Optical Photometry

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Foreword

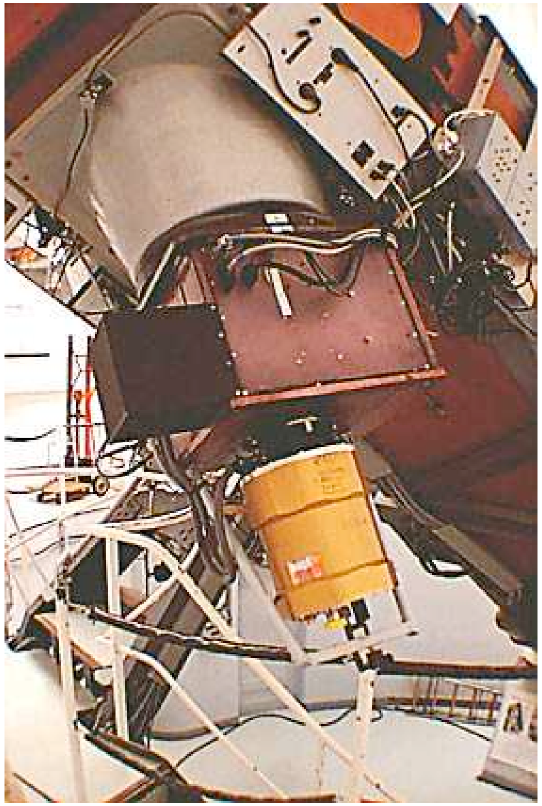
- Starlight coming to us has :
  - traversed the Earth's atmosphere
  - reflected off the telescope mirrors
  - passed through the filters and dewar window
  - absorbed by the CCD chip
  - before the data was read out and digitized

Our task is to remove the signature of the atmosphere and instrument and try to recover as much information as possible from what entered the Earth's atmosphere

summary

- Getting to know your instrument
- CCD and filter characteristics
- Atmospheric extinction
- Flat-fielding: is it an art or a science ?
- PSF-fitting *vs.* Aperture photometry
- Differential *vs.* All-sky photometry
- Transforming into a standard system

Getting to know your instrument



- The camera is attached to the telescope using an adapter or bonette
- The CCD is housed in a dewar and is held at low temperature (-90°C)
- Software controls all instrument functions
- The adapter normally holds:
  - A filter wheel
  - A shutter
  - A viewing / autoguider system

Something about shutters

- There are two types of mecanical shutters used in CCD cameras:

  Iris-type: Since the opening and closing are done in a radial mouvement, the exposure in the center of the image will be greater than at the edges. You must calibrate this effect and correct for it in the case of short exposures

  Curtain-type: Here all pixels get the same amount of exposure if the opening and closing sequence are done in the same sense. This type is to be preferred, but you cannot change what an observatory will offer you…

CCD parameters

- A given CCD camera system is characterized, among other things, by:
  - Dynamic range (full-well capacity)
  - Number of bits of A/D converter
  - Read-out noise (RON)

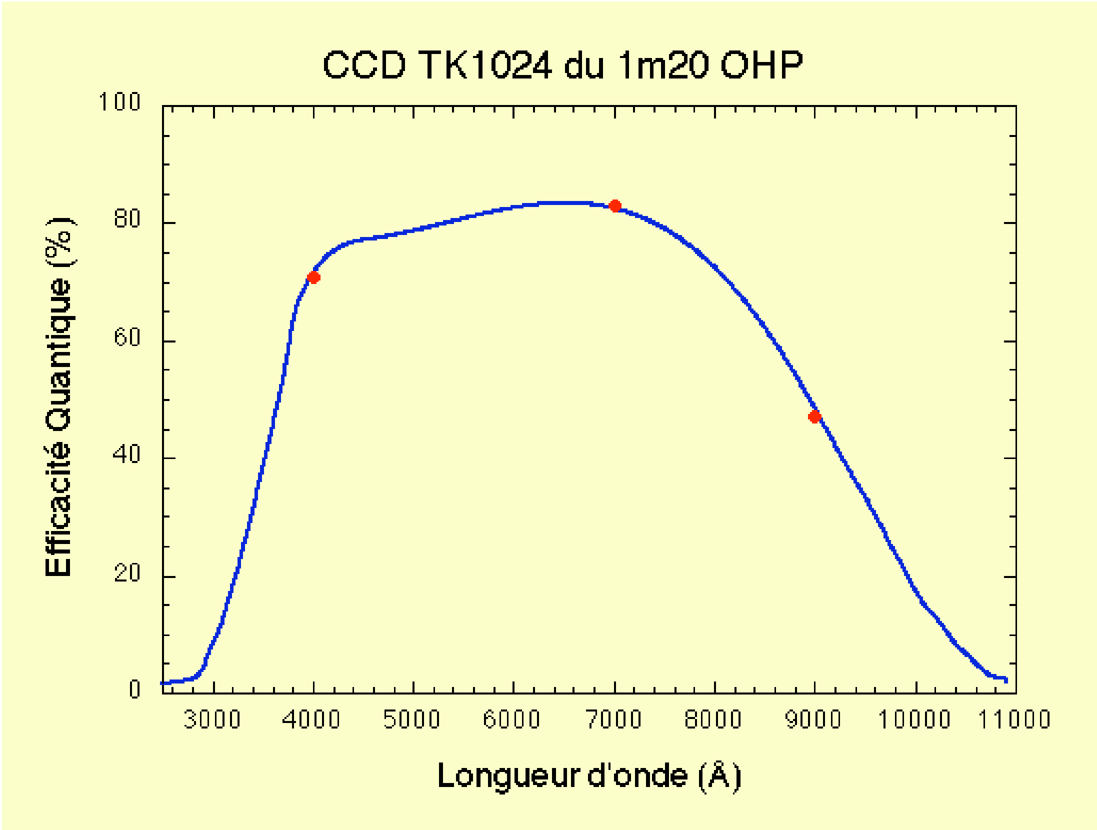
- In order to use the full dynamic range of the system, the gain setting should be : **gain ~ (dynamic range)/(2^{Nbits})**, with the added constraint that : gain < read-out noise

- For the TK 1024 camera of the 1.2-m OHP telescope, the well depth is 200000 e^- and N_{bits} = 16 (65536 discrete levels). The best gain value should thus be ~ 3e^-/ADU

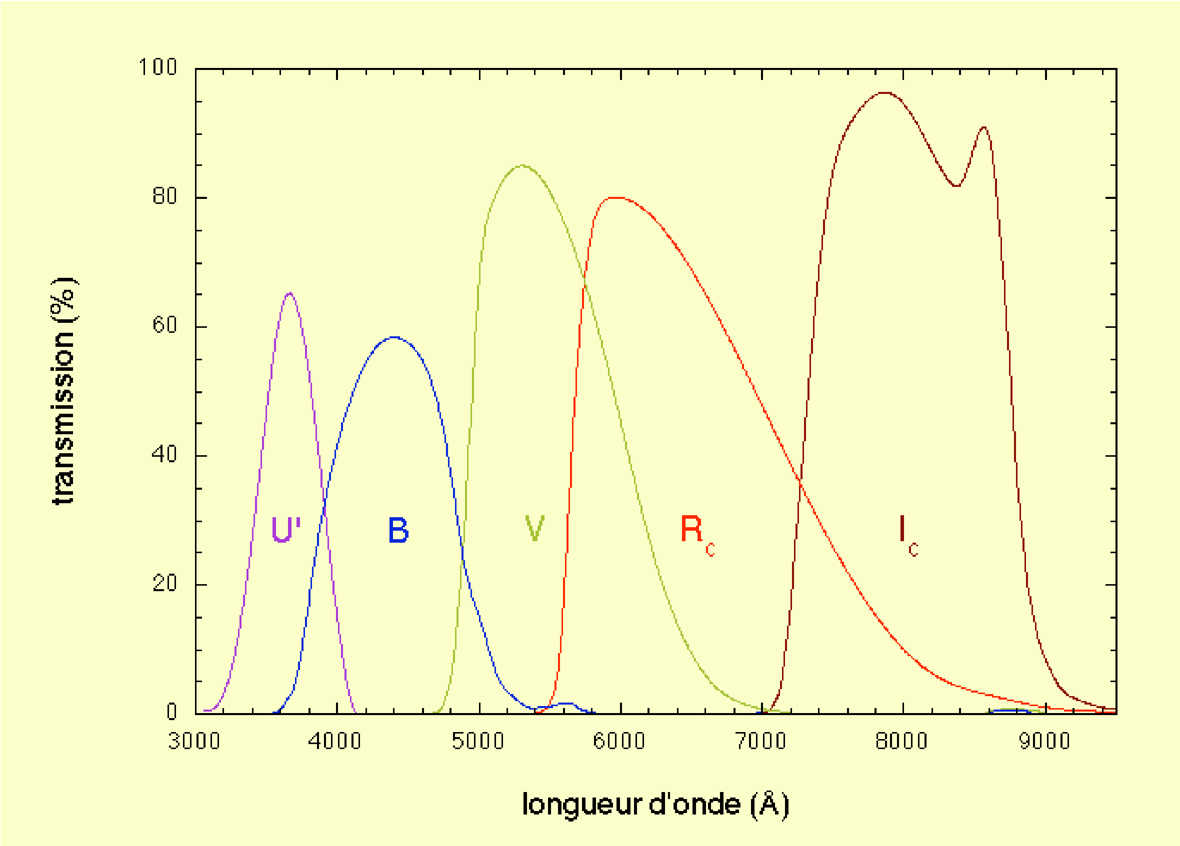
FACTS :

For the 1.2-m system the gain is 3.5 e^-/ADU and the RON is 8.6 e^-

Example of CCD wavelength response



UBVRI filter transmission curves



This is the so-called Johnson-Kron-Cousins system

Other filter systems exist…

- Johnson : UBVRI + JHKL
- Geneva : $UB_1BB_2V_1VG$
- Walraven : VBLUW
- Stromgren : uvby $H_{\beta w}$ $H_{\beta n}$
- Thuan-Gunn : uvgr + iz
- Sloan Survey : *griz*
- Hipparcos+TYCHO : H_P, B_T V_T

Not all *R* and *I* filters are alike !

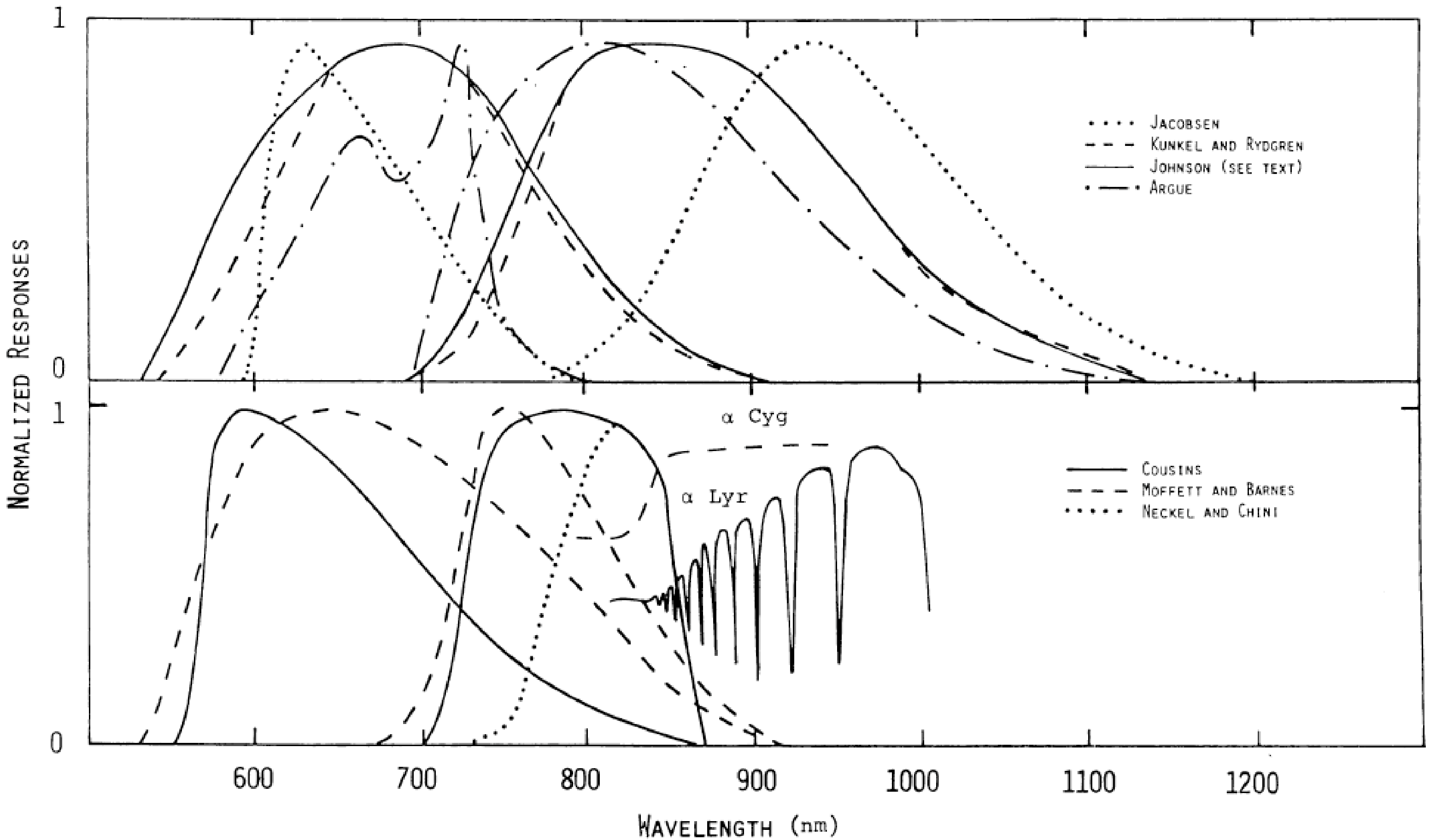
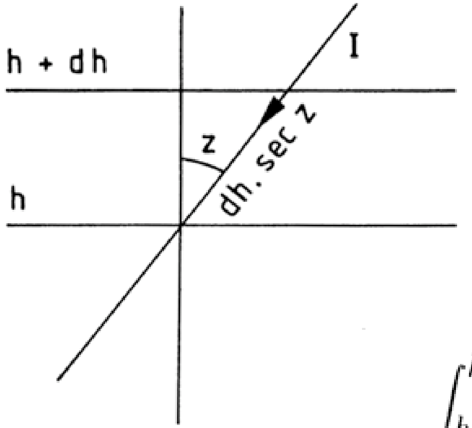


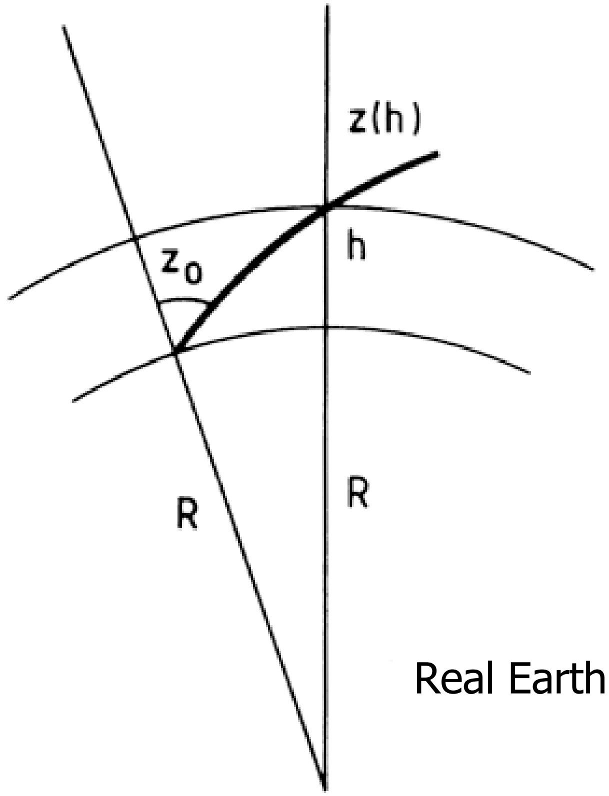
FIG. 1—*R* and *I* passbands for several photometric systems. The region of the Paschen discontinuity is shown for α Cyg a supergiant and α Lyr.

Air mass

Flat Earth approximation



$$X = \frac{\int_{h_0}^{h_1} \rho(h) \sec z(h) dh}{\int_{h_0}^{h_1} \rho(h) dh}$$



Real Earth

An approximation : $X = \sec z \cdot (1 - 0.0012\ (\sec^2 z - 1))$

Magnitudes and color indices

- Astronomical magnitudes are defined, following Pogson (19th century), as :

$$m = -2.5\ log(I)$$

- The difference between the magnitudes in two different passbands is called a color index:

$$B\text{–}V = m_B - m_V = -2.5\ log(I_B/I_V)$$

in the case of the *B* and *V* bands

Bouguer's Law

- Absorption by the atmosphere can be described by a standard exponential law:

$$I = I_o \, exp\,(-K \cdot h)$$

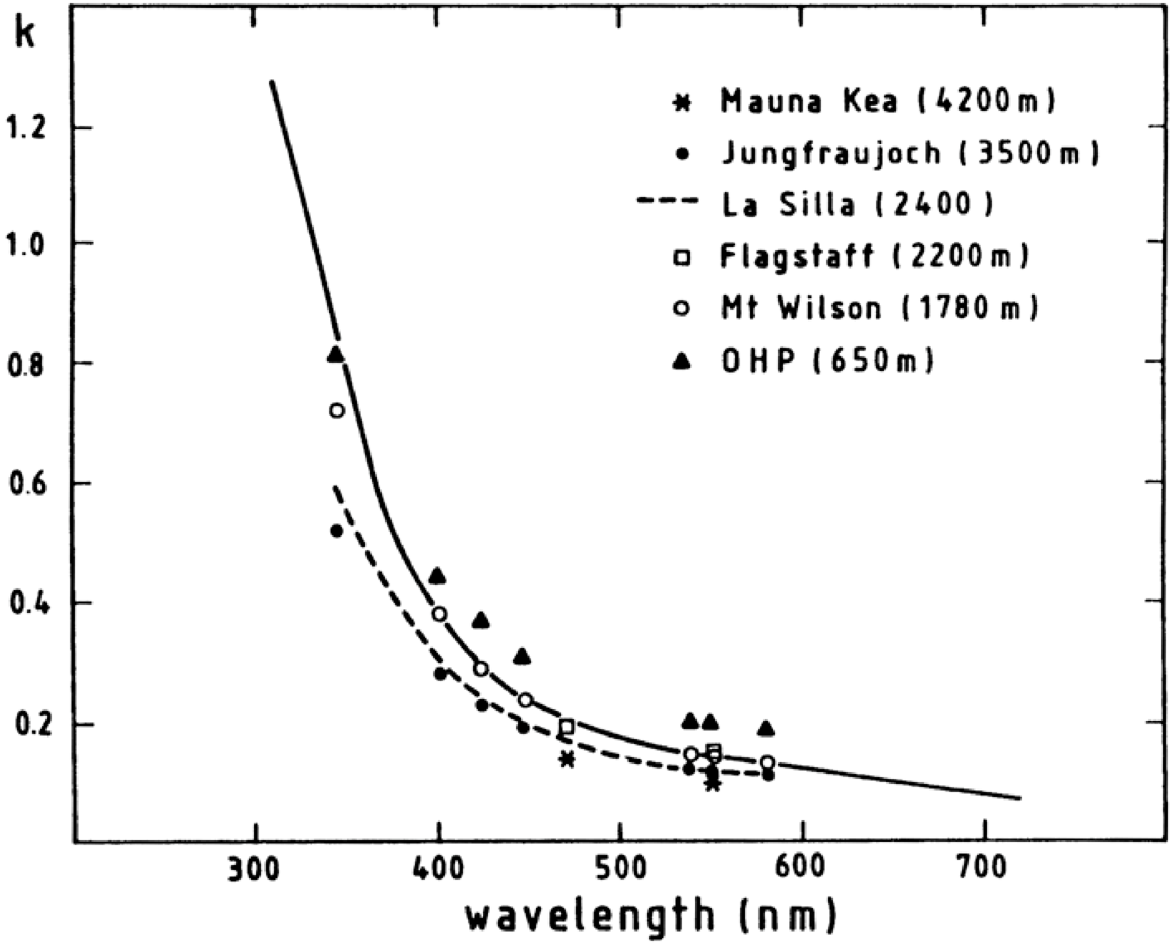
where I_o is the intensity outside the atmosphere, I is the value measured after traversing a thickness h and K is the absorption coefficient per unit length caracterizing the properties of the absorbing medium. $K \cdot h$ is called the "optical depth".

- Taking logarithms, we can re-write this in magnitudes as:

$$m = m_o - k \cdot X$$

where X is the airmass and k is called the extinction coefficient per unit airmass. This is called **Bouguer's law** (18th century).

Atmospheric extinction

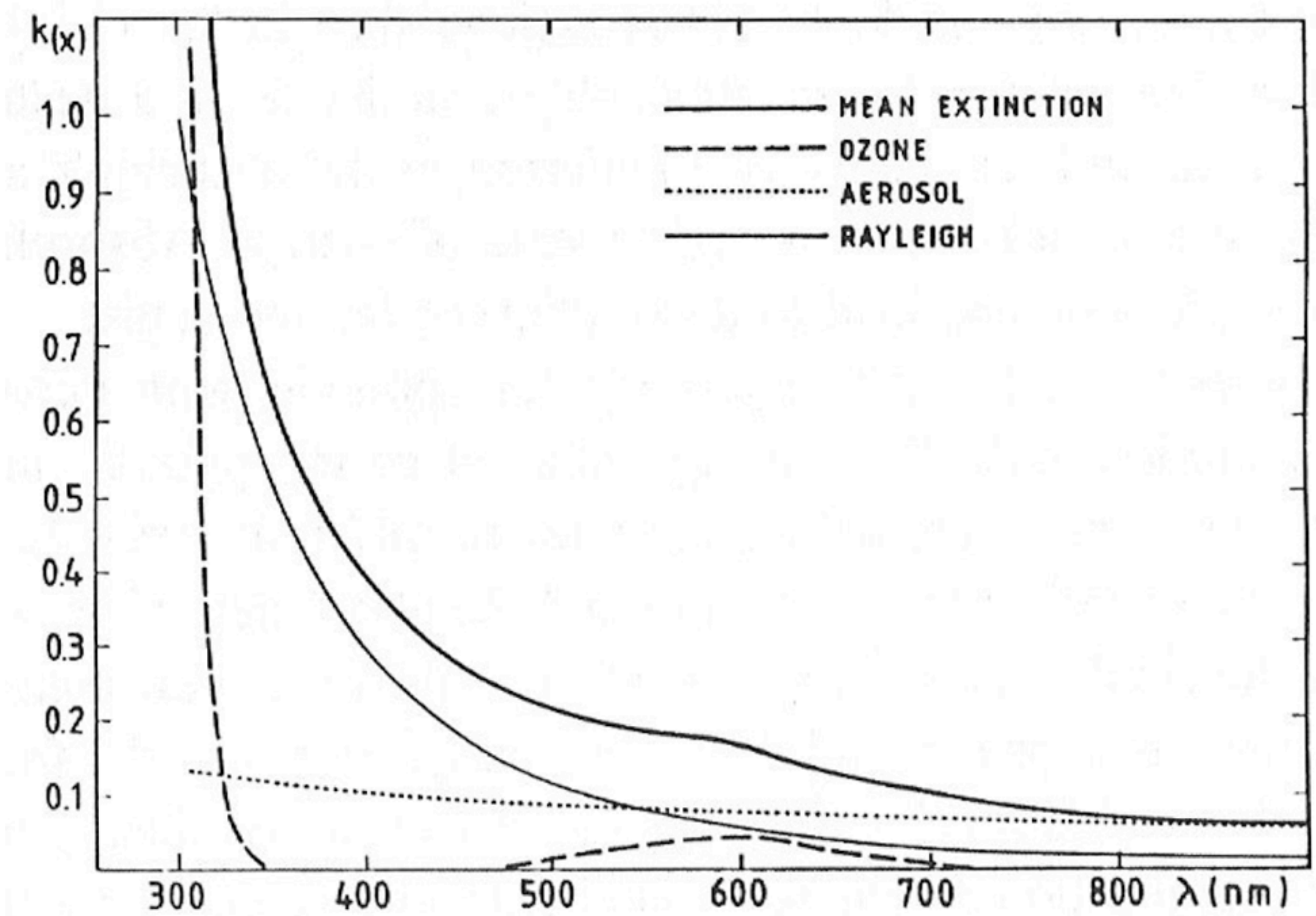


Atmospheric extinction coefficients depend on wavelength and on the altitude of the observing site.

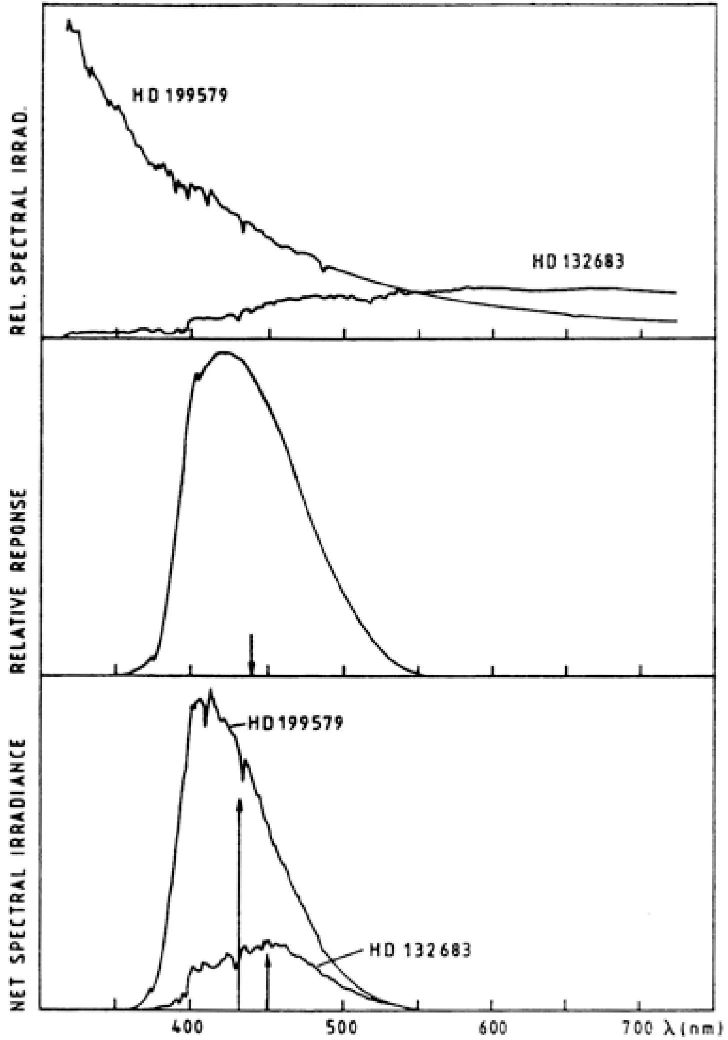
They can vary with time (from season to season, from night to night and within a single night).

For OHP, the coefficients are at least 70% larger than the values for La Silla. We recommend assuming they are **twice** those for La Silla.

Components of extinction



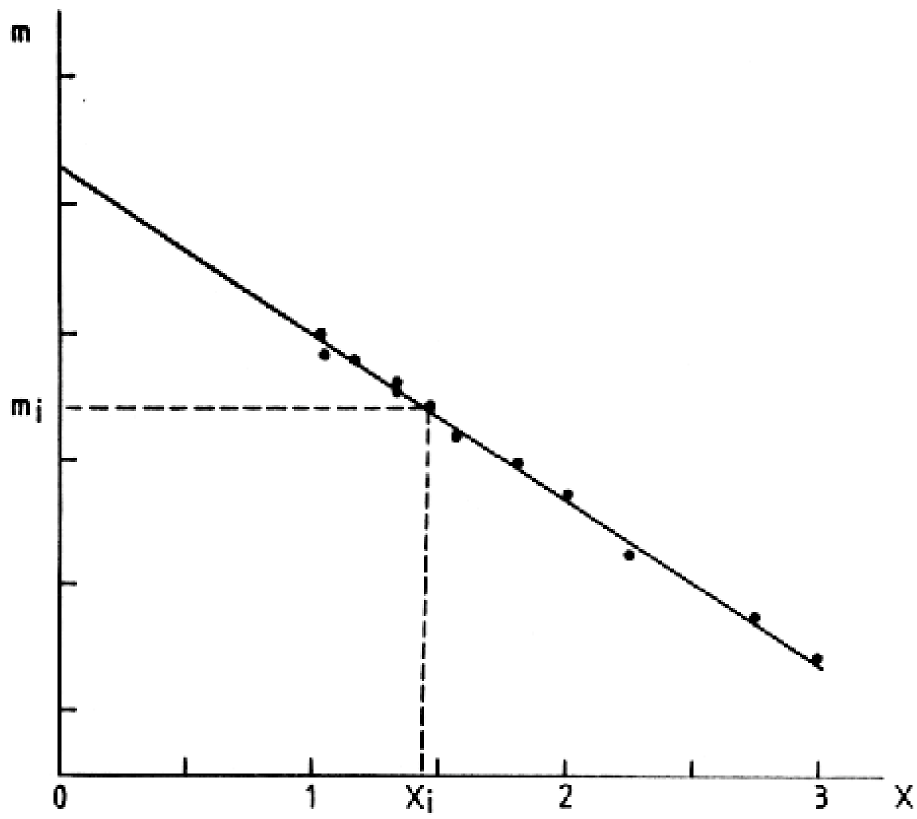
Effective wavelength



- Measuring objects whose spectra have different colors implies that the effective wavelength of a **broad-band filter** changes with the color of the object
- The atmospheric extinction coefficient changes accordingly
- We speak thus of the *effective wavelength* of a given filter for a given star color

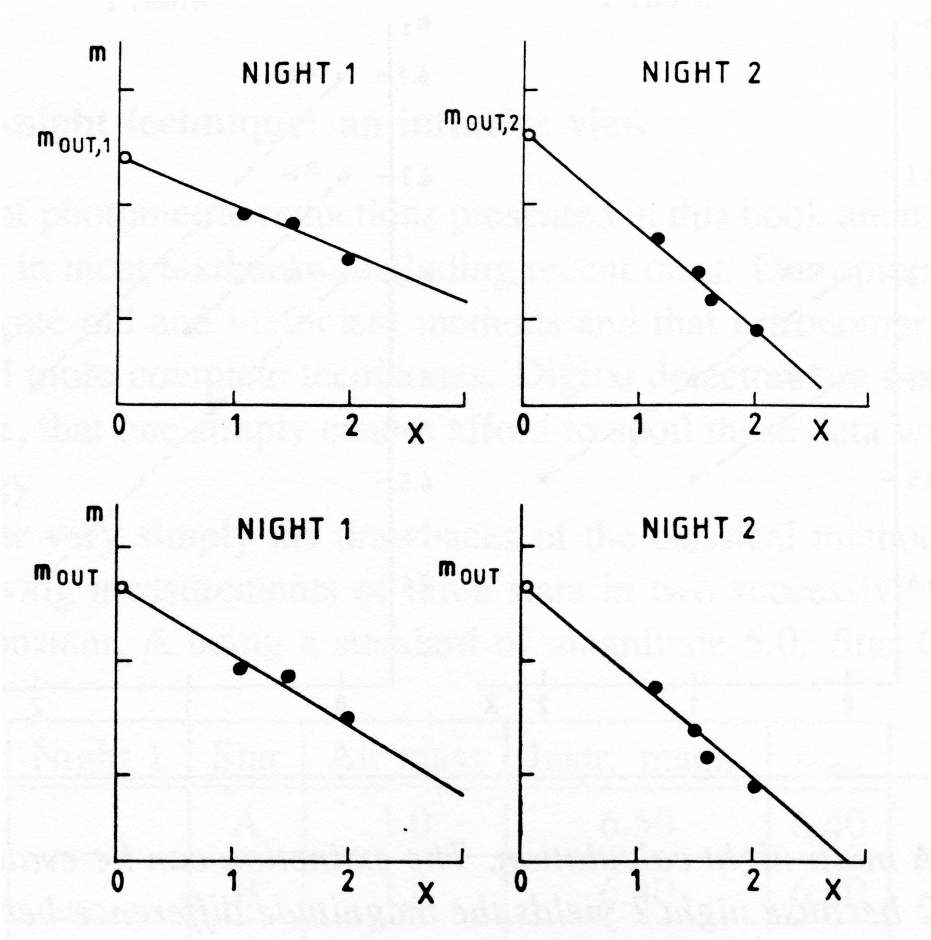
$$\lambda_{eff} = \int \lambda \cdot e(\lambda) \cdot S(\lambda) \cdot d\lambda \Big/ \int e(\lambda) \cdot S(\lambda) \cdot d\lambda$$

Bouguer plot



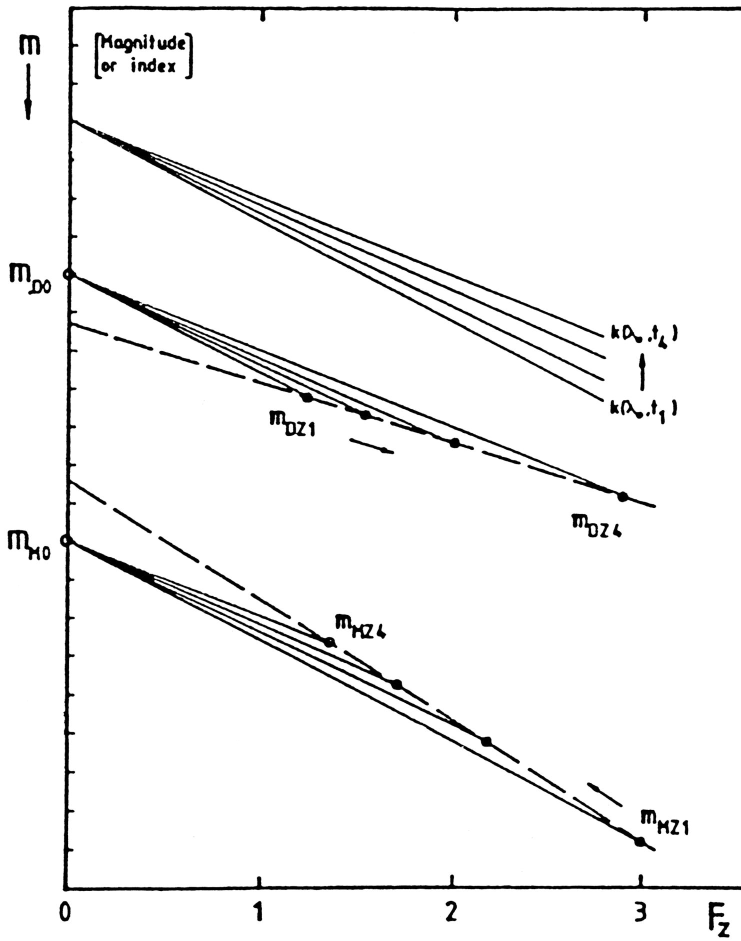
- A plot of apparent magnitude versus airmass
- A least-squares fit through many observations of the same star trhough the night results in a reliable determination of the extinction

If extinction varies from night to night



- A simple example shows that it is useful to combine information obtained during different nights in order to obtain better reductions
- In the top half, two nights are reduced independently, giving different extra-atmospheric magnitudes
- In the bottom half, the same value is imposed to m_{out}, resulting in a more accurate extinction

If extinction varies during the night



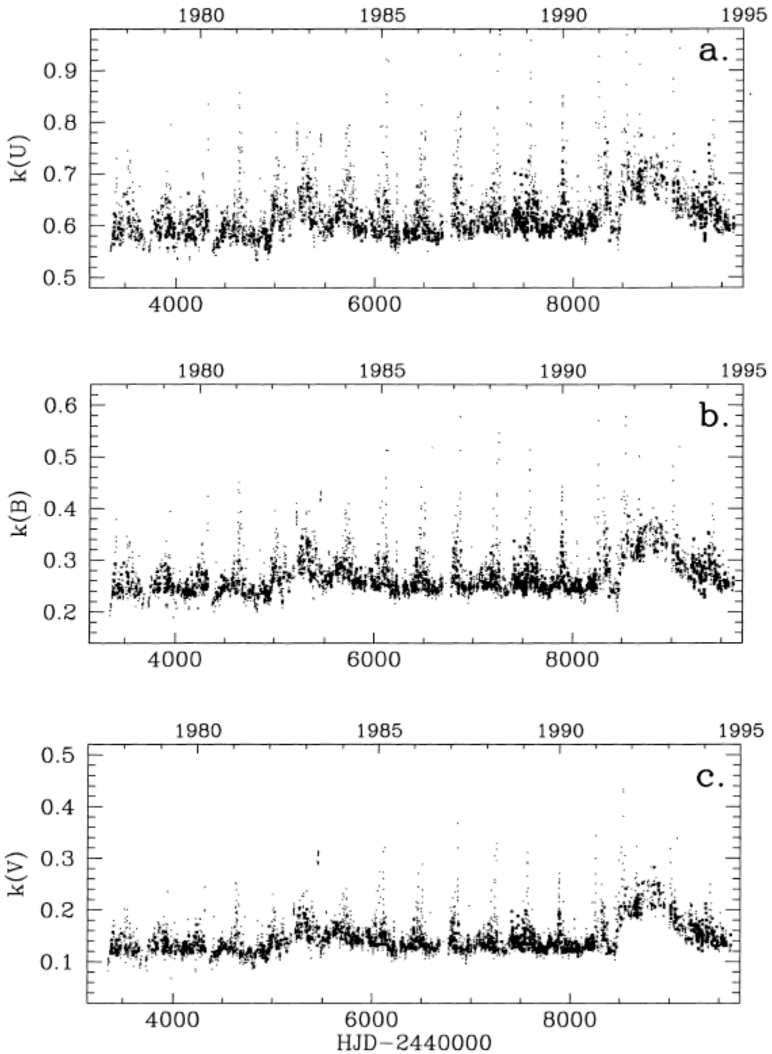
Simulation of a night with variable extinction (k_V = 0.26, 0.24, 0.22, 0.20) decreasing with time

- Star M is before meridian and rising
- Star D is past meridian and setting

Taking the measurements at face value (dotted lines) we derive incorrect extinction AND extra-atmospheric magnitudes

Assuming extinction is the same for both stars and that it varies slowly and isotropically, one can solve the necessary equations to get the extra-atmospheric values and derive the extinction

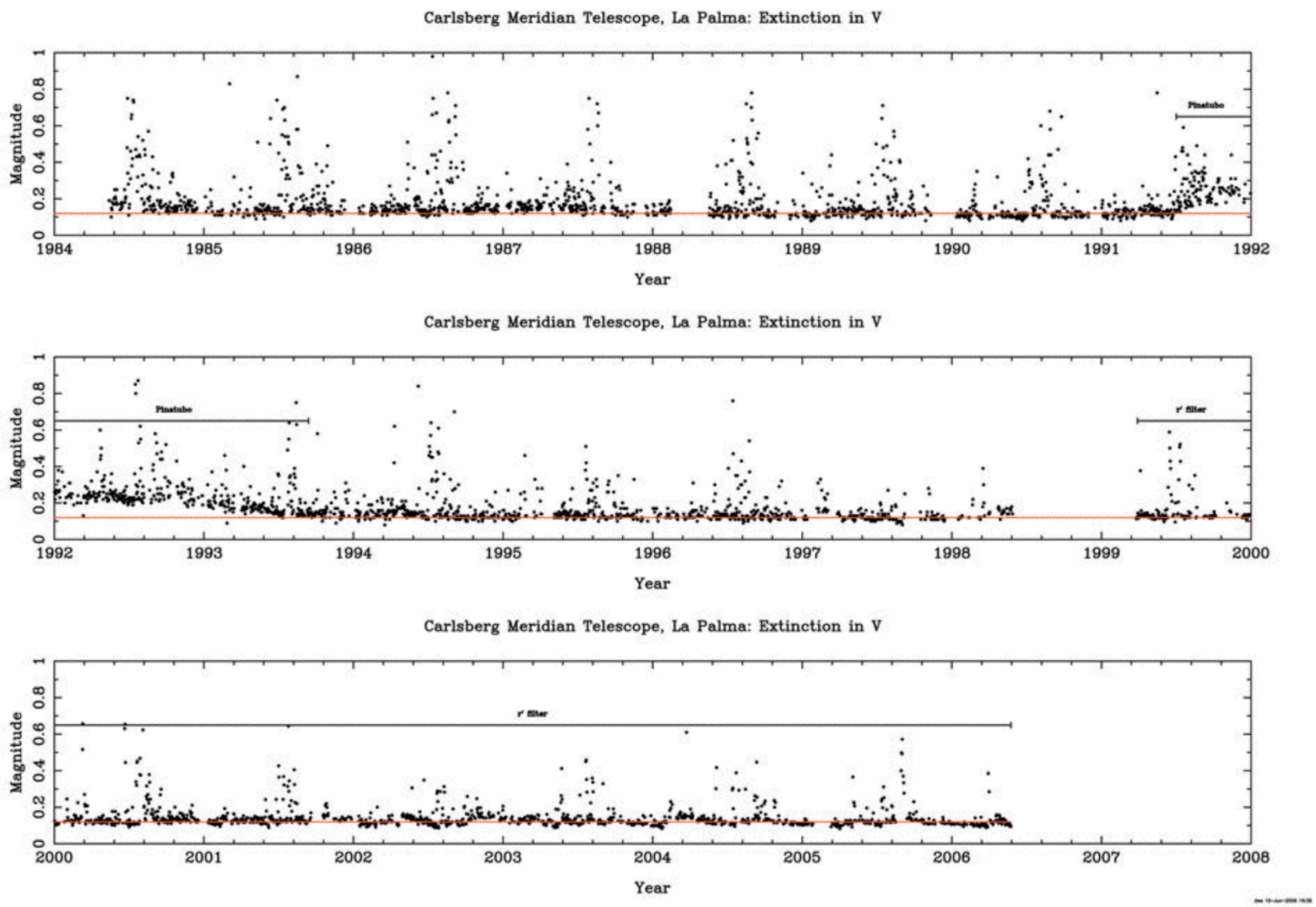
Extinction at La Silla



Two volcanic eruptions took place during this monitoring by the Geneva group:

- **El Chichón** (March 23 and April 4, 1982)
- **Pinatubo** (June 12 and 13, 1991)

Extinction at La Palma



How extinction works

- For broad-band filters, extinction coefficients have to take into account a dependence on object color. For a filter having a central wavelength λ and an associated color index c_o:

$$k_\lambda = k_\lambda' - k_{\Delta\lambda}'' \cdot c_o$$

The **first-order** term is the atmospheric extinction proper while the **second-order** term takes into account the dependence on object color due to the width of the filter bandpass.

The first term varies with time but the second term usually remains constant for a given instrumental setup. The instrumental color should be the ‘extra-atmospheric’ value, but observed values are used.

How to determine extinction

- Extinction coefficients can be determined accurately by observing a set of standard stars spanning a wide range of colors for several values of the airmass, both before and after meridian passage.

- A faster, separate determination of the primary and secondary extinction coefficients is possible :

  – For k'_λ observe pairs of stars having the same known color at **low** and **high** airmass (ascending, descending) so the second-order term goes away

  – For k''_λ observe pairs of stars of different known colors, located in the **same field of view**, at different airmasses, so the first-order term goes away

What if extinction is unknown ?

- Best way around is to measure your program stars and your standard stars **at the same airmass**

- If the extinction is not only unknown but variable, then pick your standard stars *as close as possible in the sky* to your program stars and *alternate between the two* to be able to interpolate any extinction changes taking place

Reduction process

- Steps taken to minimize the influence of data acquisition imperfections on the estimation of the desired astronomical quantity

- At some time, REDUCTION steps are replaced by ANALYIS steps, which depend on the research subject being pursued, although the dividing line is not well defined

How to reduce data

- The best approach to dealing with a problem is to avoid it to begin with
- Perform only reduction steps that matter. If application of a reduction process results in final **lower** noise, then apply it
- Know when to stop attemps to better reduce your data. Have you reached the ultimate precision you expect ?
- Know how to estimate how well you should do in a set of CCD reductions

Removing instrumental signature

- Before making any measurement on your CCD frames, the data are have to be corrected for two kinds of effects:
  - **Additive**
    - Dark counts and "cosmic" rays
    - Bias level systematics
    - Scattered light or background gradients
  - **Multiplicative**
    - Pixel-to-pixel variations in sensitivity

What's flat-fielding ?

- In order to correct for changes in sensitivity across the detector, you need to take exposures of a uniformly illuminated source
- Correction for pixel-to-pixel variations in quantum efficiency is usually the most important reduction process and is one of the most difficult to obtain correct calibration data to support
- Pixel-to-pixel variations are normally coupled with optical vignetting corrections although they differ in nature
- *Be prepared to spend substantial time at the telescope and a large part of the total effort in the reductions to arrive at good flat-fields*
- **Difficulties:**
    - Provide uniform illumination to 10^{-3} or better
    - QE variations may have a dependence on wavelength. Thus the correction is valid only if the spectral distribution of the light over the filter bandpass matches that of the object being observed

The first is difficult enough to satisfy, the second is essentially impossible to satisfy for broad-band photometry

Flat-fielding methods

- Flats using the dawn or dusk sky
  - Advantages: Really *flat* fields for small fields of view; High illumination levels
  - Disadvantages: Color not well matched to night sky or stars; Possible polarization; Rapidly changing illumination levels; Stars may appear in frame
- Flats using dome illumination
  - Advantages: Controllable illumination; Can be done in daytime; Possibility of averaging many such frames
  - Disadvantages: Color not well matched by lamps; Possible shadows, diffuse light or gradients
- Flats using "empty" star fields
  - Advantages: Good color match for sky; Same conditions as data frames
  - Disadvantages: low-illumination levels; lots of reduction effort; Wastes dark observing time

How to prepare your flats

- Since you are going to divide your science frame by the flat-field frame, it should have the highest S/N possible
- Obtain several frames (minimum 5) for illumination levels close to 1/2 of saturation
- Compute a median frame to reject "spikes"
- Subtract well-averaged bias frame or bias value
- Divide by the average value of the frame to obtain a **normalized flat**
- Obtain flats every day or two since dust specks (on filters or on dewar window) might come and go

Averaging calibration frames

- Many calibration frames have to be averaged to reduce the noise and the final result of the reduction will be:

  Final_result = (Science_frame - Av_Dark)/(Av_Flat - Av_Dark)

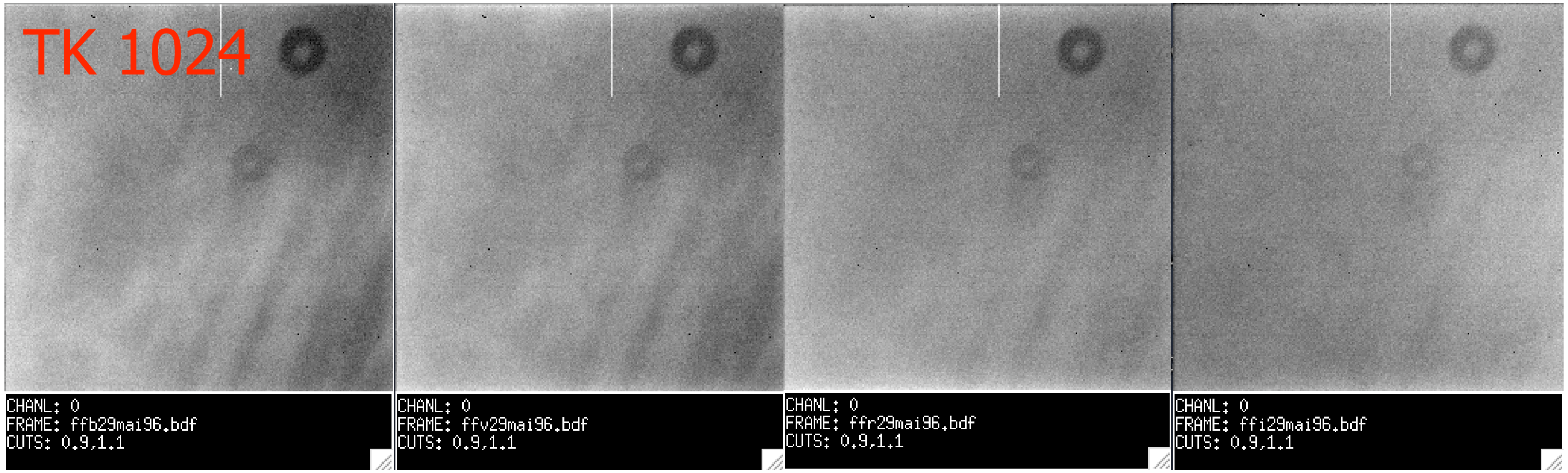
- The error in the final result frame can be expressed as:

  $\sigma^2_{FinRes} = \{(F-D)^2\sigma^2_S + (S-F)^2\sigma^2_D + (S-D)^2\sigma^2_F\}/(F-D)^4$

  Where *F, D, S* and *FinRes* stand for Flat, Dark, Science_frame and Final_result

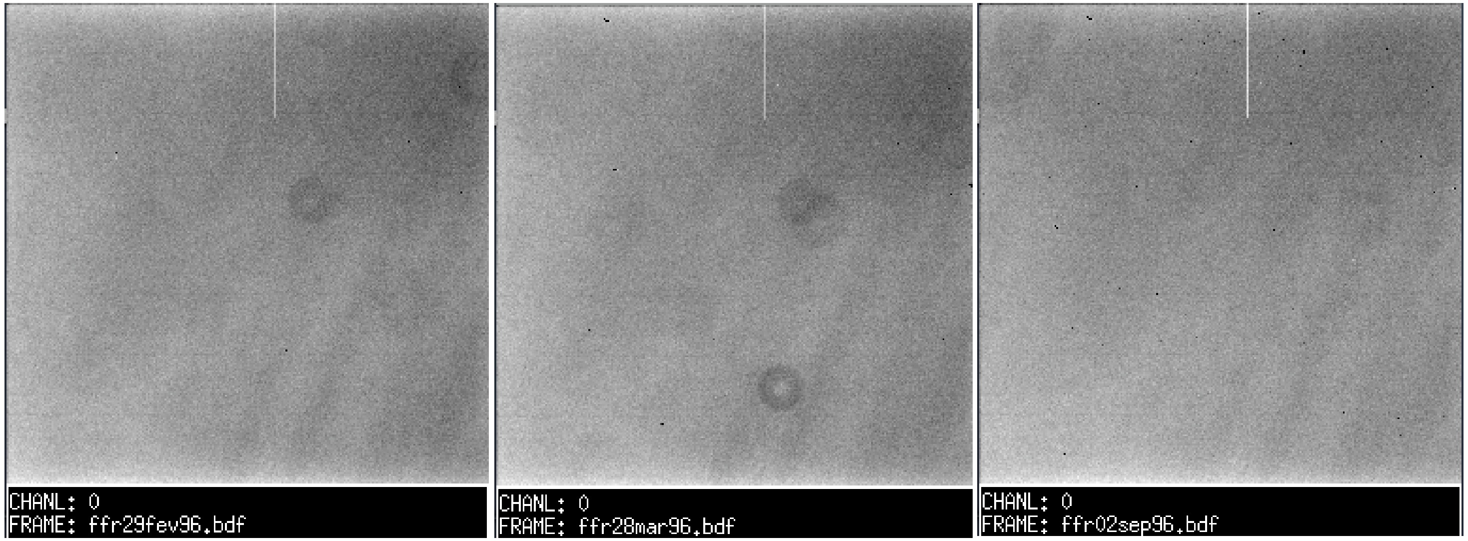
  σ^2_{FinRes} will be small if σ_S, σ_D and σ_F are small

Examples of chromatic effects



- In the top row are flats in *B*, *V*, *R* and *I* for the current TK1024 chip at the 1.2-m with little or no visible chromatic effect
- In the bottom row are flats in *R* and *I* for the old TK512 with an extreme chromatic effect

The case of the moving spots

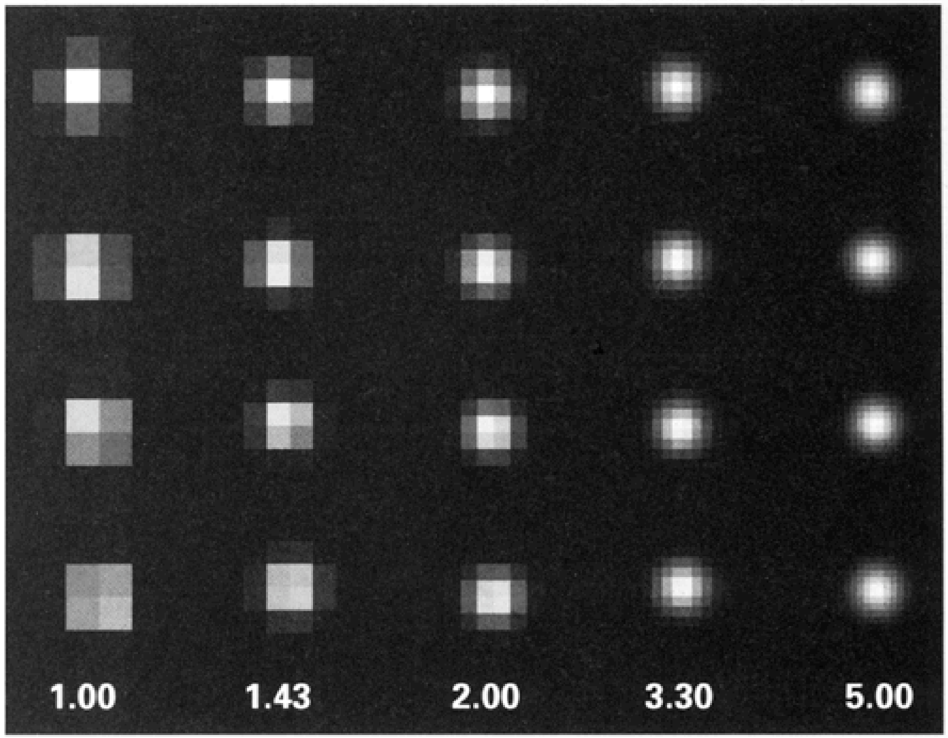


This illustrates the pitfalls when using flat-fields taken at other times: the dust specks on the dewar window have moved !

Flats taken on : 29 February, 28 March and 2 September

Sometimes they even move during a week !

Image sampling



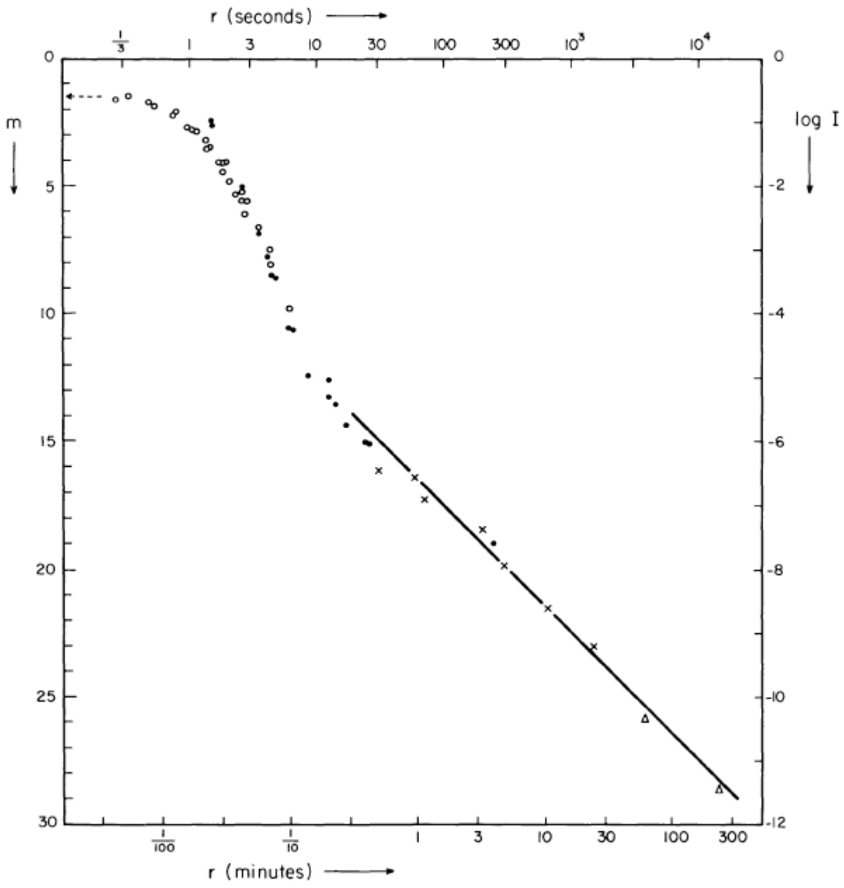
Different cases of image sampling

- horizontally: as a function of the projected image size (in pixels)

- vertically: as a function of image centering in the array

Critical sampling (Nyquist criterion) ≈ width of PSF
For a Gaussian PSF this corresponds to the FWHM = 2.355 pixels

What's the real shape of a PSF ?

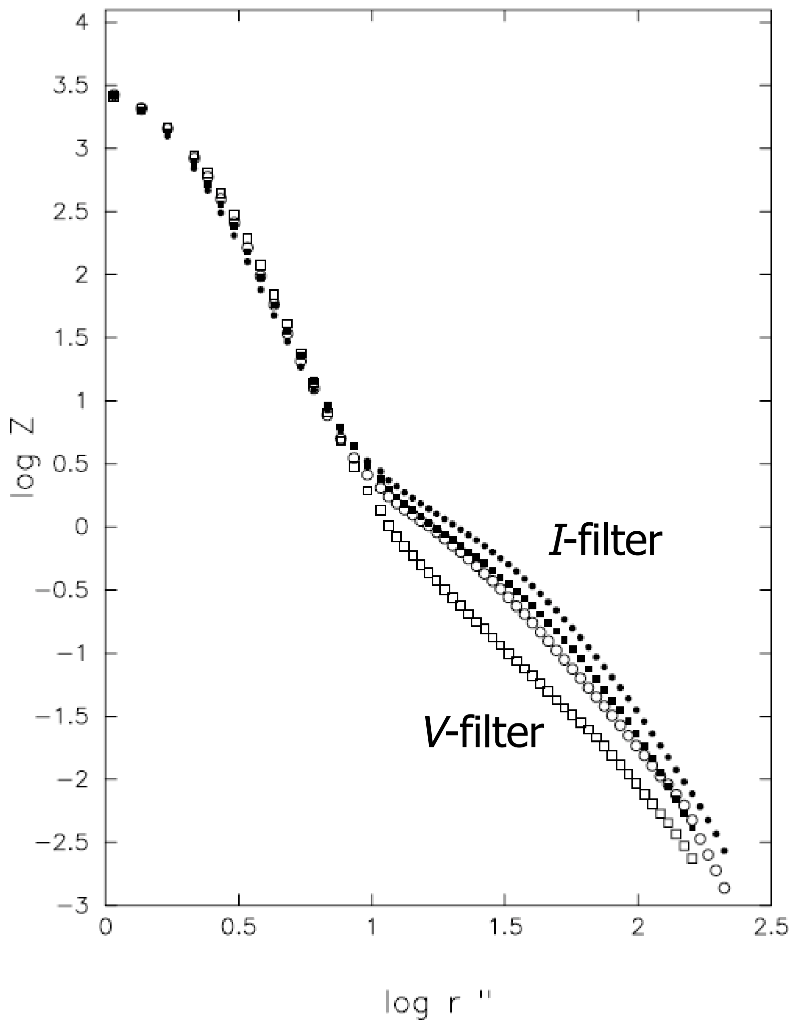


The actual point spread function of a star image is complex:

- A central core
- An exponential drop
- An extended inverse-square aureole

King (1971)

Red "halo" effect



- The PSF profiles obtained at the 1.2-m OHP telescope with the *B*,*V* or *R* filters agree with the King profile
- However, the *I* filter profile exhibits a "halo" due to light passing through the CCD, being diffused in the glass header, reflected back into the CCD from the rear metallized surface and finally being detected.
- This is a well-known effect of thinned CCDs.

Michard (2002)

Instrumental magnitudes

The photons (electrons) registered by the CCD in a time *t* coming from a given star can be written as:

$$S = \int_{\lambda_1}^{\lambda_2} \phi(\lambda) \cdot \left(\frac{\lambda}{hc}\right) \cdot A \cdot \varepsilon(\lambda) \cdot T(\lambda) \cdot E(\lambda) \cdot Q(\lambda) \cdot t \cdot d\lambda$$

where $\phi(\lambda)$ is the flux outside the atmosphere (in erg/cm2 s Å), A is the effective collecting area, $\varepsilon(\lambda)$ is the efficiency of the telescope optical system, $T(\lambda)$ is the filter transmission, $E(\lambda)$ is the atmospheric extinction and $Q(\lambda)$ is the quantum efficiency of the CCD.

The instrumental magnitude of a star is obtained from the number of electrons generated in the CCD by the light from the star :

$$m_{inst} = -2.5 \log(S_*)$$

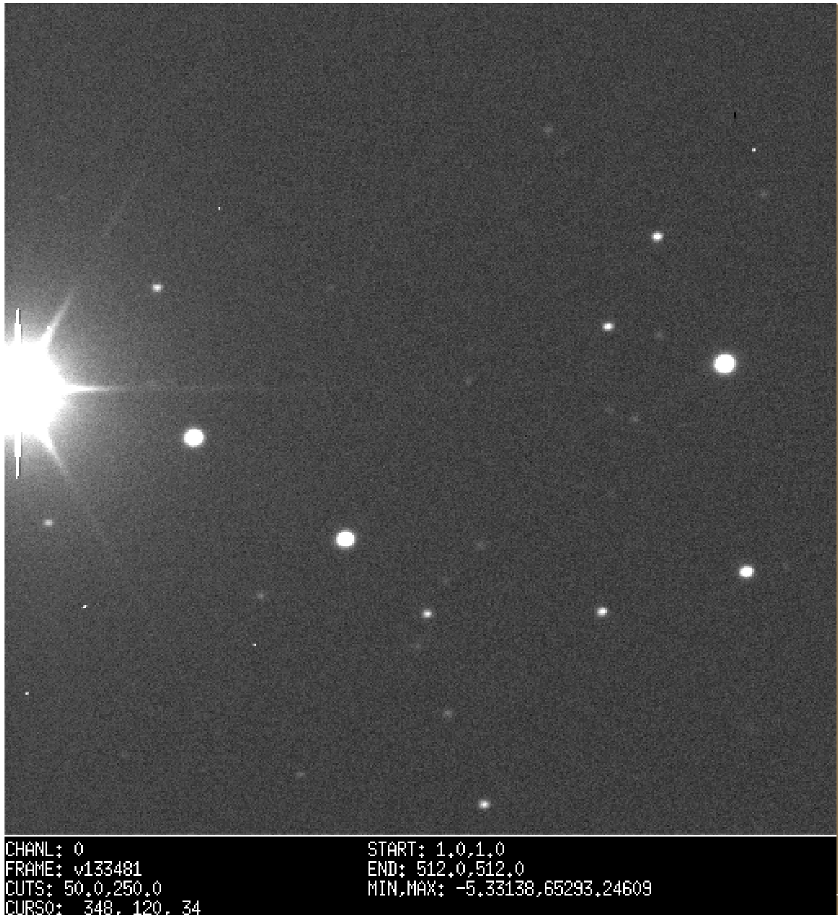
S_* is obtained by suming is over the n_{pix} pixels included in the digital aperture centered on the star:

$$S_* = \sum_{j=1}^{n_{pix}} a_j \cdot s_j - \sum_{j=1}^{n_{pix}} a_j \cdot b$$

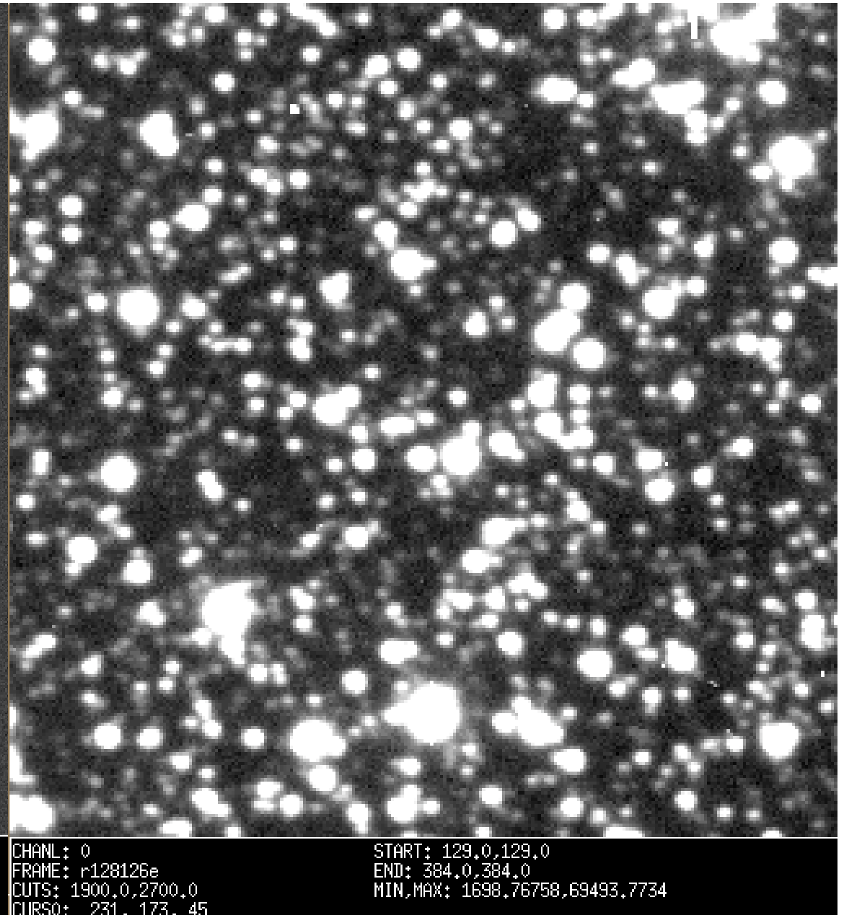
where a_j is the area of the jth pixel, s_j is the electron count in the jth pixel (star+sky) and b is the sky background count per pixel.

Determining the background ?

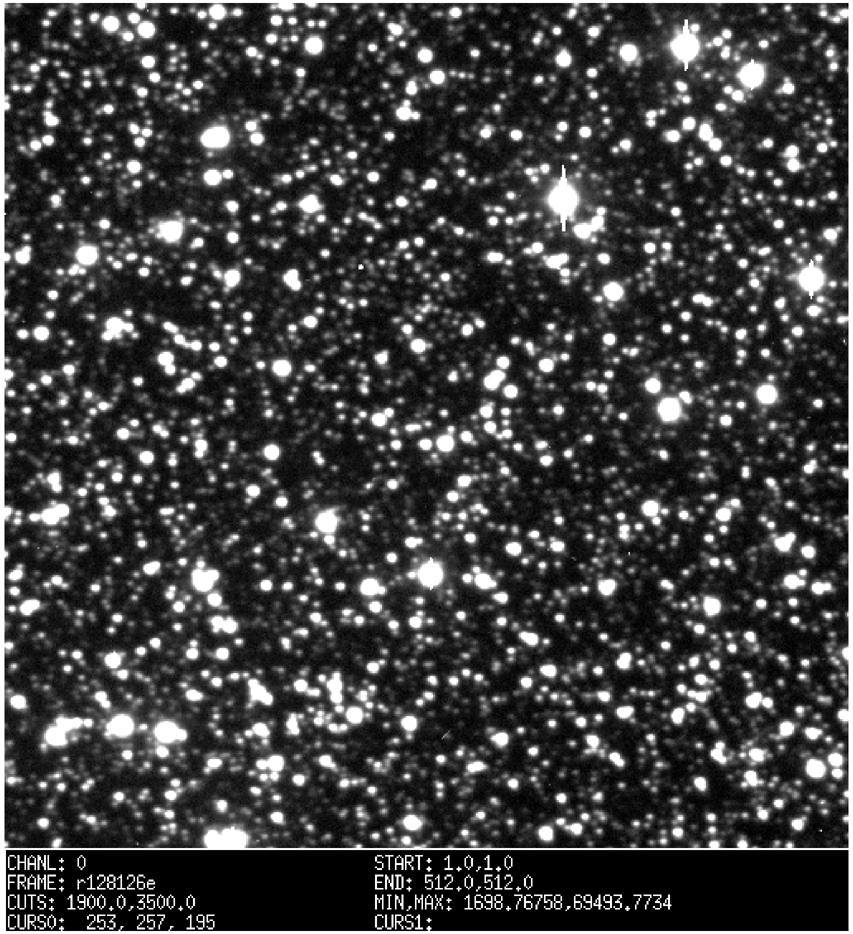
EASY

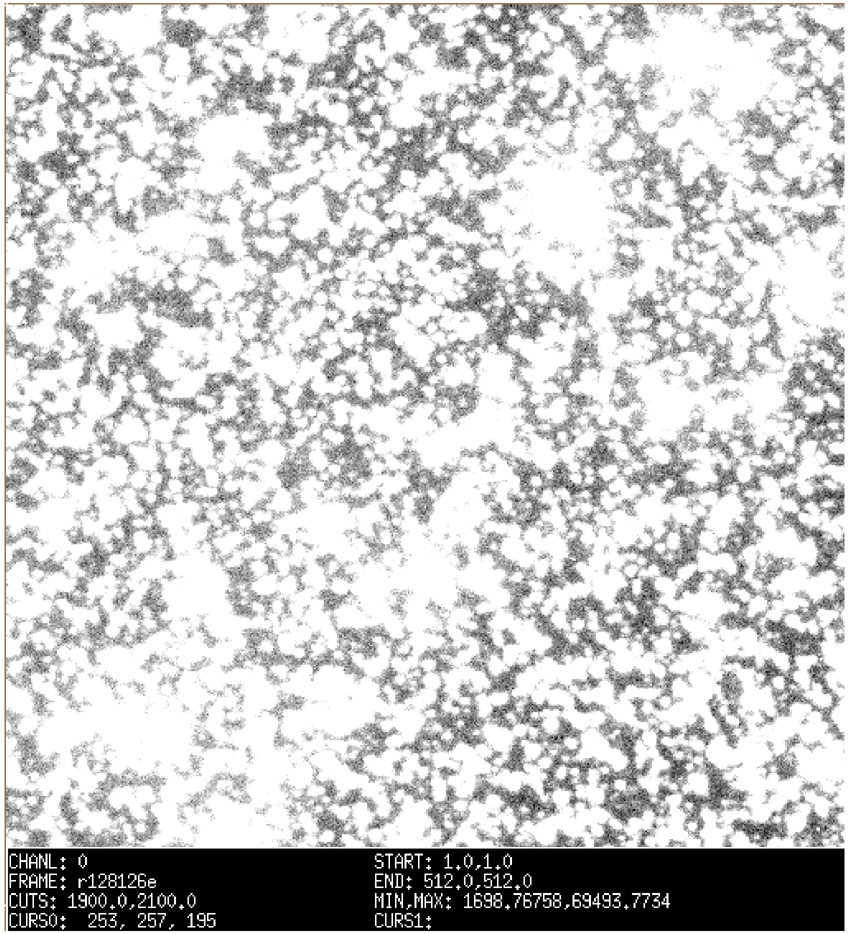


HARD



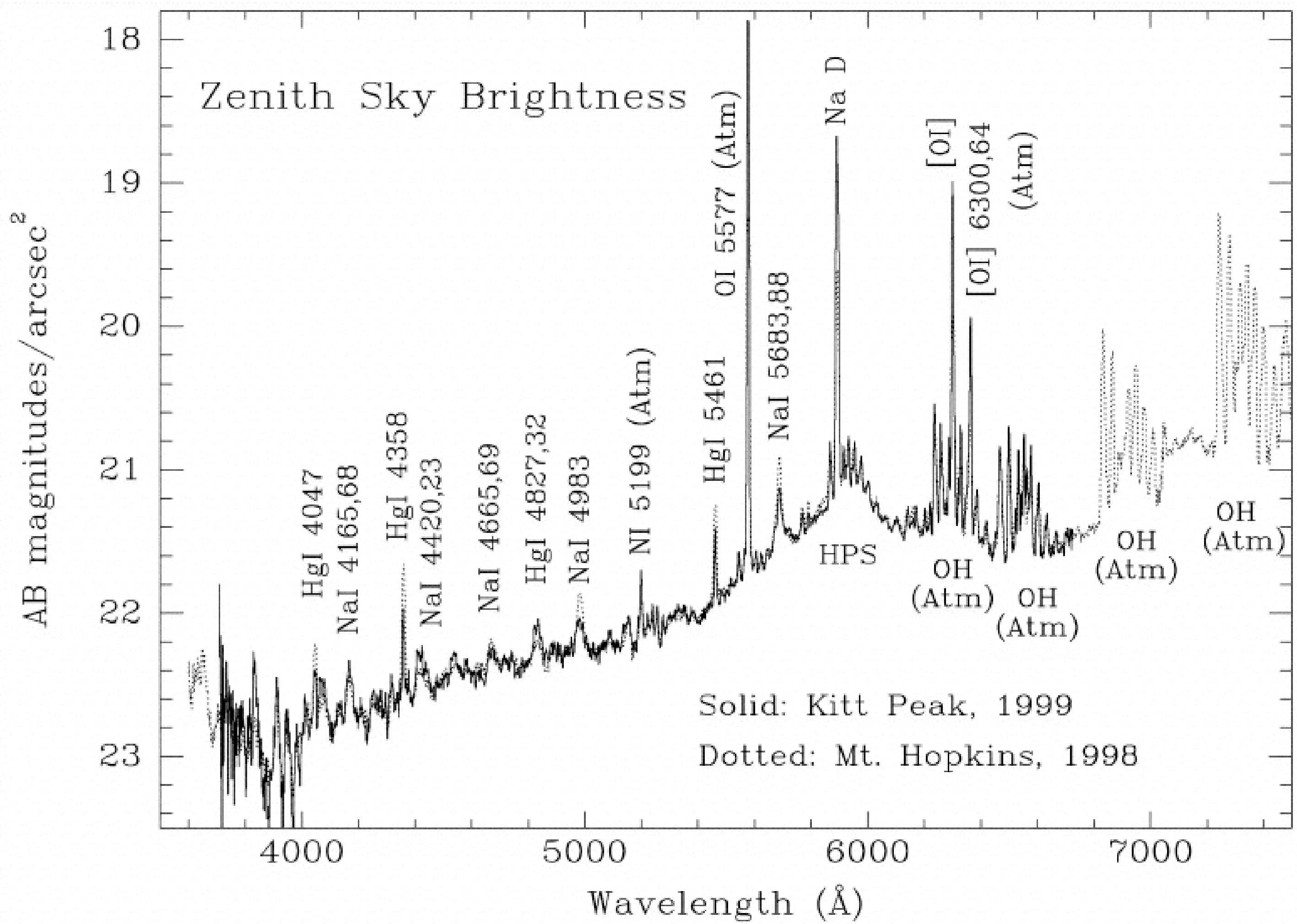
Where *is* the background here ?





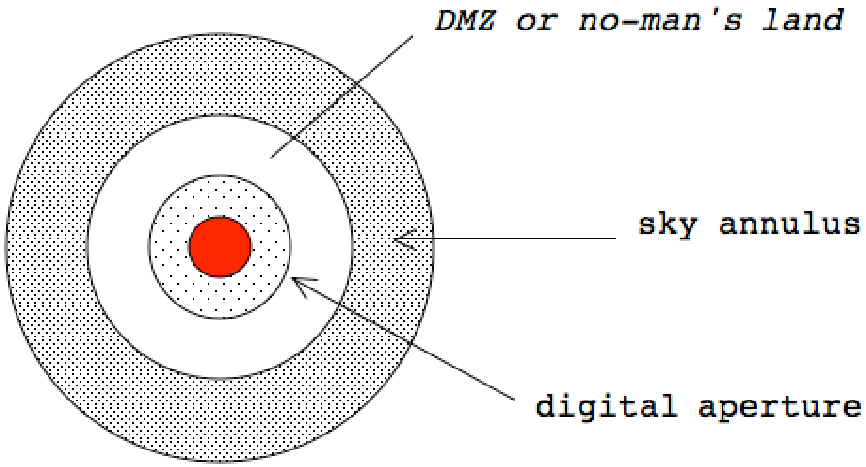
Same field, but shown with different cut values

Spectrum of the background ?



Foltz & Massey (2000 Publ. Astr. Soc. Pacific, 112, 566)

Characterizing the background



The optimal radius of the aperture is close to the FWHM of the stellar profile

The optimal inner radius of the sky annulus is close to 3 times the FWHM

The background is computed from the histogram of the pixels in the annulus. If noise spikes or other objects are present in the sky, they should be rejected before computing its value (sigma-clipping).

The **mode** is the best estimate of the sky. It is defined as the maximum of the histogram (the most probable value). Assumptions: (1) the histogram is unimodal (only one peak) and (2) there are enough pixels to get meaningful statistics.

The sky annulus should contain at least 100 pixels. The outer radius should not be too large since the background may be different far away.

Starlight within a given aperture

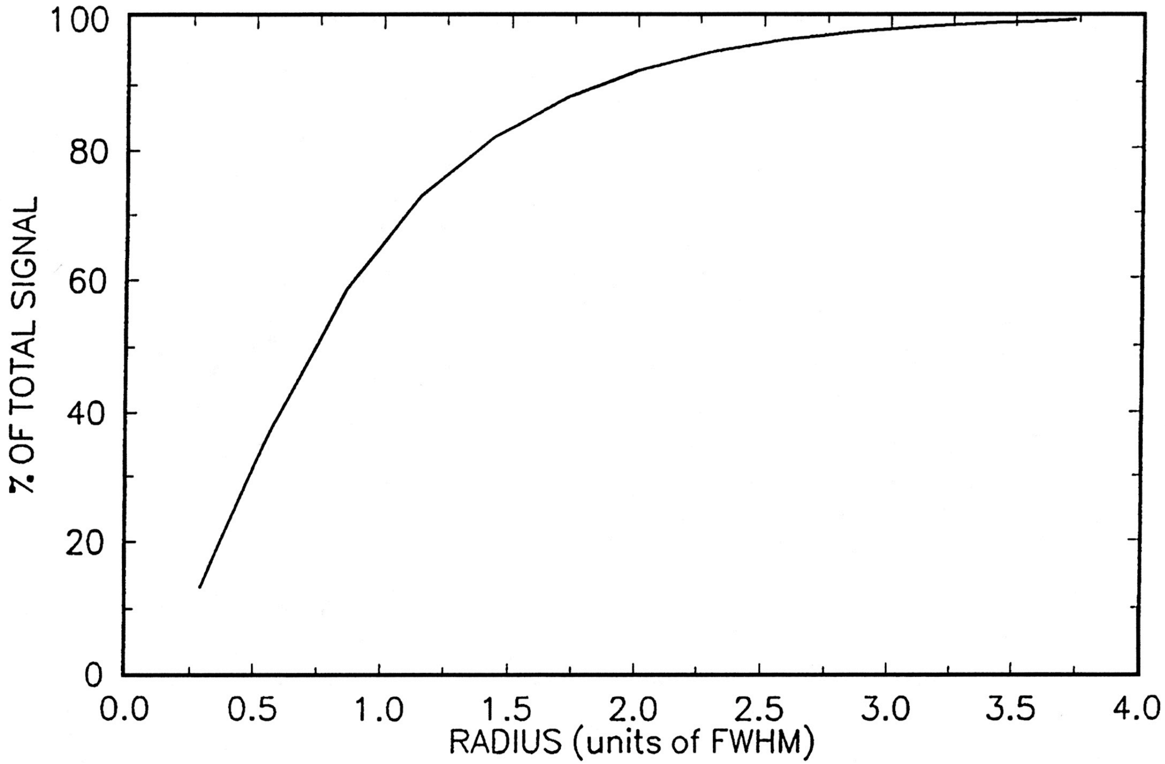


Fig. 5.5. For any reasonable PSF approximation, the figure above shows the run of the total encircled signal with radius of the PSF in FWHM units. Note that within a radius of $3 \cdot \mathrm{FWHM}$ essentially 100% of the signal is included.

Signal-to-Noise

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix}(N_{Sky} + N_{dark} + N_{RON}^2)}}$$

CCD Equation: N_* is the total number of photons (electrons) from the star, N_{Sky} and N_{dark} are the number of electrons/pixel from the sky and dark signal, and N_{RON} is the read-out noise per pixel. n_{pix} is the number of pixels within the aperture.

Bright star :

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_*}} \approx \sqrt{N_*}$$

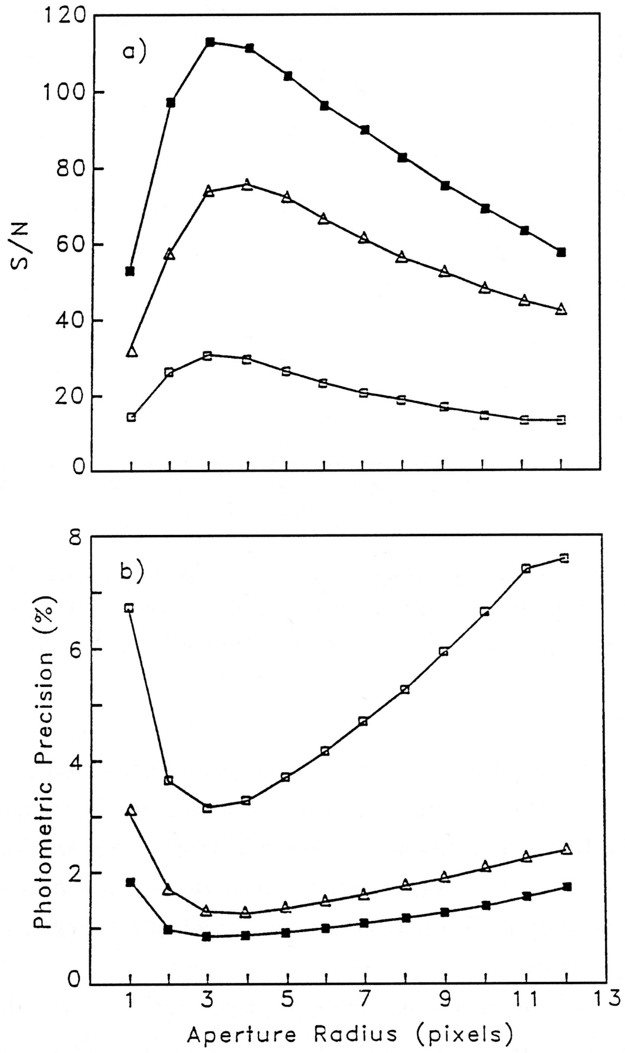
Poisson noise dominates !

Faint star :

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix}(1 + \frac{n_{pix}}{n_B})(N_{sky} + N_{dark} + N_{RON}^2 + G^2\sigma_f^2)}}$$

n_B is the number of pixels used in the background estimation, G is the gain and σ_f^2 is an estimate of the error introduced in the A/D converter (the round-off error of ±0.5 ADU)

S/N *vs.* aperture radius



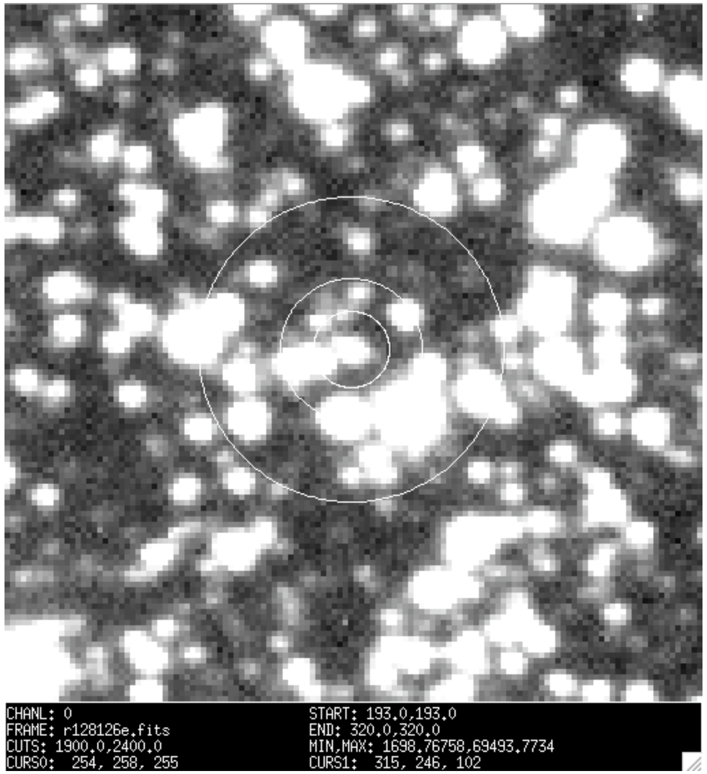
- The signal to noise ratio obtained for the measurement of a point source is not constant as a function of aperture radius

- There is an **optimum radius** at which the S/N will be a maximum. This is because the signal from the sky background

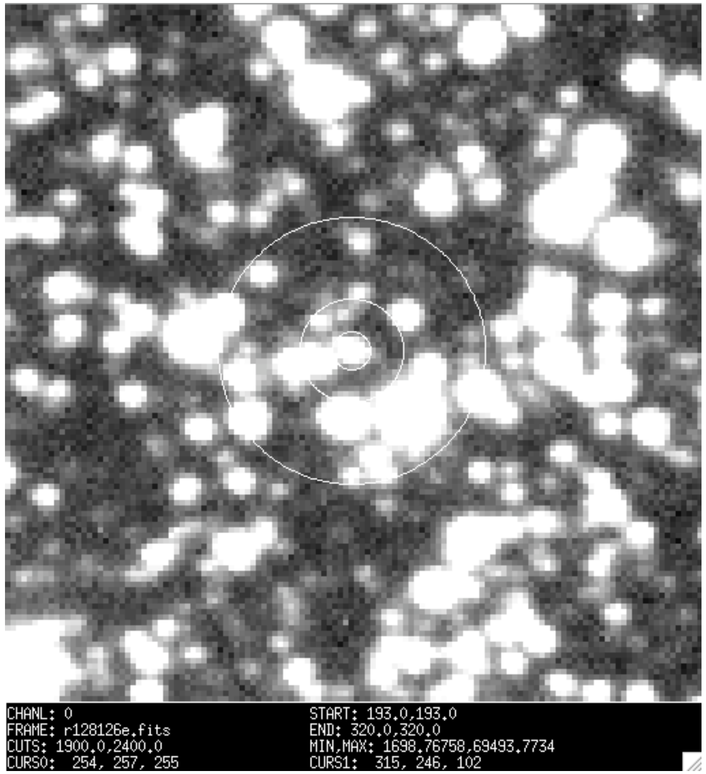
- This optimum radius the FWHM of the stellar profile.

(In this illustration the pixel size is 0.4" and the FWHM is 1.2")

Classical aperture *vs.* Optimum aperture

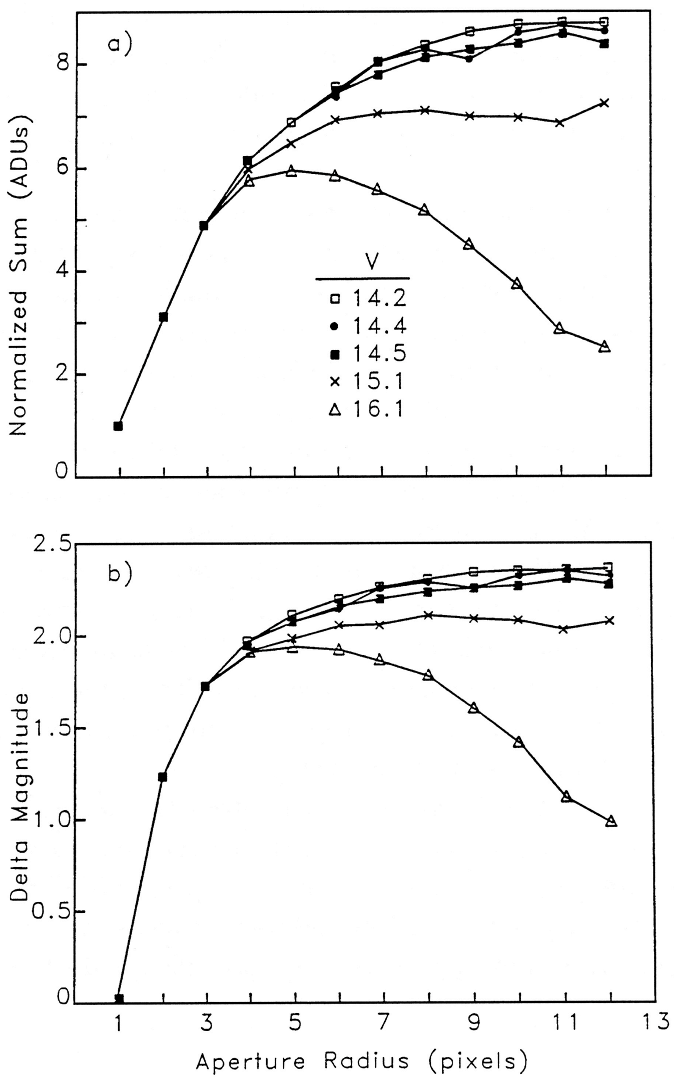


In the left-hand image one would expect to get best results with a radius large enough to enclose all the light for the brightest stars in the frame



In the right-hand image one gets the best S/N with an **optimal radius** equal to the FWHM of the star profile (0.68"/pixel and 2" FWHM)

Actual growth curves



- Here are actual growth curves measured from five different stars in a given CCD frame.

- The three brightest stars follow the theoretical expectation

- The two faint stars start out in a similar manner, but eventually the background level is high enough to overtake their PSF in the wings

- **Corrections**, based on the bright stars, can be applied to these curves to obtain good estimates of their true brightness

(Remember, in this illustration the FWHM is 3 pixels)

CCD Aperture Photometry

- Basic assumption :
  - well-isolated stars
- Determine centers of the stars :
  - use digital centering algorithms
- Determine sky background :
  - software annulus starting at 3 FWHM
  - reject stars and noise spikes
- Determine stellar magnitude :
  - circular aperture
  - partial pixels handled or not ?
- What aperture size ?
  - Optimal radius ~ FWHM
  - Curve of growth correction

PSF-fitting photometry

- Basic assumption
  - all point sources can be represented by a point-spread function
- Finding stars
  - use finding algorithm or input existing table from aperture photometry
- Finding the sky level
  - start with results from aperture photometry
- Building the PSF
  - use stars with high S/N ratio
  - eliminate close neighbors
- The fitting process
  - analytic function (Gaussian, Lorentzian, Moffat)
  - use only pixels near star center (fitting radius ~ FWHM)
  - fit several stars simultaneously when too close to each other
- Different implementations
  - DAOPHOT, ROMAPHOT, SPS , DoPHOT, etc.
- Complications
  - Extreme crowding
  - Variable PSF
- Follow the CookBook !

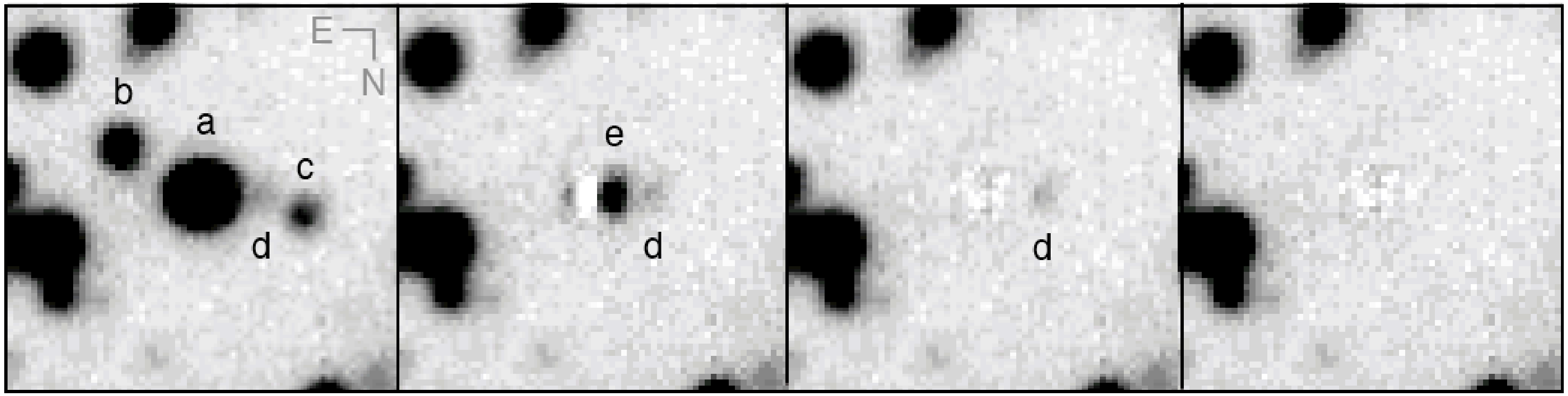
PSF CookBook

- Input existing position table or make initial pass with star-finding algorithm
- Determine sky level for each star and perform aperture photometry on all objects
- Generate an initial estimate of the PSF using the "best" stars
- Use the preliminary PSF to fit all stars to obtain more accurate magnitudes
- Subtract the stars that have been measured and run the finding algorithm on the residual image
- Fit the newly "discovered" stars and any stars from the original frame whose magnitudes have changed
- Subtract all the stars from the frame and redetermine the sky levels for each star using the new residual frame
- Refine the estimate of the PSF. There should be more usable stars since close companions have been removed
- Refit all stars in the list
- Repeat the sky estimation and PSF refinements if needed. Third-generation PSF usually give the best results

You can discover new stars !

By constructing a PSF from well-isolated stars, one can fit this PSF to stars in crowded areas and proceed to subtract them out of the frame.

New stars (star "e" below) may appear underneath (here under star "a" !



Transforming observations into a standard system

In order to correct your measurements for atmospheric extinction and for color-dependent terms, you must observe standard stars :

- having a wide range in color
- for a large range in airmass

An instrumental magnitude at a given airmass X, $m_\lambda(X)$, is related to its value outside the atmosphere, $m_{\lambda o}$ by the relation (Bouguer 's law) :

$$m_\lambda(X) = m_{\lambda o} + (k'_\lambda + k''_{\Delta\lambda} \cdot c_{\Delta\lambda})X$$

where $c_{\Delta\lambda}$ is a color index and k' and k'' are the first and second-order extinction coefficients

Transformation equations

Here we want to relate extra-atmospheric instrumental values to well-known catalogued values

- For a color index : $C_o = \alpha + \beta \cdot c_o$
- For a magnitude : $M_o = m_o + \gamma + \delta \cdot c_o$

Where the subscript "o" denotes extra-atmospheric values, lower-case symbols represent instrumental values and upper-case symbols represent catalogued values. α and γ are the "zero-points" while β and δ are proportionality constants.

These proportionality constants should be close to 1 if the instrumental system is **well-matched** to the standard system

A least-squares fit to m_o and c_o determined for a good number of stars of different colors and magnitudes should yield the unknown constants α, β, γ and δ

Differential photometry

- The difference in magnitude between two objects depends on the color difference and the airmasses. In the case of B and V measurements taken at two different airmasses X_1 and X_2:

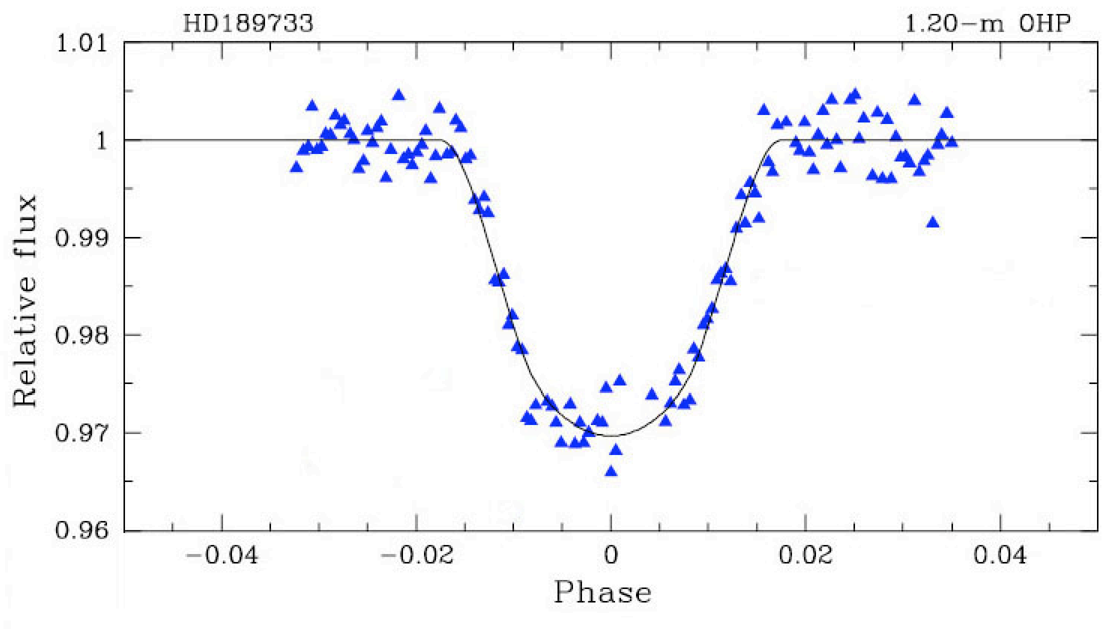
$$\Delta V = \Delta v - k'_v \Delta X + \delta \cdot \Delta(B-V)$$

$$\Delta(B\text{-}V) = \beta \cdot \Delta(b-v) - \beta \cdot k'_{bv} \Delta X - \beta \cdot k''_{bv} \Delta(b-v) \langle X \rangle$$

where $\Delta X = X_1 - X_2$ and $\langle X \rangle = (X_1 + X_2)/2$. Lower-case denotes instrumental magnitudes at a given airmass while upper-case denote extra-atmospheric values in the standard system.

High-precision photometry

- In the case of variable objects, the best approach is to select several comparison stars within the same frame and measure the variable object relative to them. In this manner very high accuracy can be reached
- As an example, here is the light curve of the exoplanet transit discovered last year at OHP in the very bright (V=7.7) star HD189733. The errors are 2-3 mmag



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