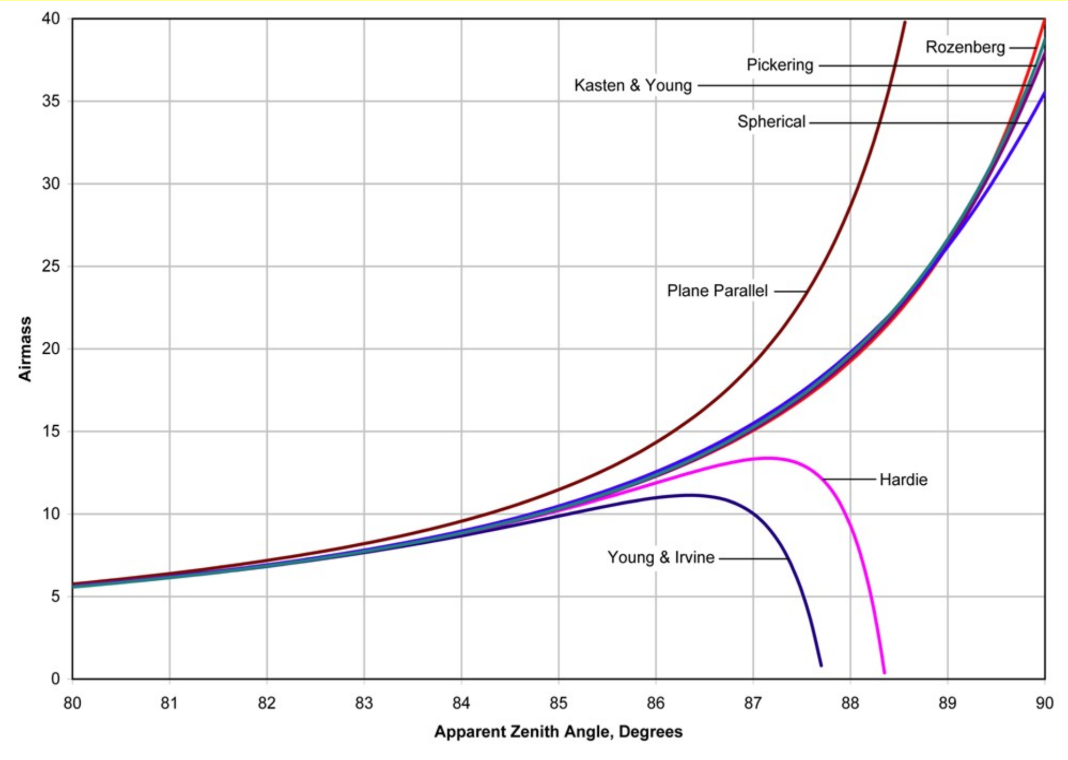
$$\frac{I}{I_0} = e^{-K \sec z} \quad \text{with} \quad \sec z = \frac{1}{\cos z}$$

$$m - m_0 = -2.5\,\log(I/I_0) = -2.5\,\log(e^{-K\,\sec z}) \approx 1.086\,K\,\sec z$$

Extinction and air mass

However, the Earth is not flat; there have been a variety of formulae given to account for the curvature of the Earth, e.g. Hardie (1961):

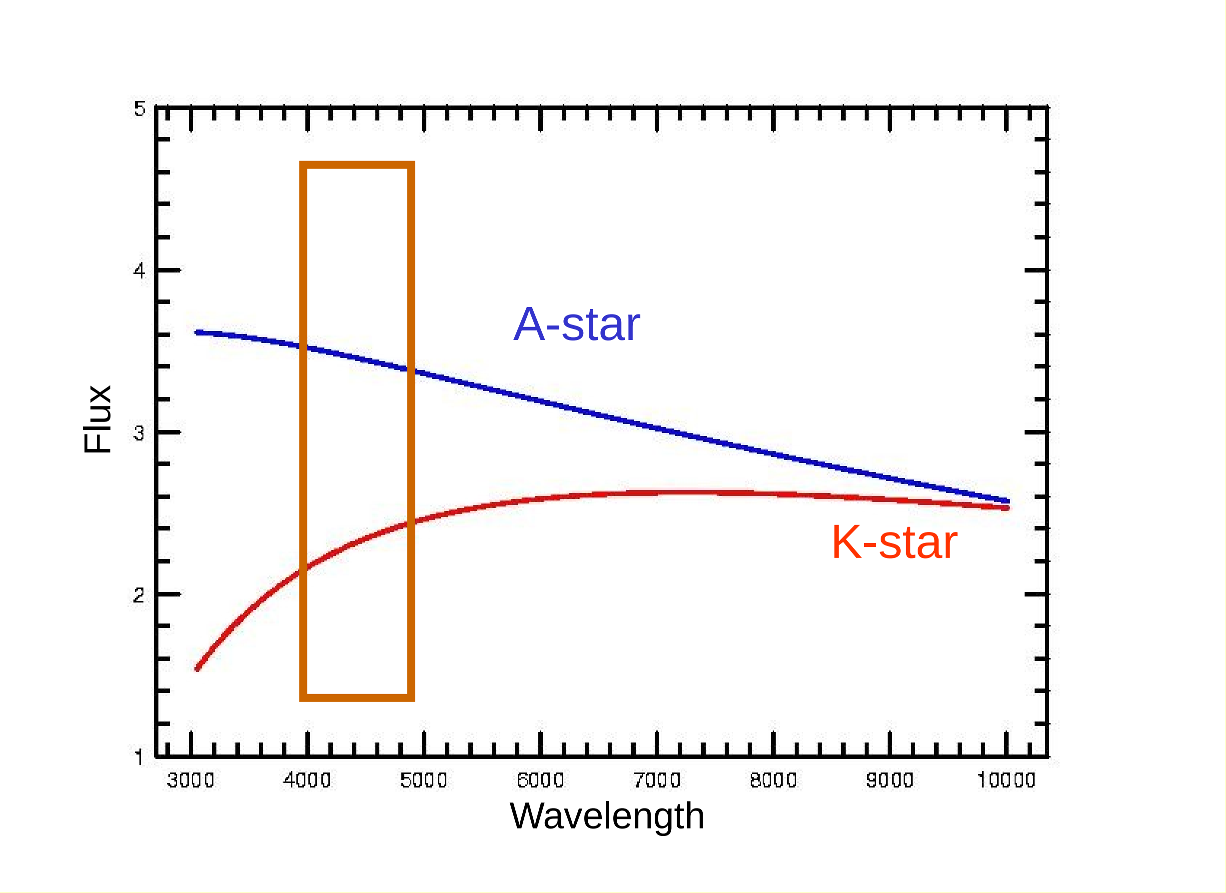
$$X = \sec z - 0.0018167\,(\sec z - 1) - 0.002875\,(\sec z - 1)^2 - 0.0008083\,(\sec z - 1)^3\,,$$



These differ from the plane parallel approximation only for zenith angles greater than 80 degrees (air mass > 5). One should never do photometric observations at such a large air mass (in practice: air mass < 2.5).

Extinction and air mass

If reference stars are not the same spectral type as the targets, their extinction coefficients are different.



Atmospheric extinction (e.g. Rayleigh scattering) will affect the A star more than the K star because it has more flux at shorter wavelength where the extinction is greater (differential colour extinction).

Standardizing

To make the magnitudes and colours measured with your equipment, at your site, comparable to values in the literature and calibrations of your photometric system you need to transform those to standard values of your photometric system.

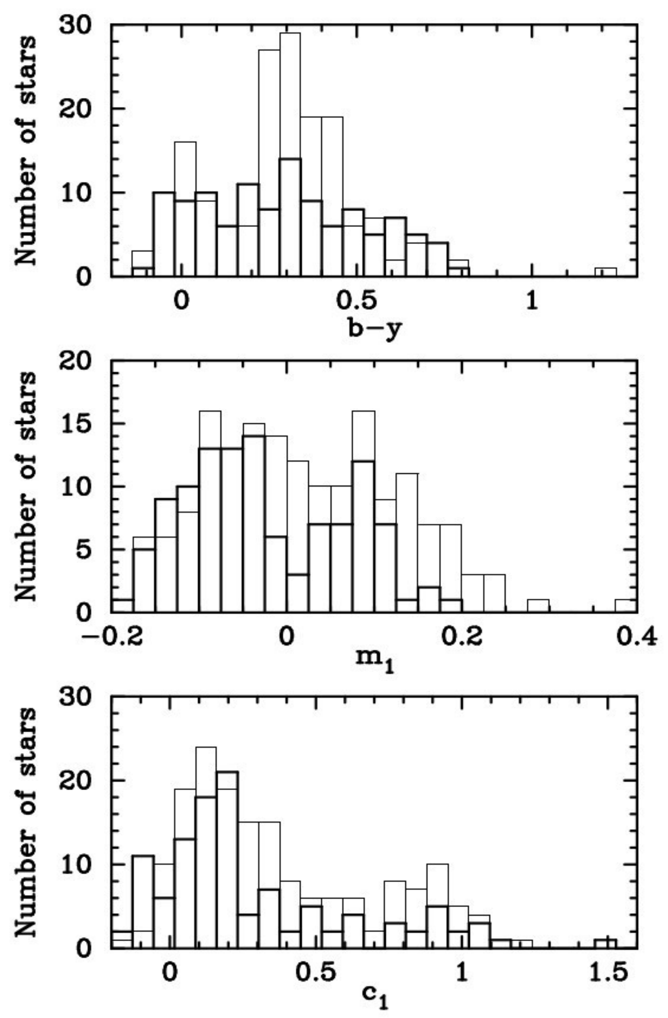
As you will already have expected, there are also plenty of pitfalls.

First, you need to observe standard stars. Lists are available in the literature, e.g.
UBVRI – Landolt (1992), Landolt (2007), Menzies et al. (1991)
uvbyβ – Perry et al. (1987), Kilkenny & Laing (1992)
Sloan filters – J. Allyn Smith et al. (2002)

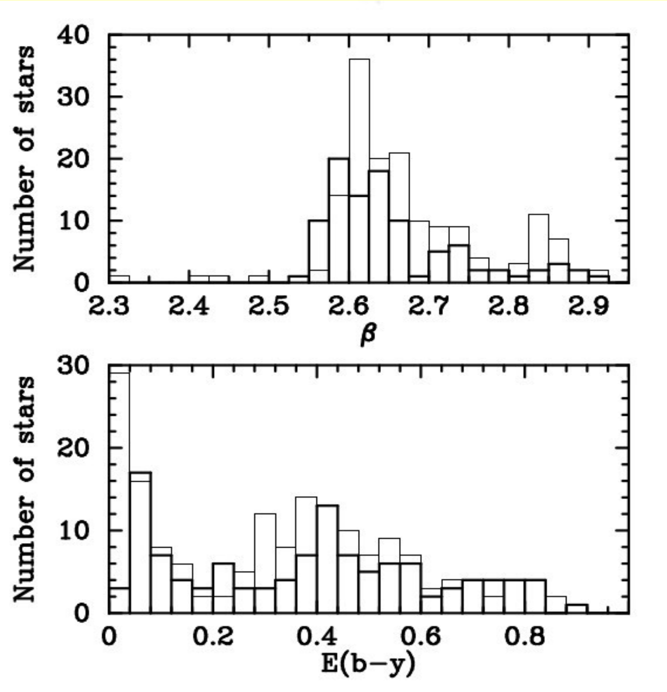
You need to observe standards about as frequently as your targets, and in regular intervals – observing conditions can change and your detector is much more sensitive than your eye!

You need to take care that your standard stars span the full colour and magnitude range of your targets, otherwise your measurements may be unreliable (and referees like I will reject your paper ;o)).

Standardizing



In this example, the standard stars span with few exceptions all the measured colours, but also the interstellar extinction the targets suffer.



Standardizing

Assuming that the instrumental system is reasonably close to the standard one (which it'd better be!), linear transformation equations are sufficient. Examples:

$$(b-y) = 1.0563(b-y)_N + zpt(b-y)$$

$$m_1 = 1.0195 m_{1,N} - 0.0162(b-y)_N - 0.8469$$

$$c_1 = 1.0025 c_{1,N} + 0.1018(b-y)_N - 0.5484$$

$$\beta = 0.8302\beta_N - 0.0439(b-y)_N + 0.9532$$

$$V = 0.9961 y_N + 0.0425(b-y)_N + zpt(y)$$

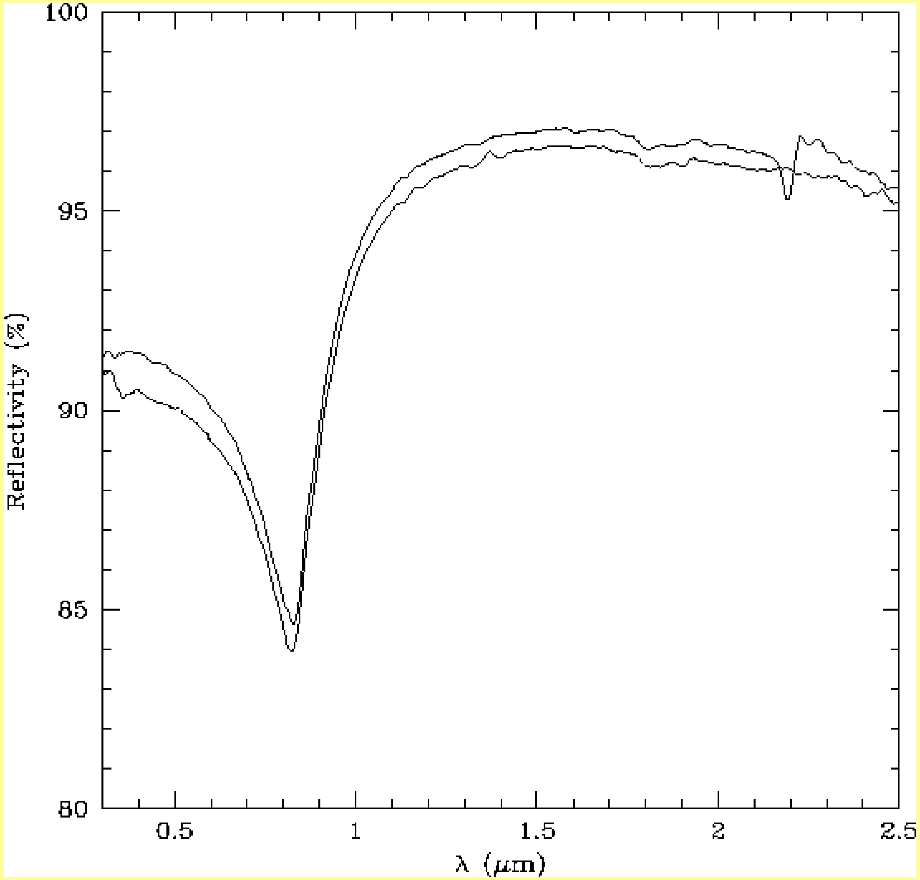
Check for changing observing conditions!

Observing run	Standard stars	$zpt(b-y)$
Autumn 2008	O stars	1.3497 ± 0.0026
Autumn 2008	Cep OB3	1.3514 ± 0.0034
Autumn 2008	h & χ Per	1.3413 ± 0.0025
Autumn 2008	NGC 6910/13	1.3566 ± 0.0021
Autumn 2008	above combined	1.3485 ± 0.0014
Spring 2009	NGC 1502, 2169, 2244	1.3916 ± 0.0037
Autumn 2010	Lac OB1, field	1.3302 ± 0.0023

Civil date	$zpt(y)$
07 Oct 2008	20.022 ± 0.004
08 Oct 2008	20.036 ± 0.006
09 Oct 2008	20.001 ± 0.007
16 Oct 2008	20.003 ± 0.004
04 Mar 2009	20.102 ± 0.005
01 Oct 2010	19.739 ± 0.005
02 Oct 2010	19.703 ± 0.008

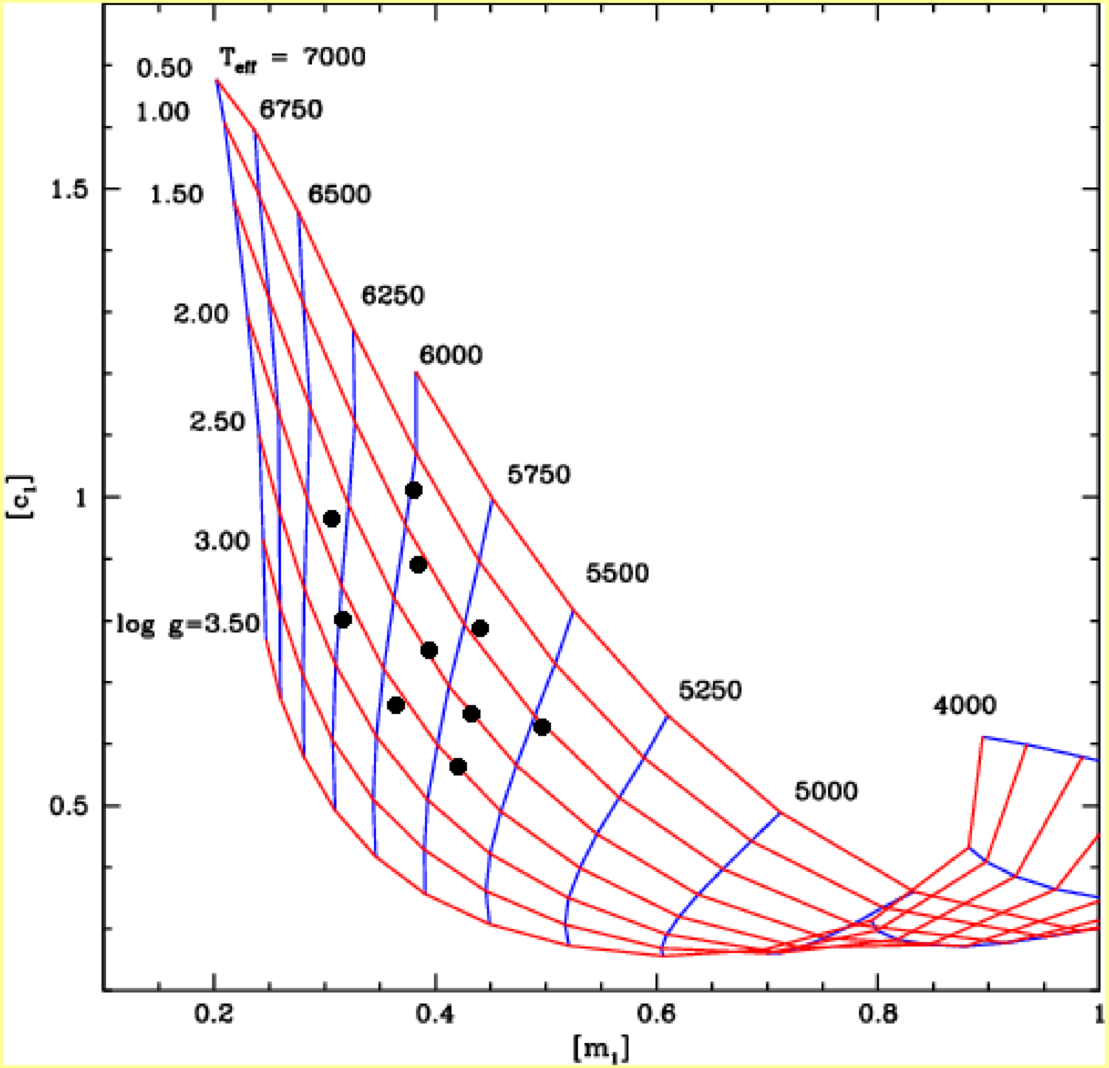
Telescope

- Mirrors
- Lenses



Subaru telescope primary mirror

Finally you can interpret your data!



Basic CCD imaging reduction steps

Brief recap:

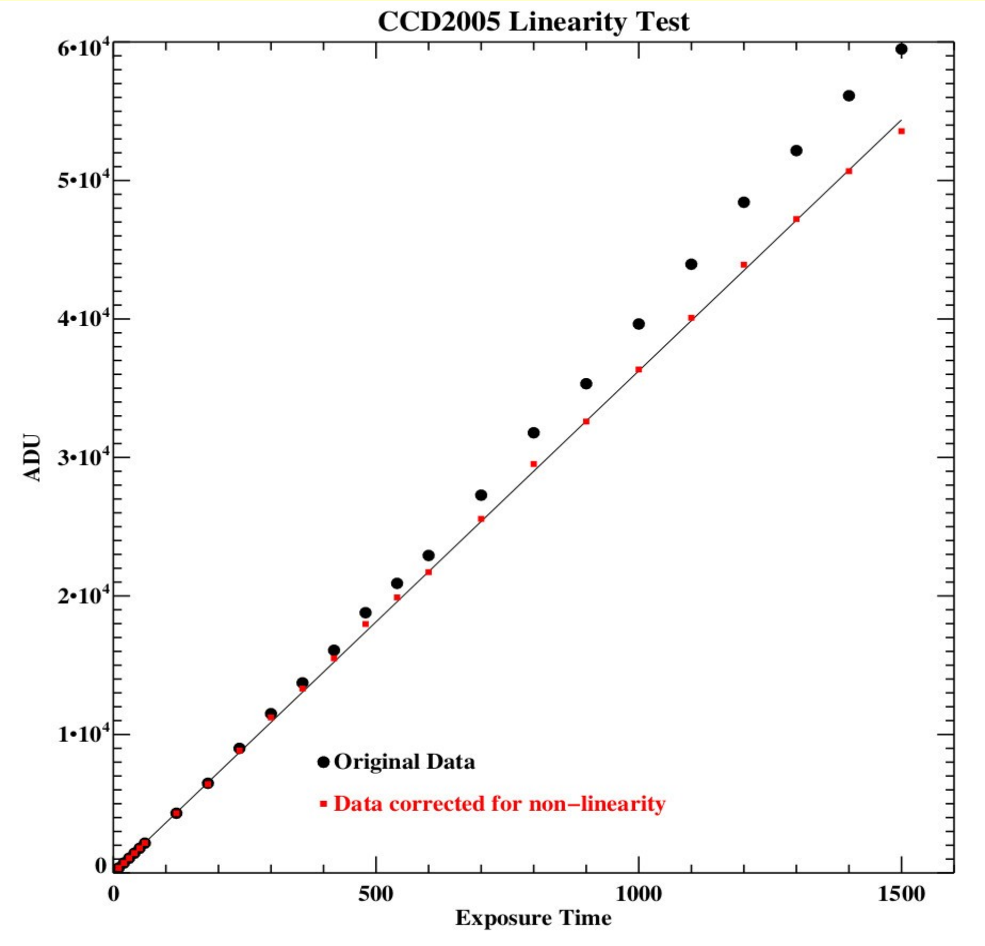
- Overscan correction
- Bias subtraction (if needed)
- Dark correction (if needed)
- Flat field correction

- Instrumental magnitude calculation
- Extinction correction
- Transformation into the standard system

But, as you presumably already expect, other things can come into play...

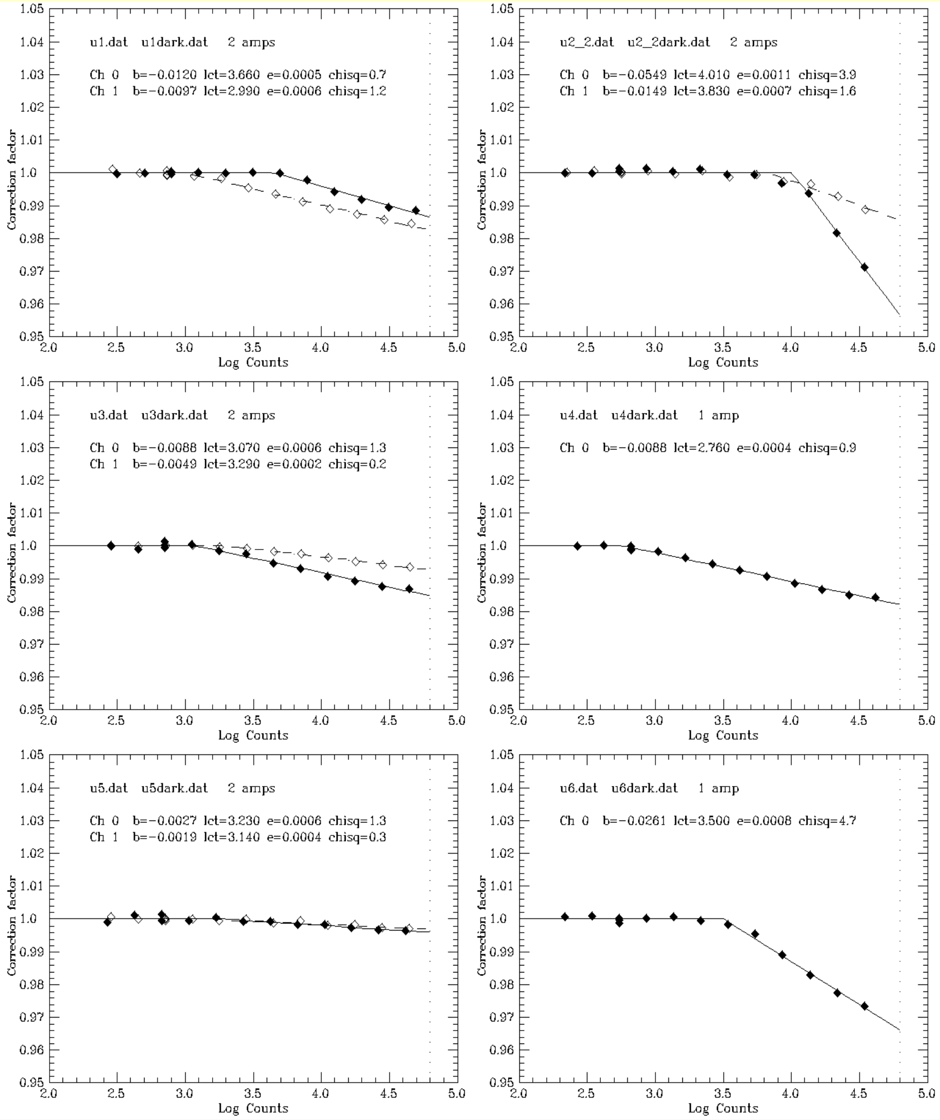
CCD nonlinearity

Take a series of frames of a low-intensity lamp and plot the mean counts as a function of exposure time. This should result in a perfectly linear correlation. This is however not always the case.

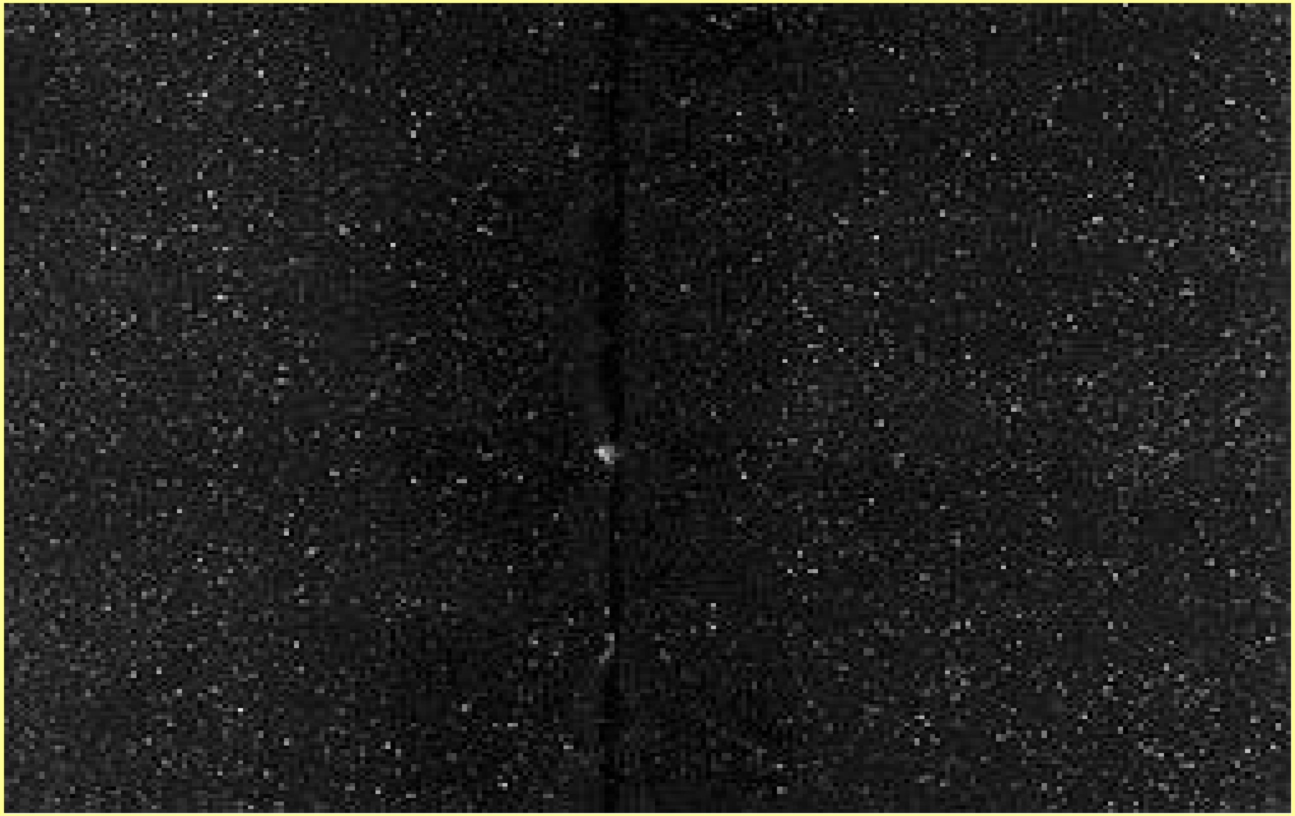


CCD nonlinearity

This can even reveal itself in several different forms.



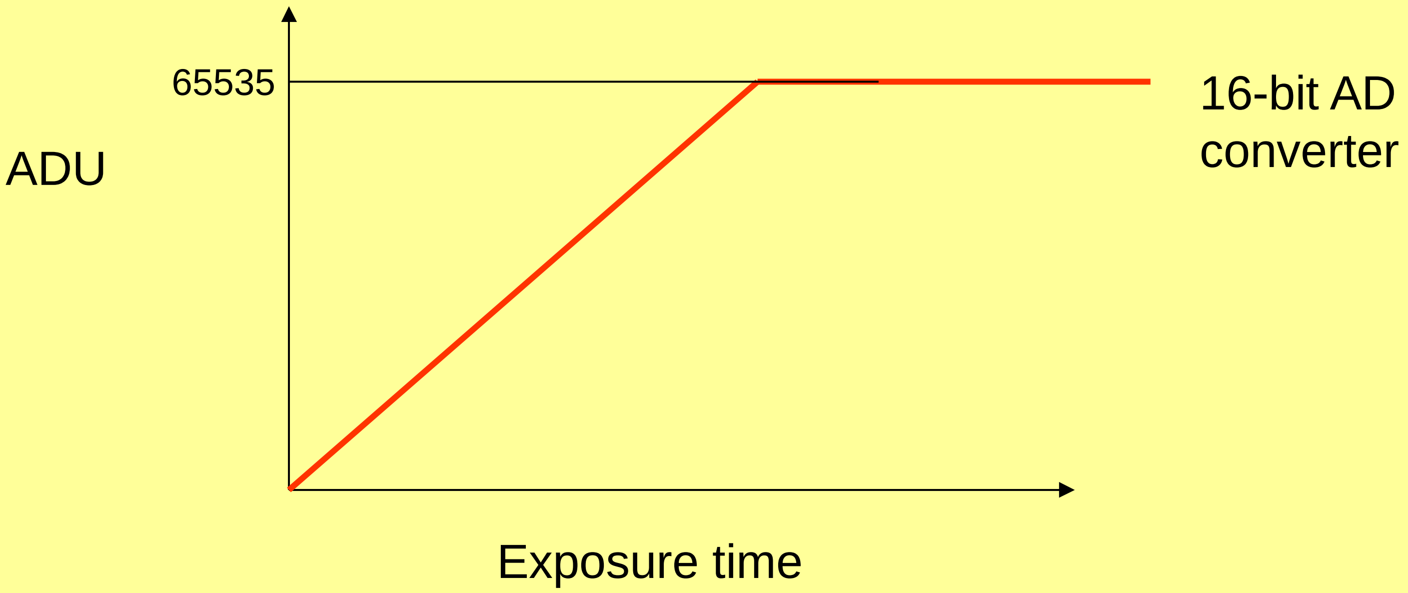
Cosmic Rays



- CCDs are good cosmic ray detectors
- Cosmic rays are always found on long exposures
- To correct for cosmic rays, take at least three object exposures, and combine them with a median filter

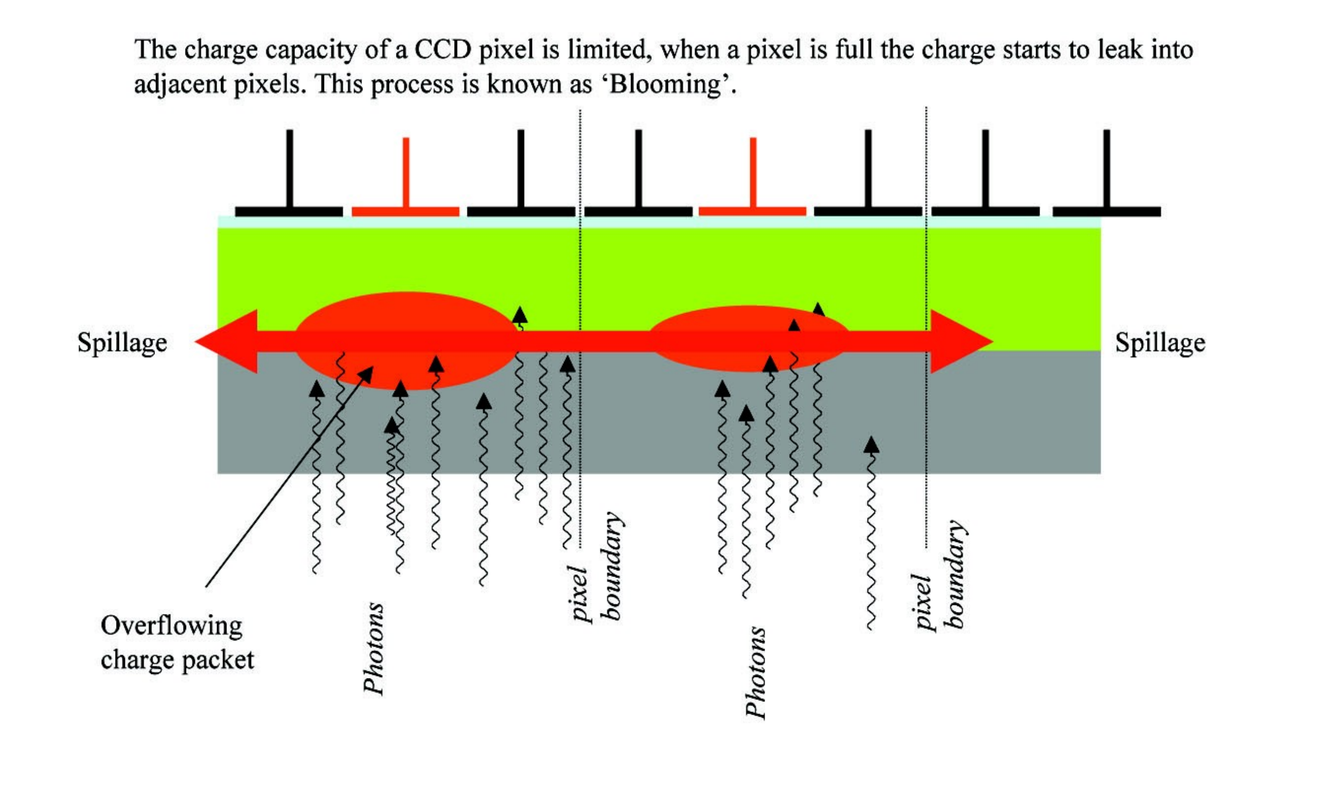
Saturation

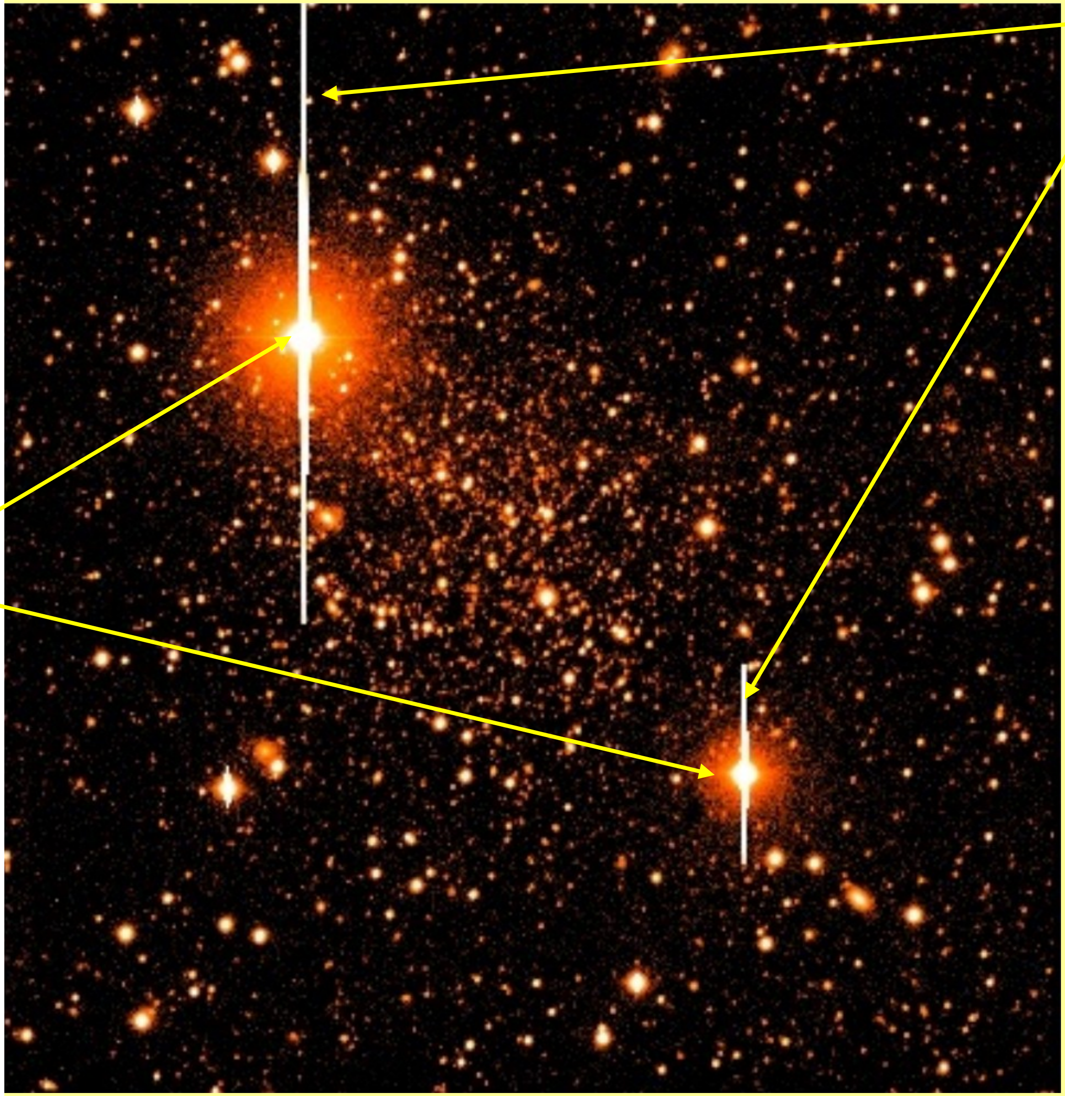
If too many electrons are produced (too high intensity level) then the full well of the CCD is reached and the maximum count level will be obtained. Additional detected photons will not increase the measured intensity level:



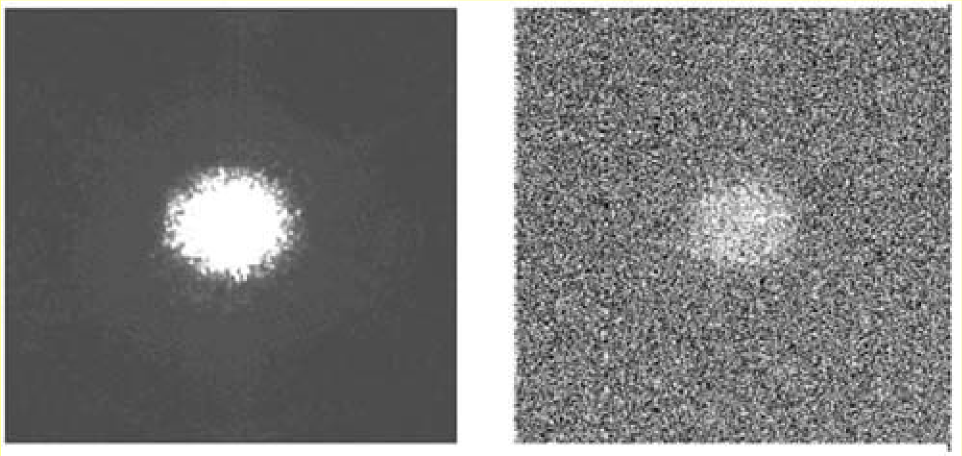
Saturation

Blooming/bleeding:
If the full well is exceeded, charge starts to spill over in the readout direction, i.e. columns. This can affect or destroy data far away from the saturated pixels.




Blooming
columns
Saturated
stars

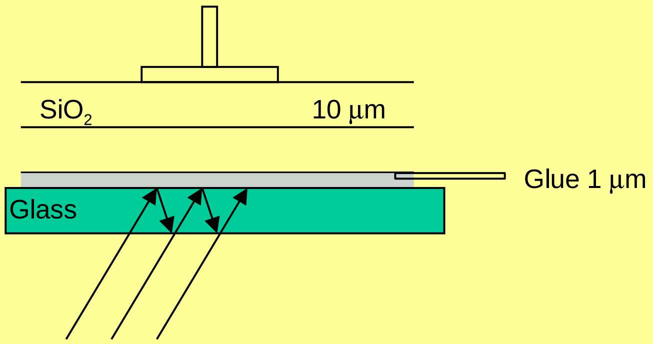
Residual Images



If the intensity is too high, this can leave a residual image. Left is a normal CCD image. Right is a bias frame showing residual charge in the CCD. This can affect photometry.
Solution: read out several dark frames or shift image between successive exposures.

Fringing

CCDs, especially back-illuminated ones, are bonded to a glass plate.



When the glass is illuminated by monochromatic light, it creates a fringe pattern. Fringing can also occur without a glass plate due to the thickness of the CCD.

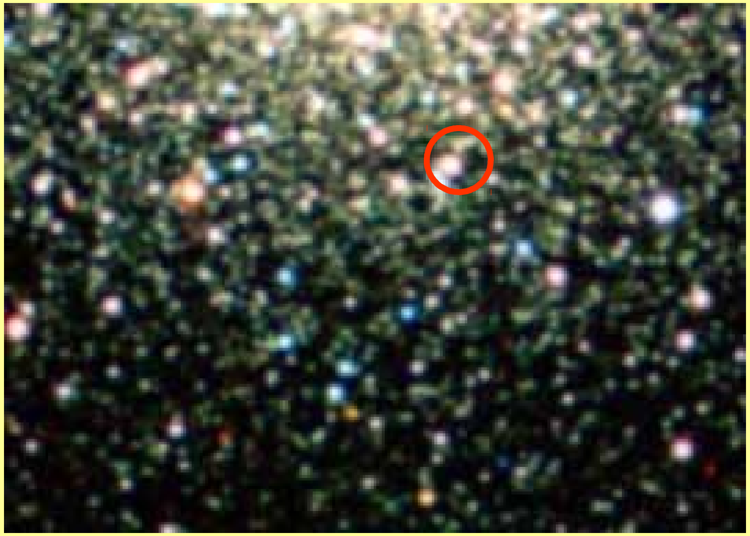
Fringing

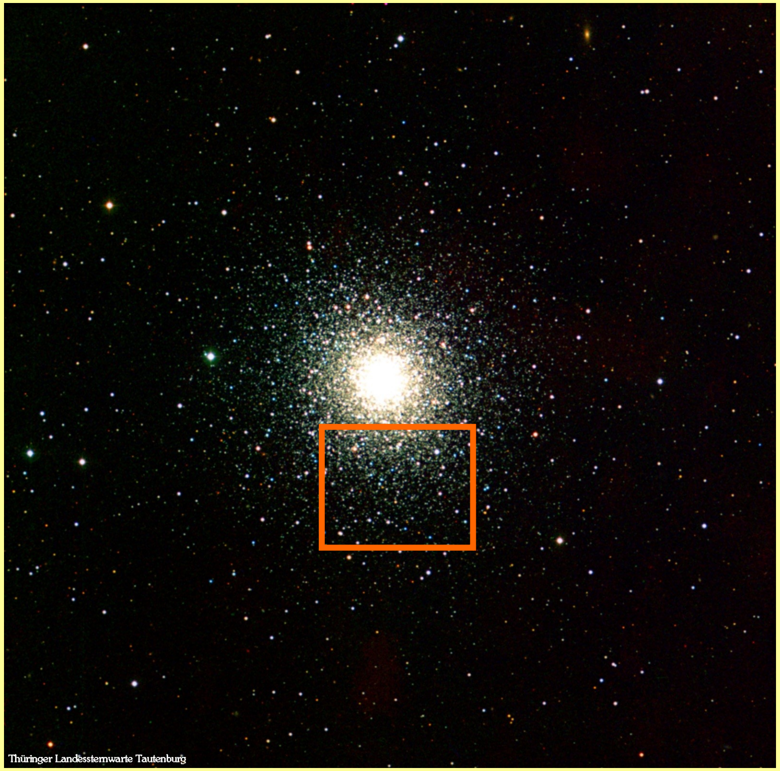
λ (Å)

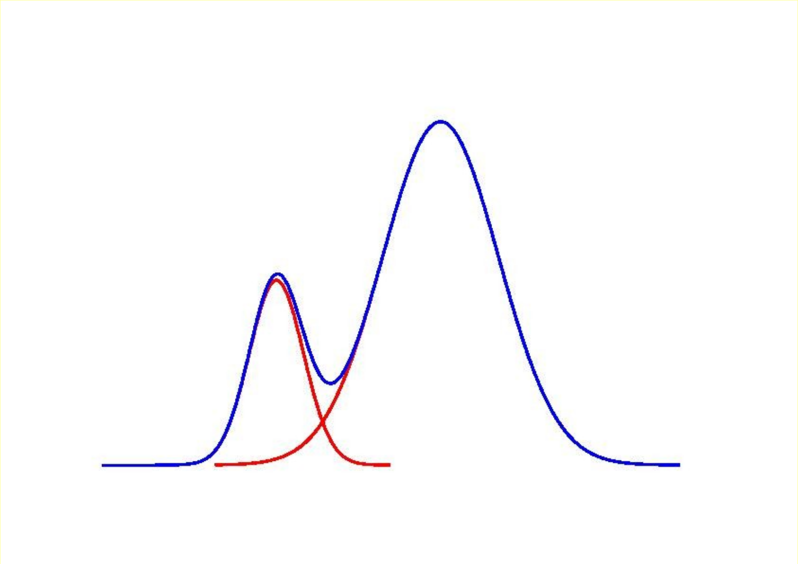
6600
6760
6920
7080
7280
7460
7650
7850
8100
8400

Depending on the CCD, fringing becomes important for wavelengths greater than about 6500 Å.
Solution: generate a “flat field” using the night sky, adjust the fringe amplitude to the observed one, and subtract this “fringe flat”.

Methods other than aperture photometry





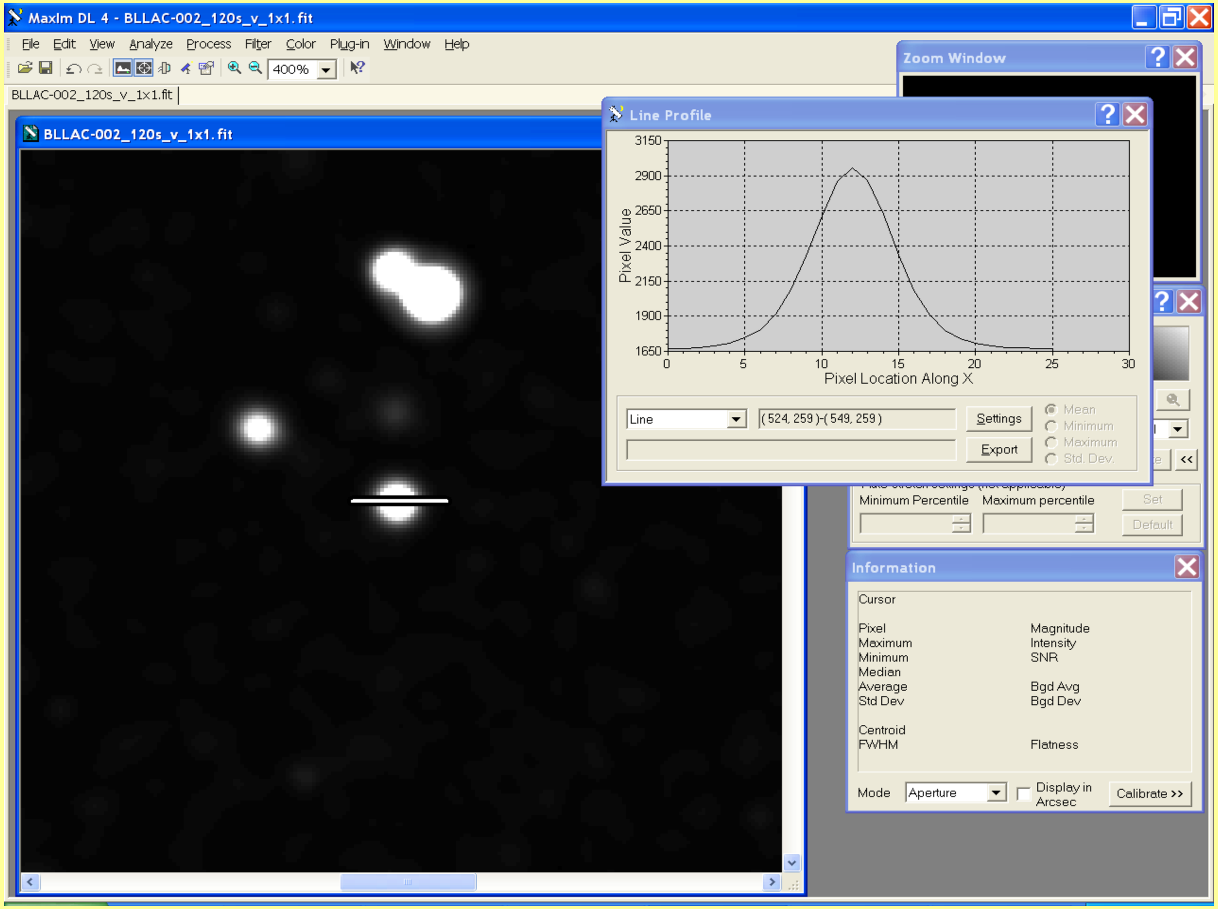


Aperture photometry is useless for crowded fields

Point Spread Function

PSF: Image produced by the instrument + atmosphere = point spread function

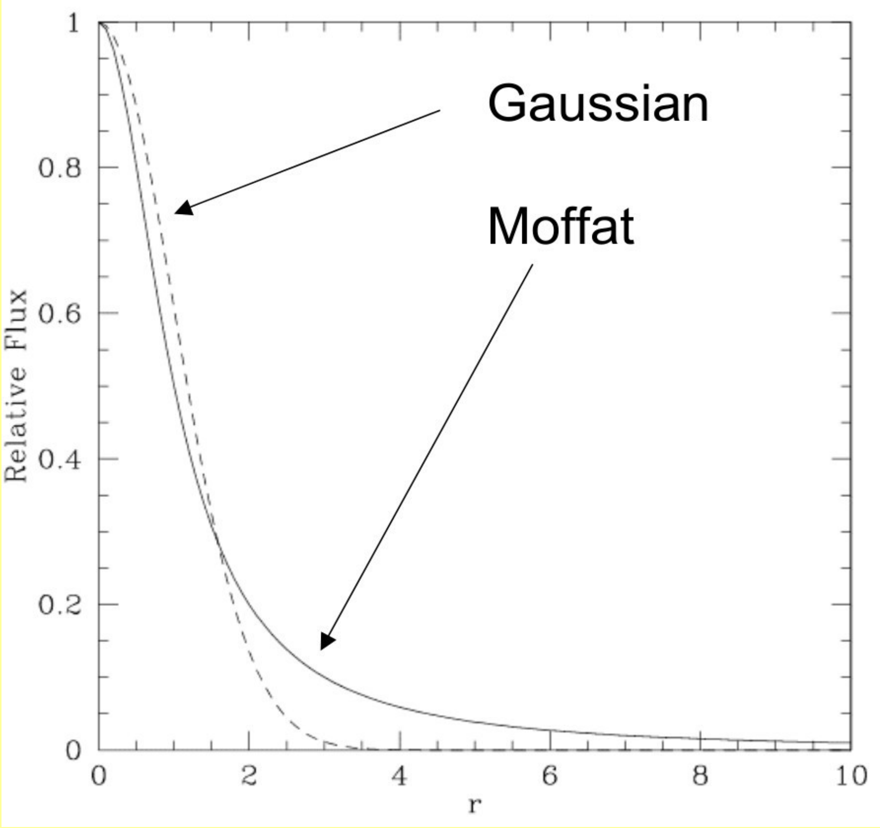
Many photometric reduction programs require modeling of the PSF



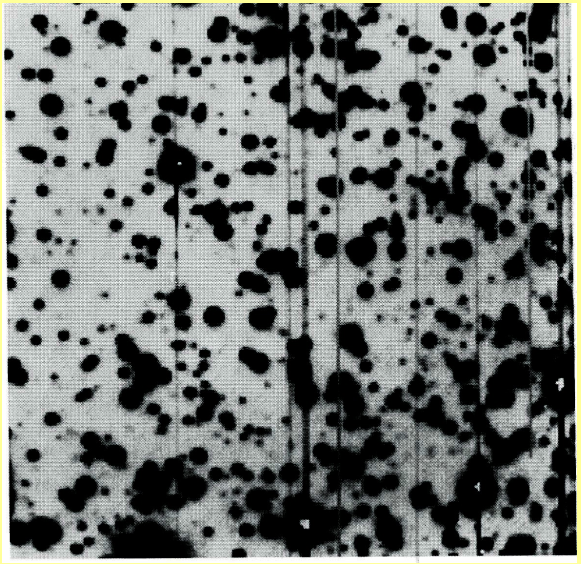
Point Spread Function Fitting

Modeling of the PSF is often done through an iterative process:

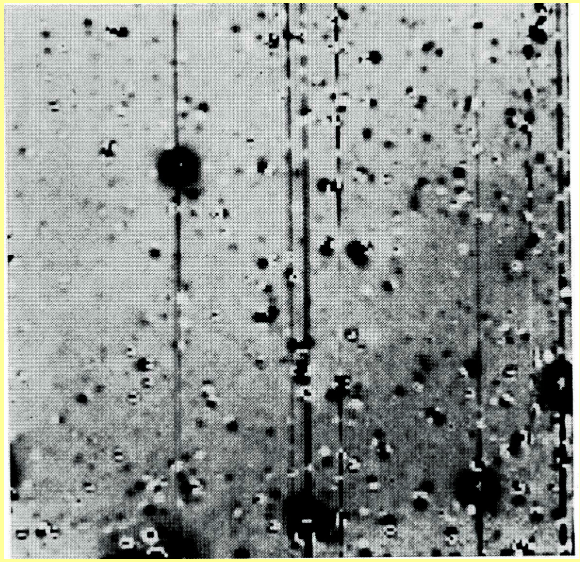
1. Choose several stars as „PSF stars"
2. Fit PSF
3. Subtract neighbors
4. Refit PSF
5. Iterate
6. Stop after 2-3 iterations



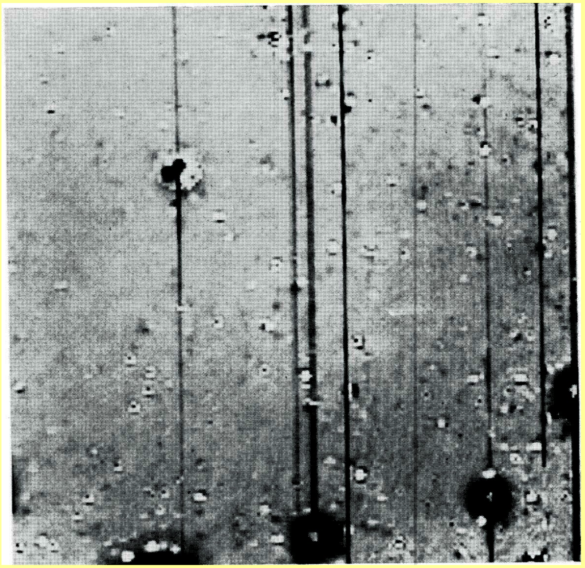
Point Spread Function Fitting



Original Data



Data minus stars found in first star list



Data minus stars found in second determination of star list

Image Subtraction

If you are only interested in changes in the brightness (differential photometry) of an object you can use image subtraction (Alard 2000):

- Get a reference image *R*. This is either a synthetic image (point sources) or a real data frame taken under good seeing conditions (usually your best frame).
- Find a convolution kernel, *K*, that will transform *R* to fit your observed image, *I*. Your fit image is $R * I$ where $*$ is the convolution (i.e. smoothing)
- Solve in a least squares manner the kernel that will minimize the sum:

$$\sum ([R * K](x_i,y_i) - I(x_i,y_i))^2$$

The kernel is usually taken as a Gaussian whose width can vary across the frame.

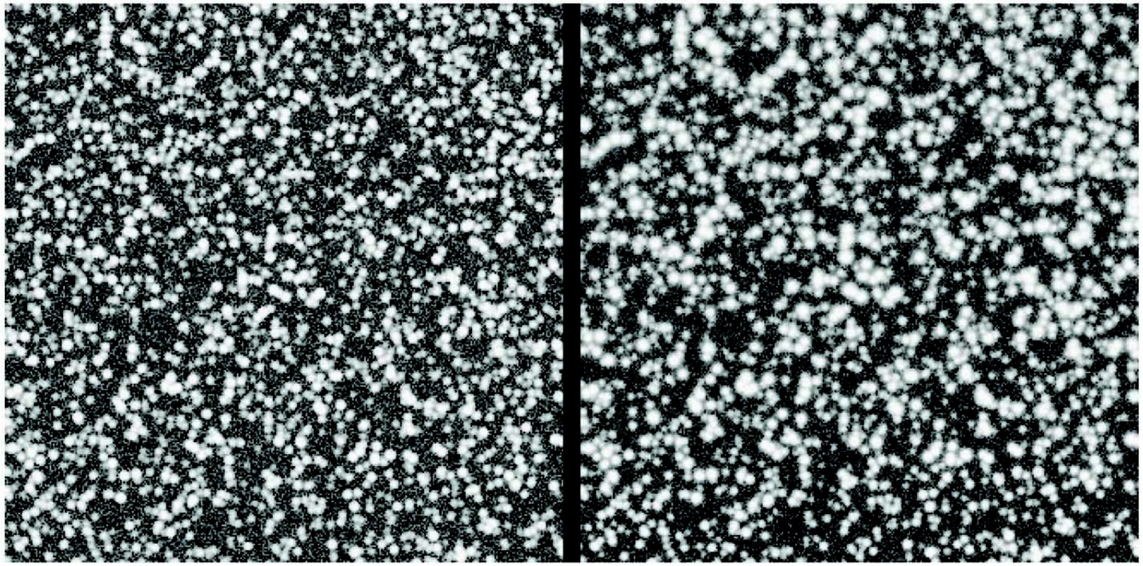


Fig. 1. Simulated of crowded field images. On the left is the image with constant PSF, and on the right is the image with PSF variations along the Y axis. Note the large amplitude of the PSF variations. A total of 2500 stars has been included in this simulation

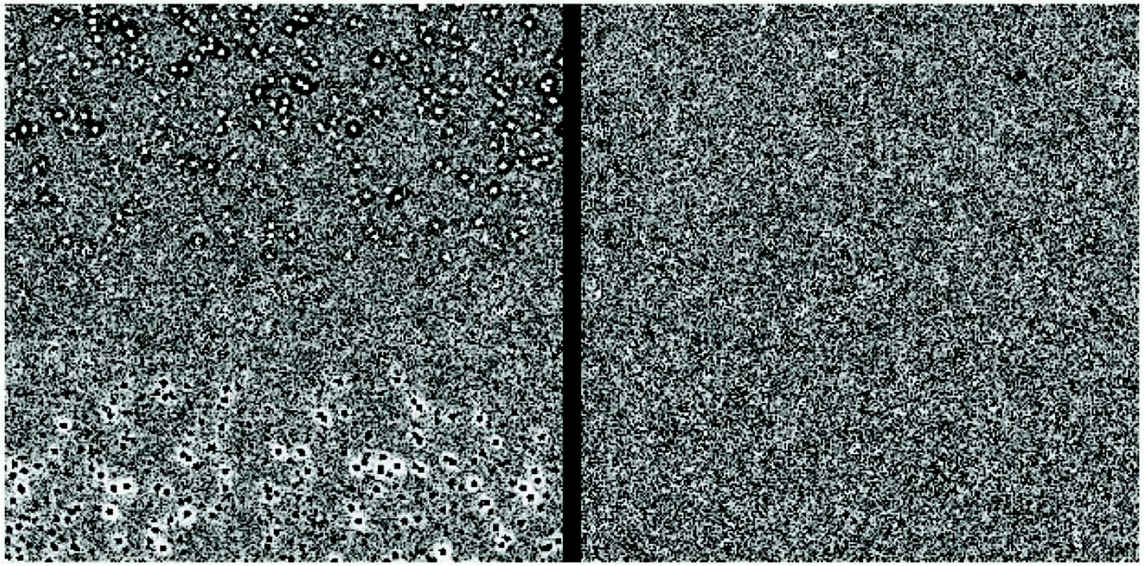
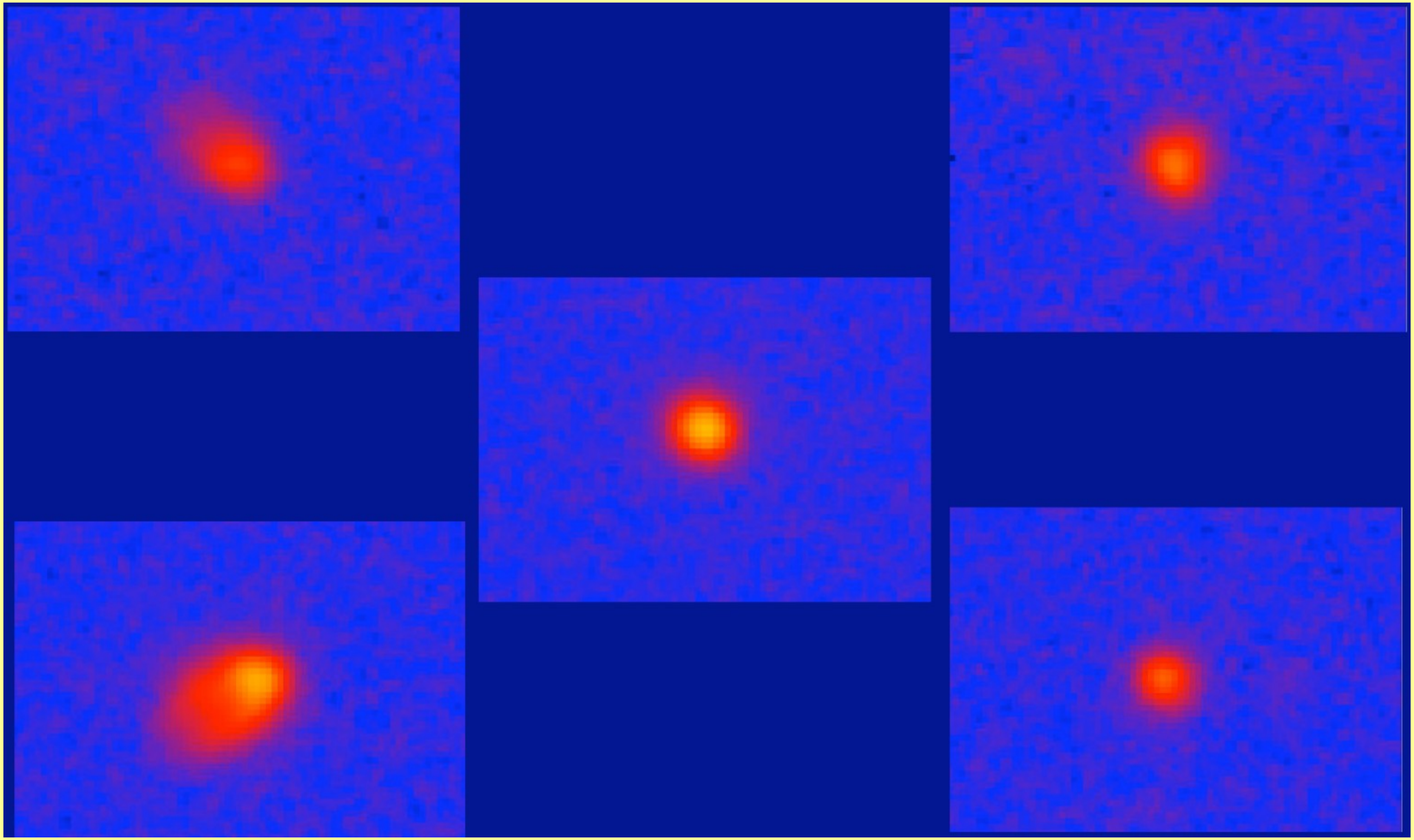


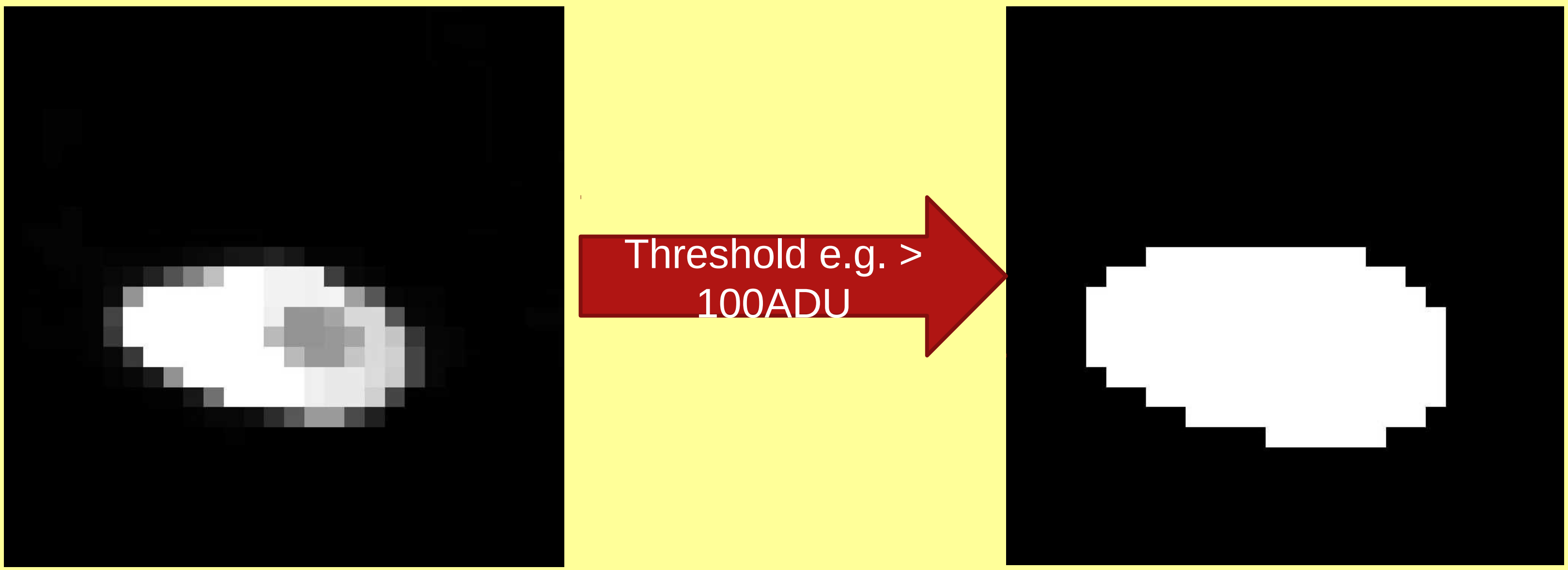
Fig. 2. On the left is the subtracted image obtained with constant kernel solution. Note the systematic pattern along the Y axis due to the kernel variations. On the right we present the subtracted image obtained by fitting the spatial variations of the kernel to order 2

PSF variations and photometry of extended sources



PSF variations and photometry of extended sources

Custom apertures:



PSF variations and photometry of extended sources

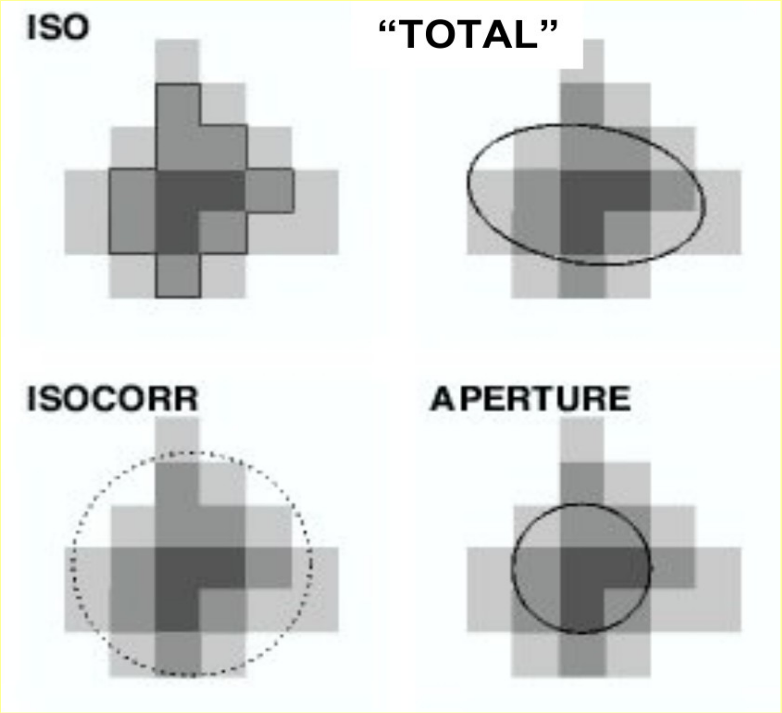
Galaxy photometry

a) aperture magnitudes:
– Optimal size of aperture depends on galaxy

b) Isophotal Magitudes
– Total light above a given surface brightness level
– Surface brightness changes with redshift, so end up with measuring different portions of galaxies at different redshifts

c) "Total" Magnitudes = extrapolated estimates of total galaxy light
– Kron
– Petrosian

d) Galaxy profile model fit magnitudes



Instead of a conclusion

When doing a photometric measurement, you observe different objects through different filters, acquired with a telescope non-uniformly responding in wavelength, as well as a non-uniformly responding detector, through the Earth's absorbing and time-variable atmosphere.

And that's just part of the possible sources of systematic error.

Therefore:
- understand your instrument
- know how to carry out your observations
- choose your photometric system carefully
- choose your standard stars carefully
- you can never have too many calibration measurements
- check your data reduction step by step
- choose your photometry algorithm and parameters well
- be aware of possible pitfalls

But above all: HAVE FUN!