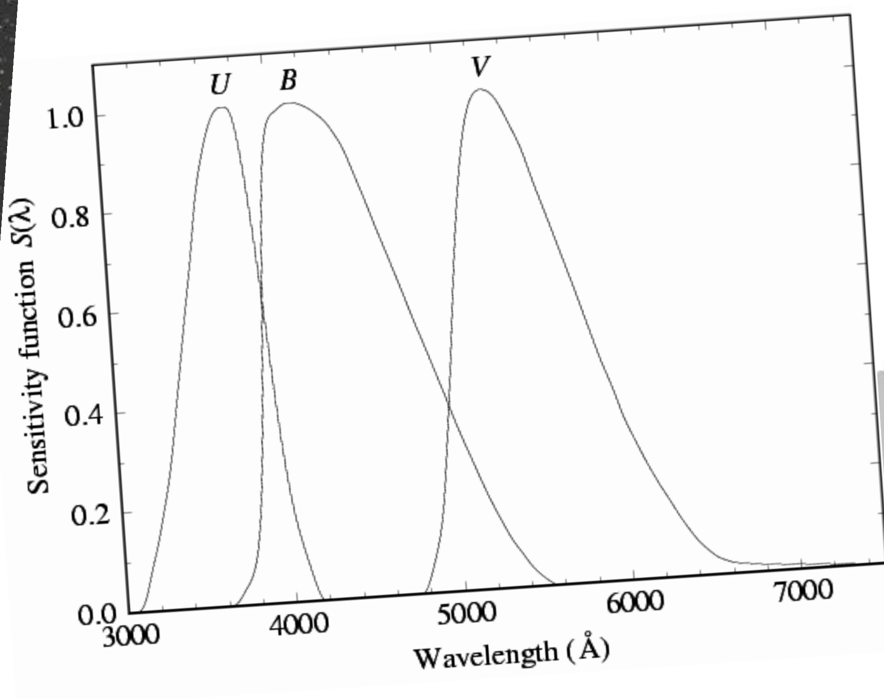
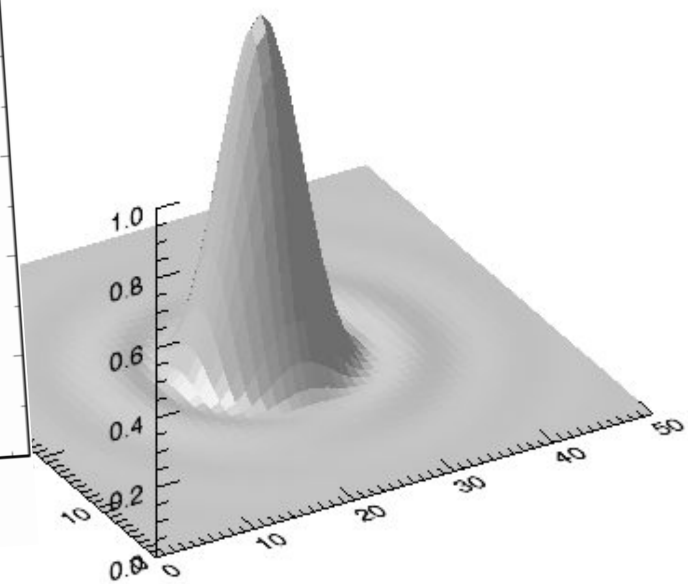
AGA 5802: Astrofísica Observacional

Jorge Meléndez

Photometry II

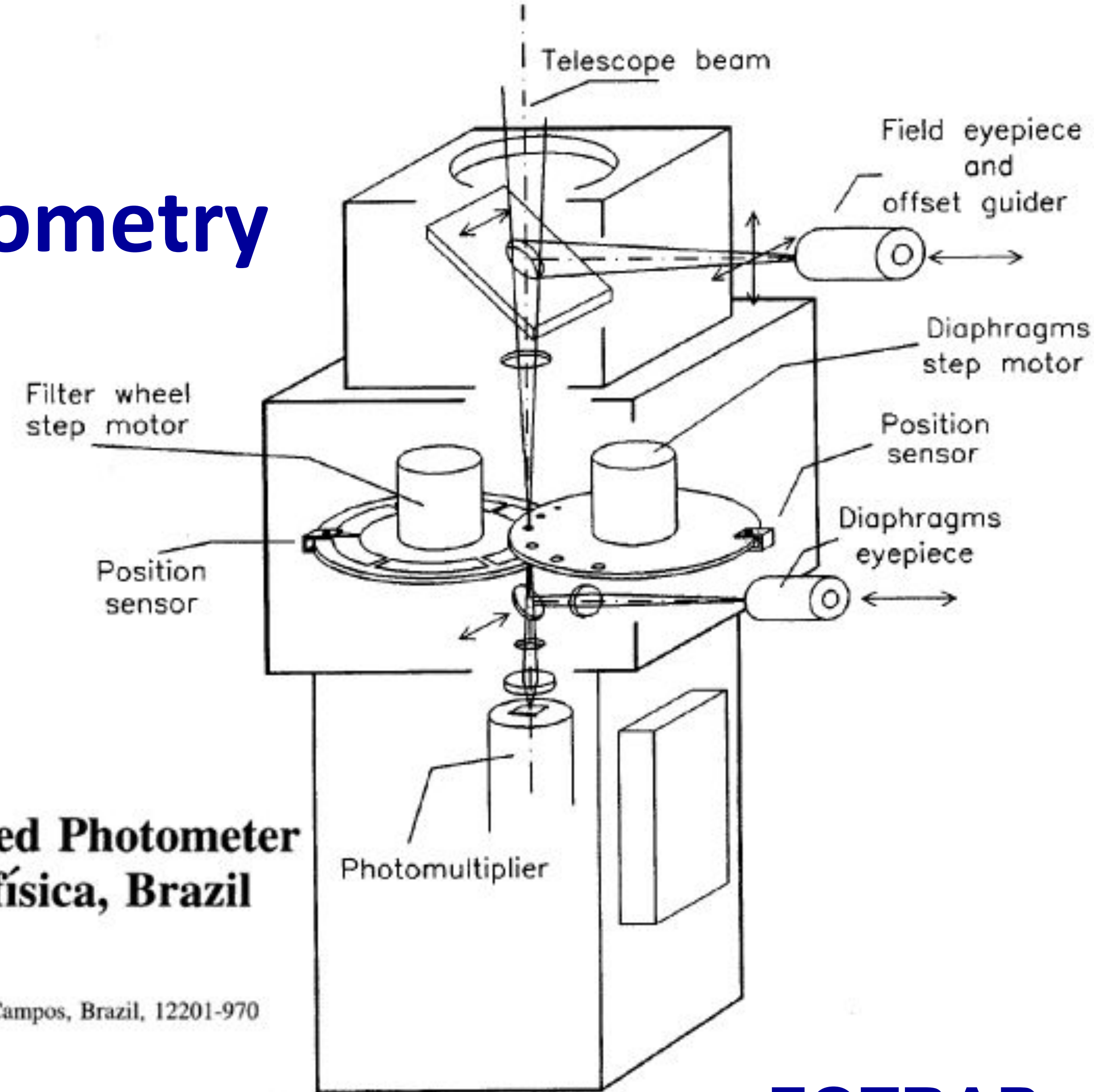




Atualização: 4/10/18

Data reduction

Photoelectric photometry



FOTRAP

Publications of the Astronomical Society of the Pacific
106: 1172–1183, 1994 November

Calibration of the *UBVRI* High-Speed Photometer of Laboratório Nacional de Astrofísica, Brazil

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Data reduction

Photoelectric photometry

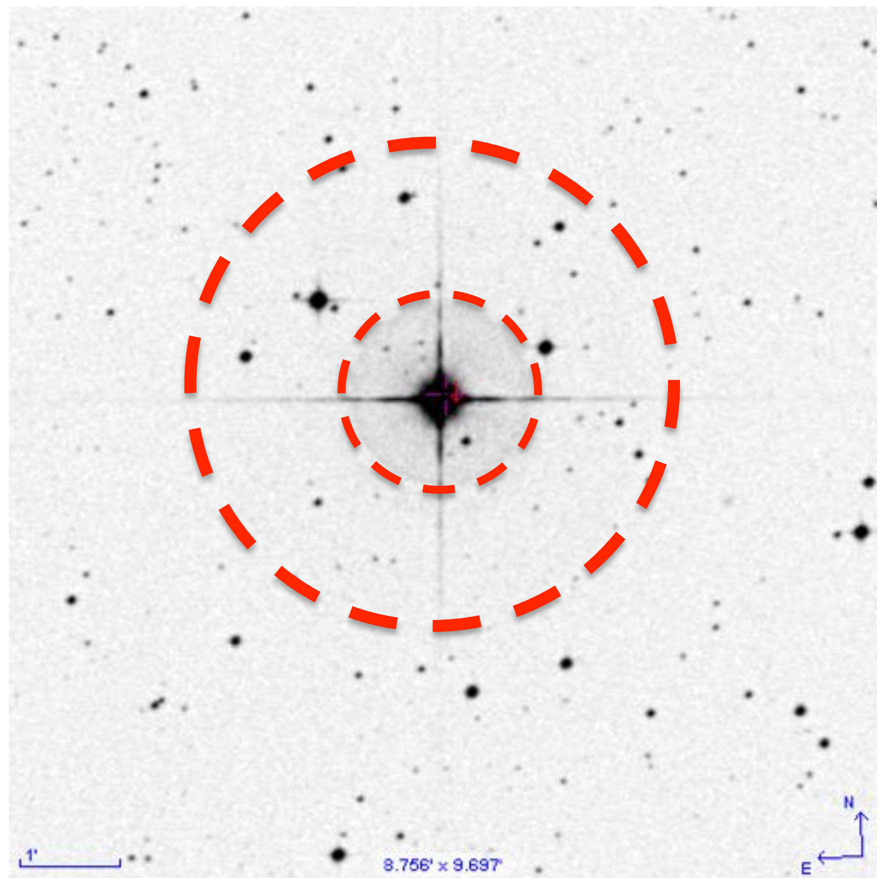
$$\text{Flux} = \text{Count}_{Star+Sky}/s - \text{Count}_{Sky}/s$$

$$m = -2.5 \log F_X$$

$$m_{instrument} = -2.5 \log \text{Flux}$$

TABLE 1
The FOTRAP Diaphragm Set

#	diameter (arcsec) 0.6 m	1.6 m
1	52.2	24.5
2	41.2	19.3
3	33.0	15.5
4	27.7	11.6
5	19.2	9.0
6	16.5	7.7
7	13.7	6.4
8	11.0	5.1
9	164.9	77.3



Data reduction

- $\text{Flux} = \text{Count}_{Star+Sky}/s - \text{Count}_{Sky}/s$
- **$m_{instrument} = -2.5 \log \text{Flux}$**
- **v** $= -2.5 \log \text{Flux}_v$
- **b - v** $= -2.5 \log (\text{Flux}_b / \text{Flux}_v)$
- **u - b** $= -2.5 \log (\text{Flux}_u / \text{Flux}_b)$
- **u,b,v** : instrumental magnitudes to be calibrated (for ex. to the system U, B, V)

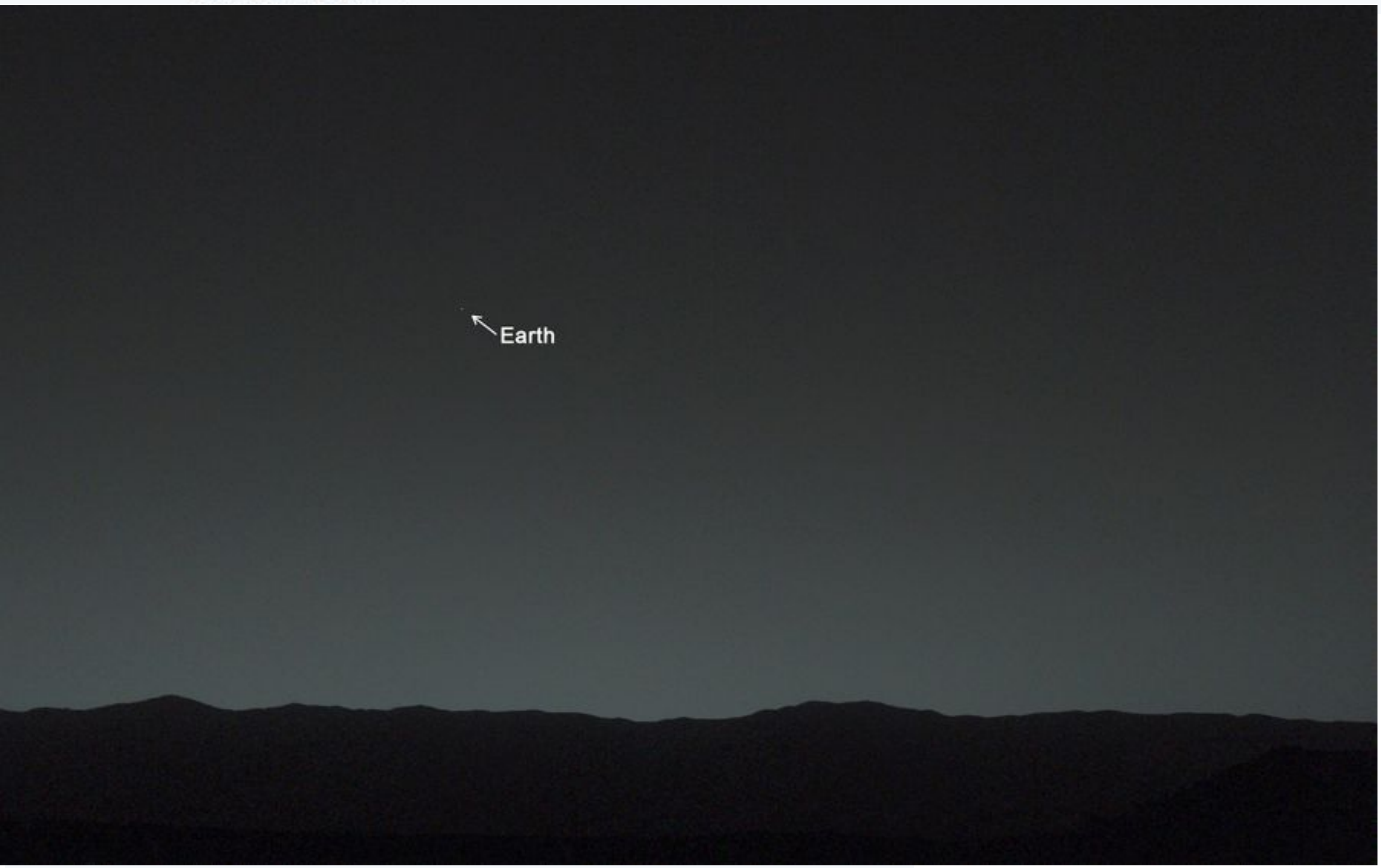
Astronomia USP Brasil @AstroUSP · 28 de mar

A Terra: um **pontinho** no espaço.

Imagem da Terra vista de Marte, tirada pela sonda Curiosity da NASA

The Earth as seen from Mars. Image taken by @MarsCuriosity #NASA

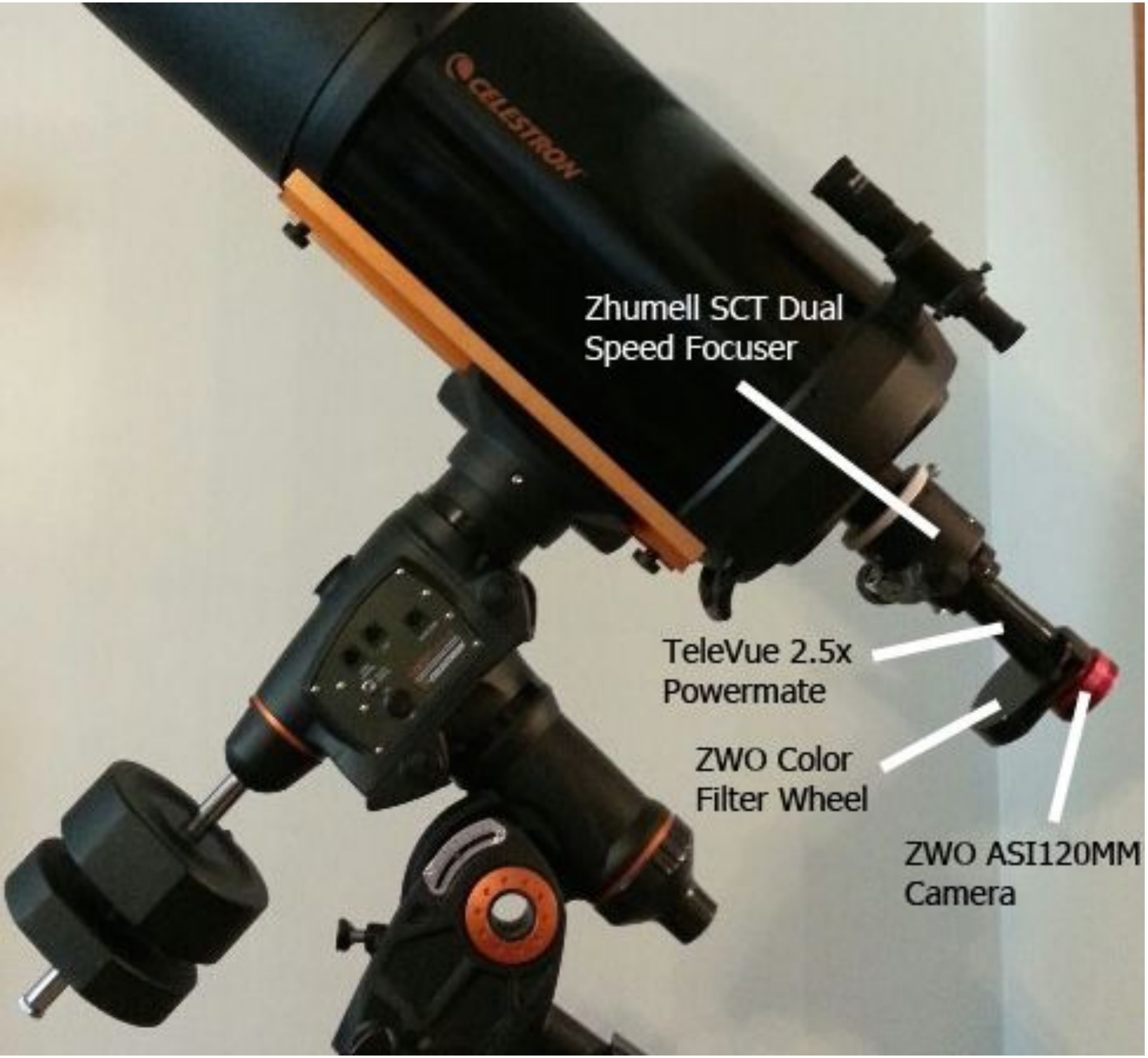
31/01/2014



4 42 108

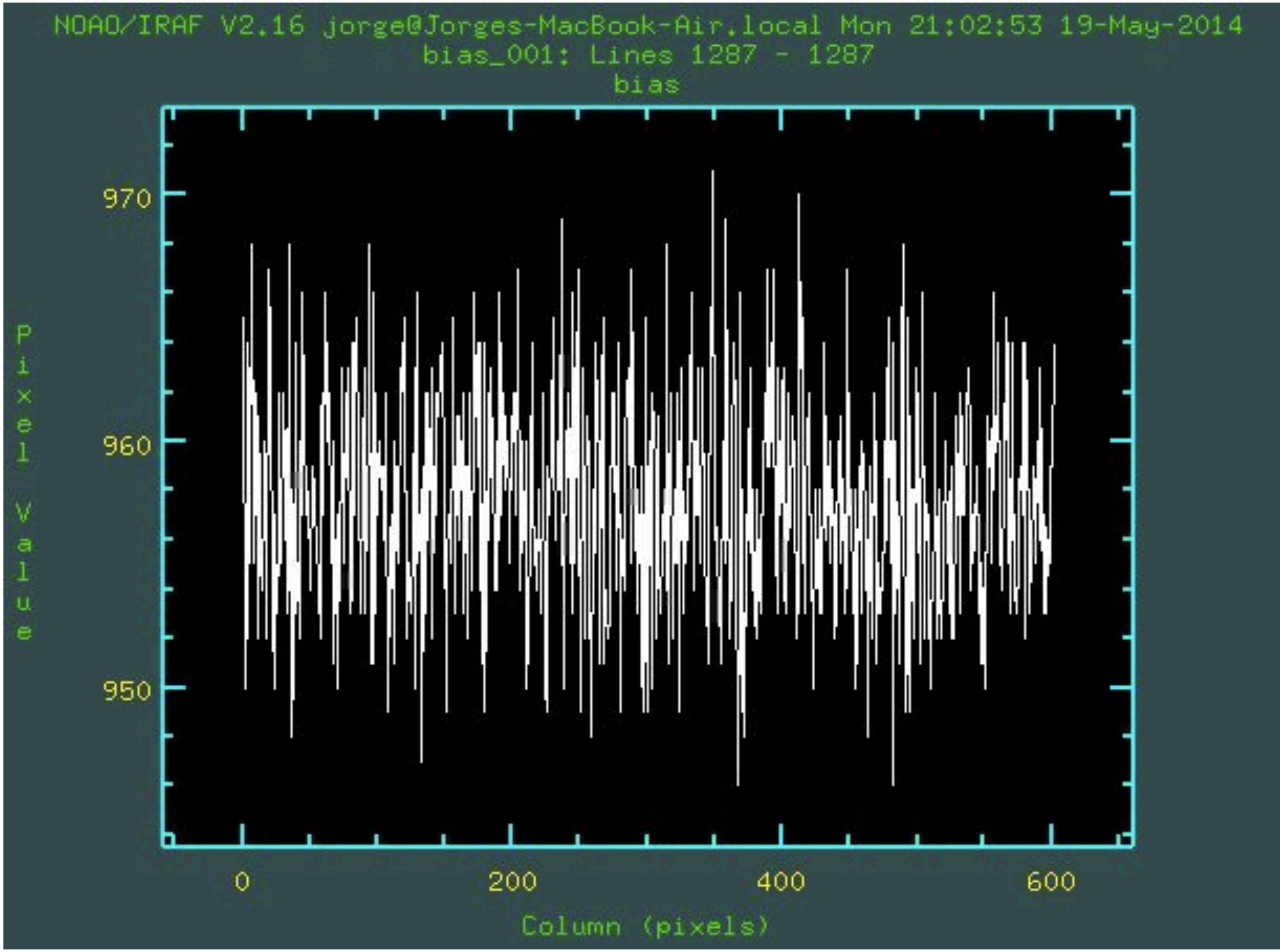
Is it really a "pontinho"?

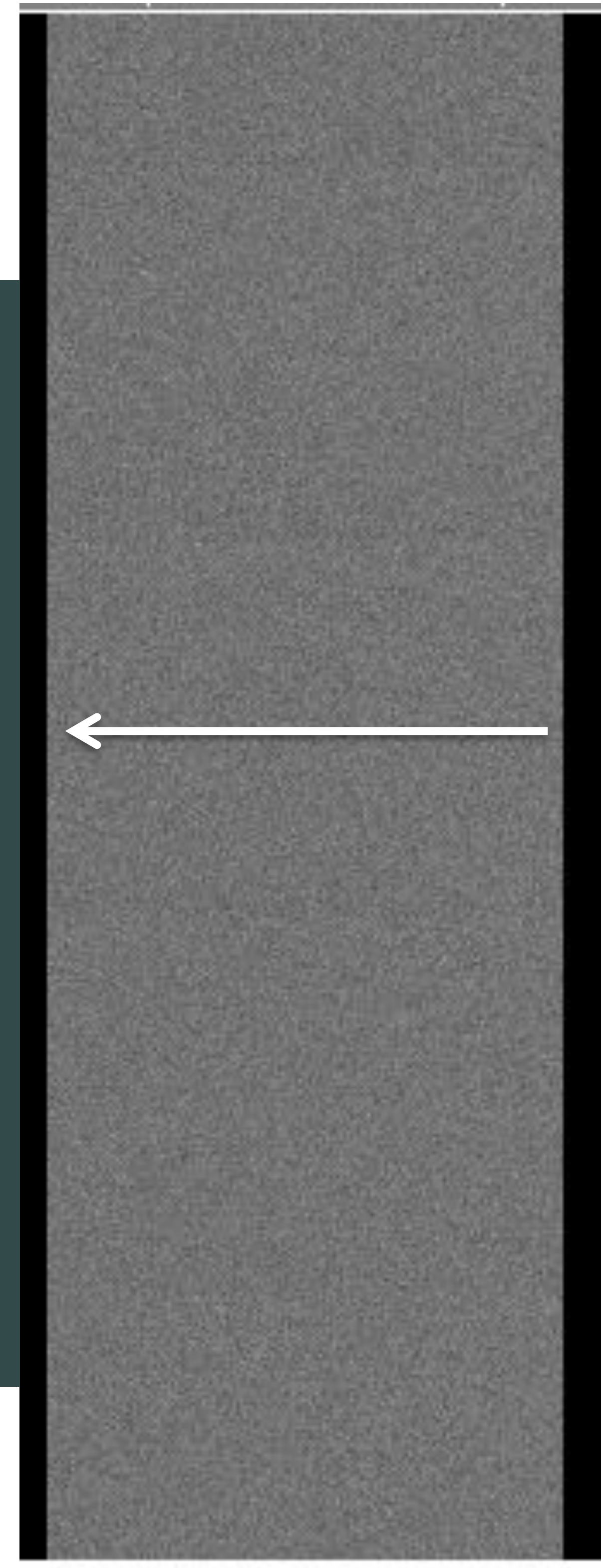
CCD photometry



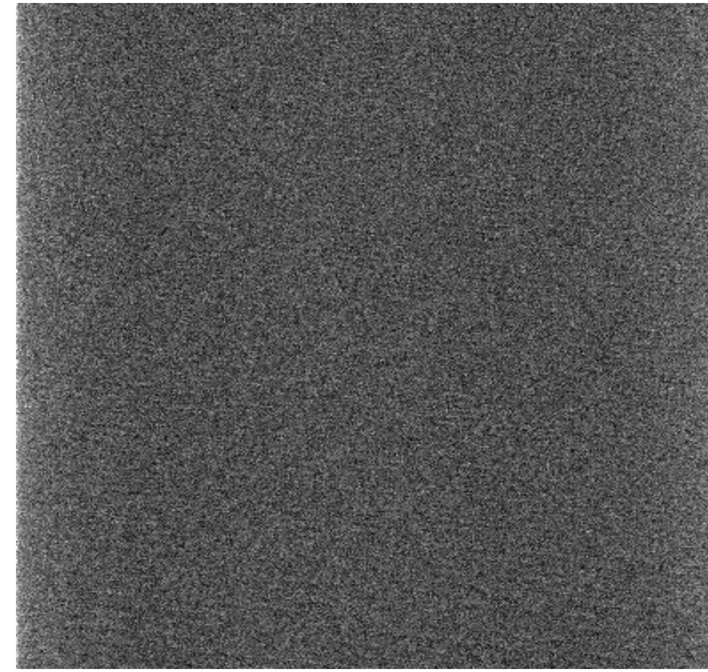
- Advantages?
- Problems?

Bias: zero-point of CCD





CCD data reduction

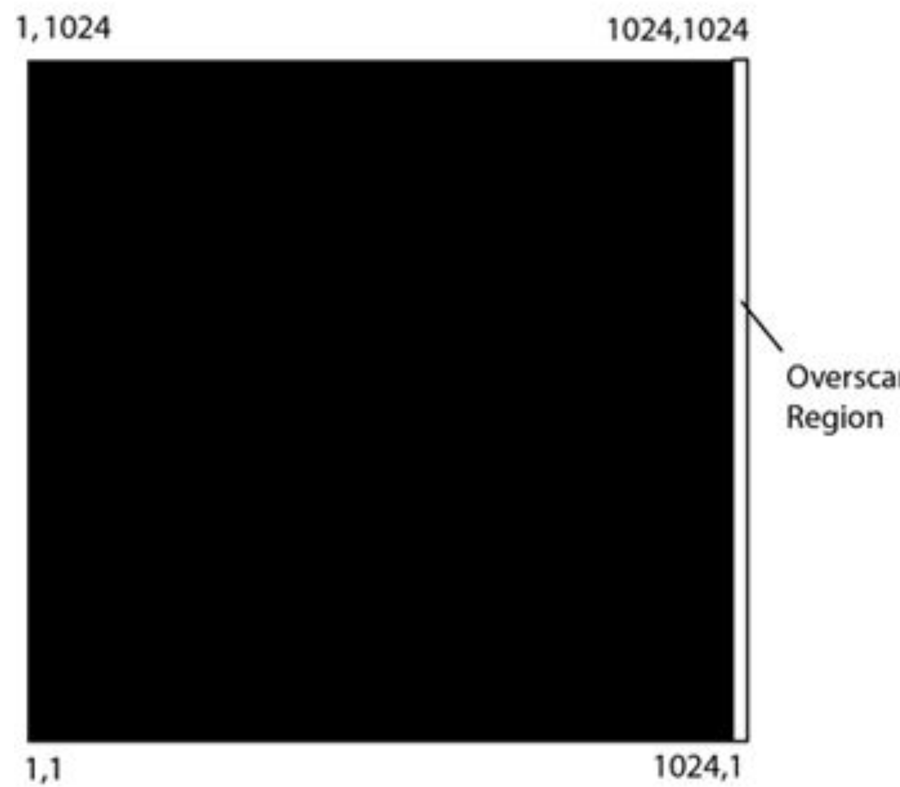


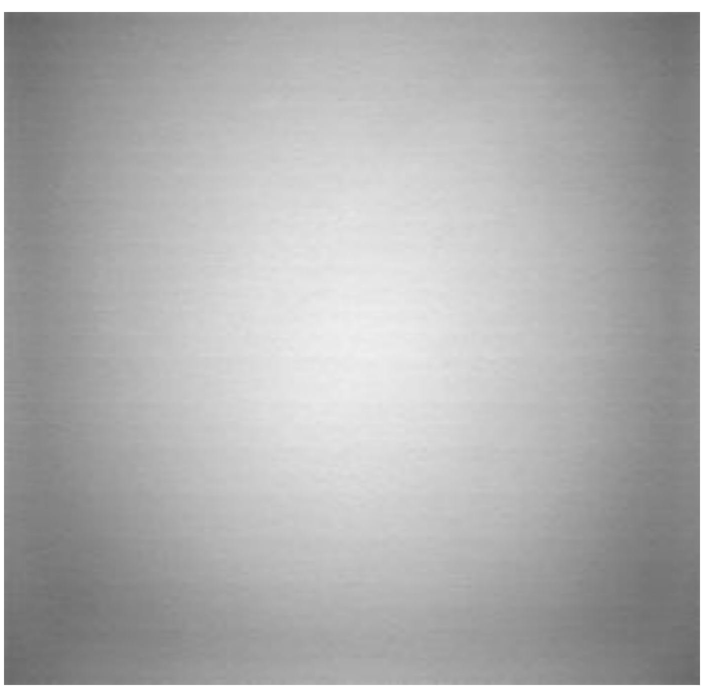
- **Bias** : zero-point level

(for t = 0 exp. time). ***Overscan region*** also indicates bias level.

- **Flat** : pixel-to-pixel variation through optical system

Overscan example for a 1024 x 1024 CCD





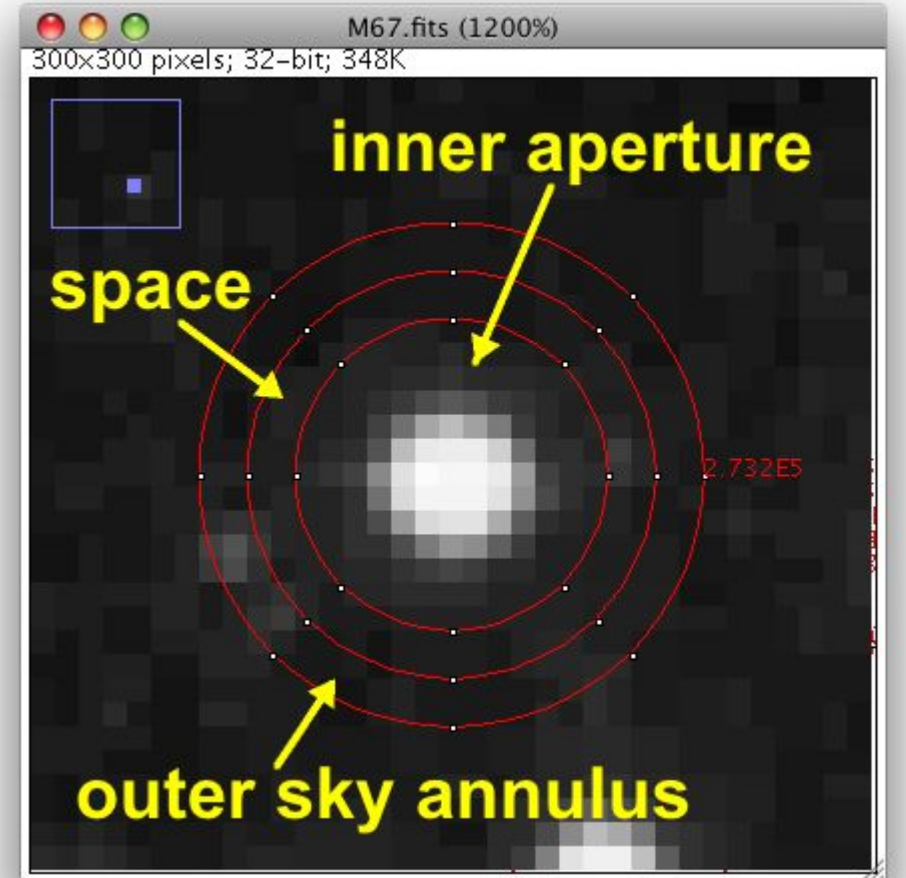
CCD data reduction

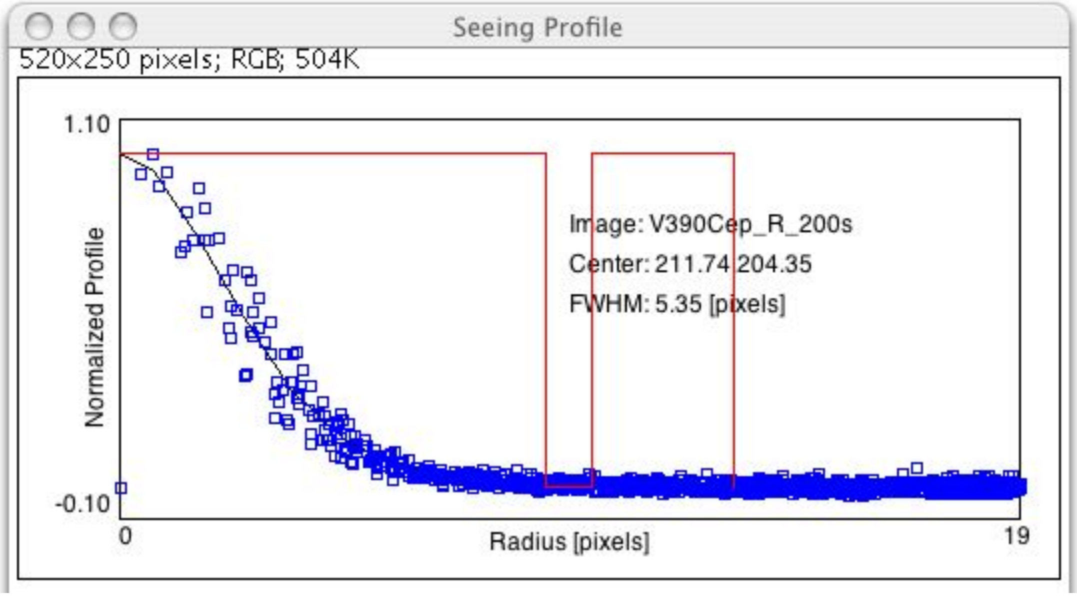
Example of simple processing

- Combine **bias frames** (e.g. median): Bias.fits
- Combine **flat frames** (e.g. median): Flat.fits
- FlatB = Flat - Bias
- FlatN = FlatB / median{FlatB} [flat normalized to ~ 1]
- Reduced_image = [Target_image – Bias] / FlatN

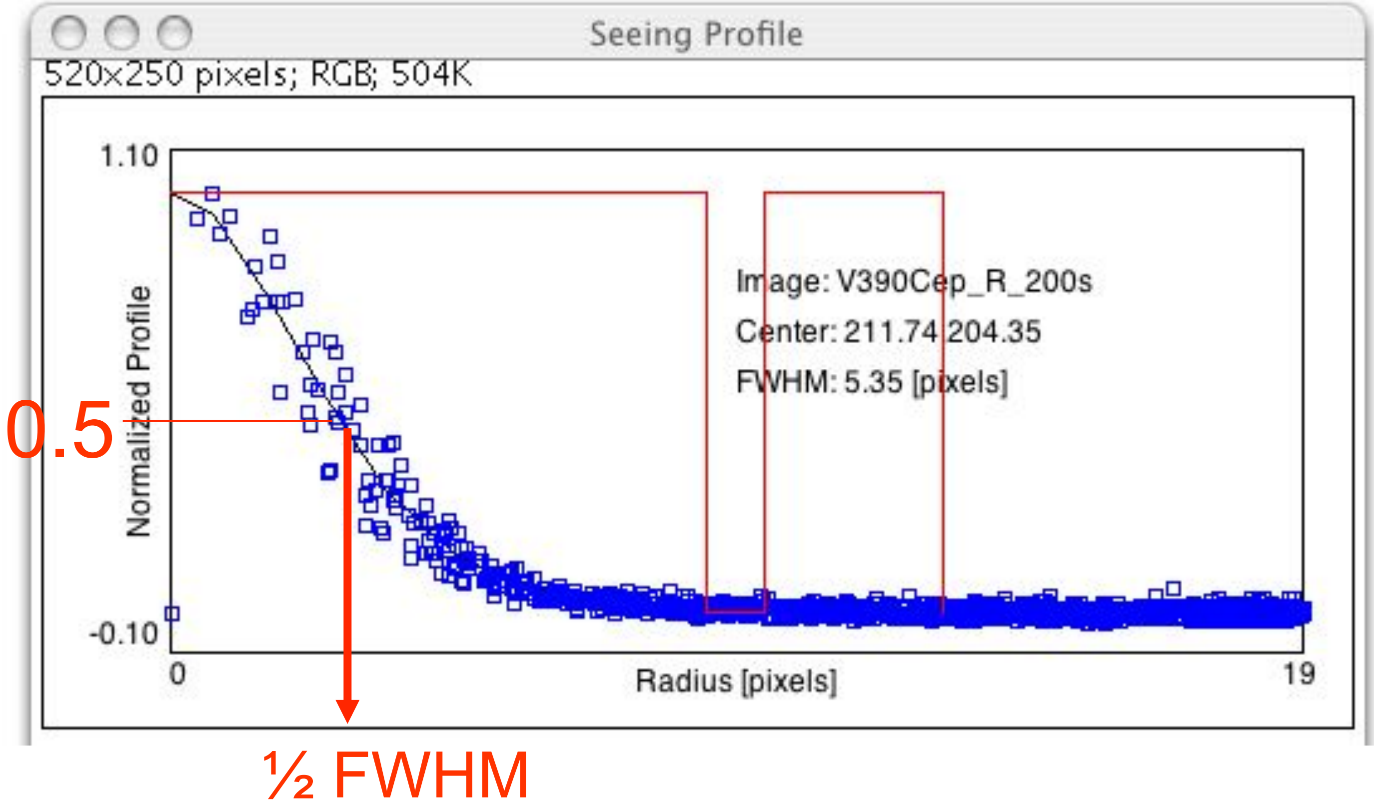
Note: normalizing the flat to 1.0 preserves the counts

Simple measurements: aperture photometry

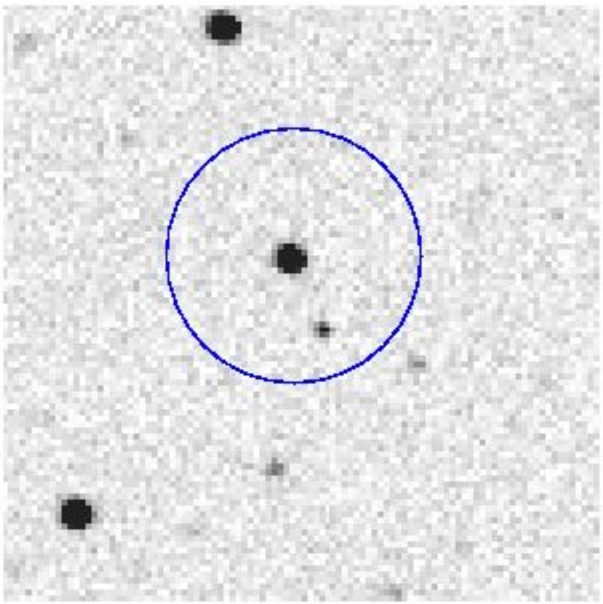
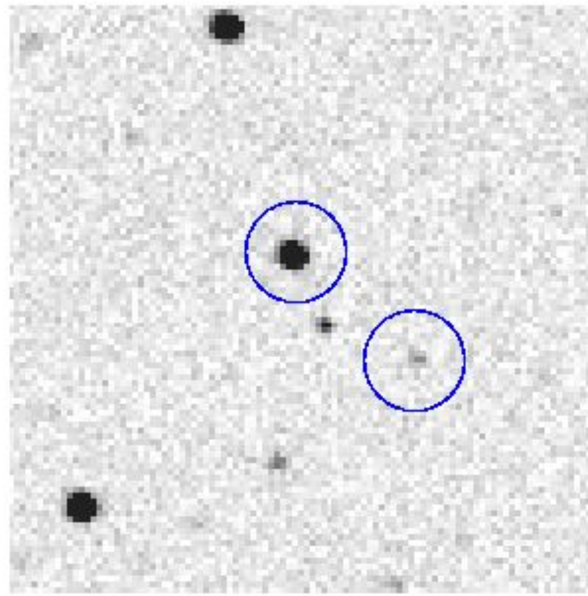
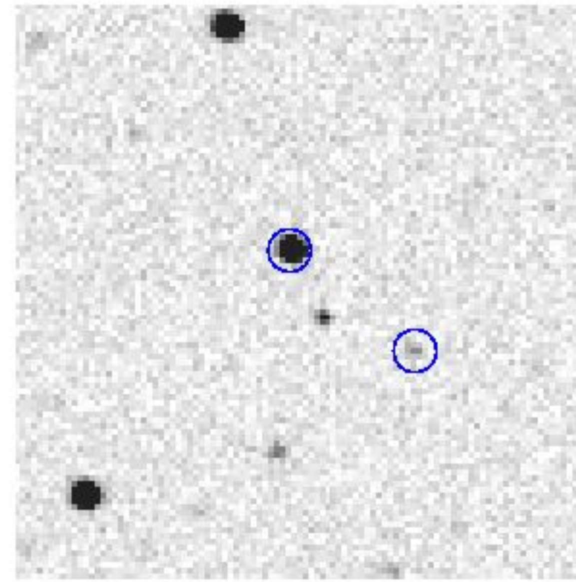


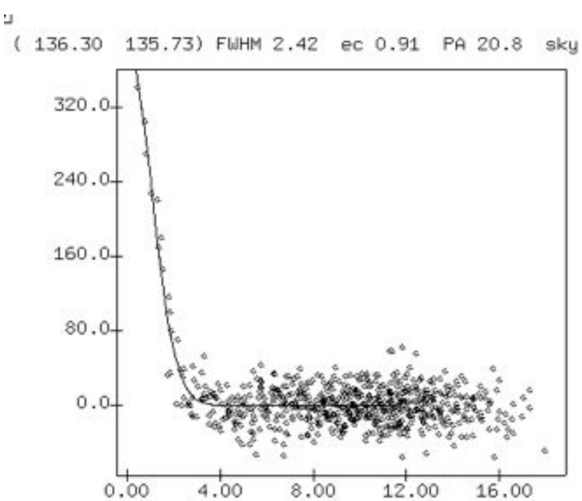


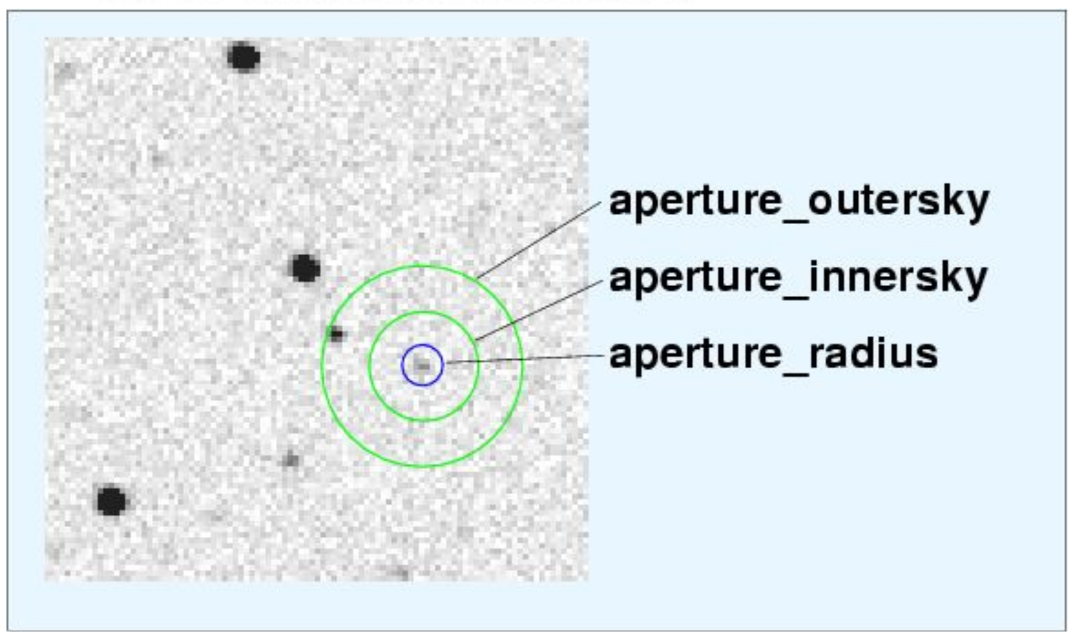
Is important to measure the FWHM of the star's profile (in pixels)



Aperture photometry
do not exaggerate in the size of the aperture!





Sum *inner* 2FWHM

Sky: 5-7 FWHM

In a crowded field, it is better to fit the PSF

Starburst Region NGC 3603 (VLT ANTU + ISAAC)

ESO PR Photo 38a/99 (13 October 1999)

http://panisse.lbl.gov/snphot/lec8_vitaliy_PSF_fit.pdf

From counts to magnitudes (ideal case)

- Linear response of the detector → flux $\propto$ counts
- If F_0 is the flux of an object with m = 0:
- $m = -2.5 \log (F/F_0)$

  $= -2.5 \log (F) + \text{constant}$
- The "constant" is called the zero point (ZP)
- **$m = -2.5 \log (F) + ZP$**

From counts to magnitudes (real case)

- m = -2.5 log (F) + ZP + A*atmosphere_term + B*color_term + C*atmosphere_term*color + ...
- **m = -2.5 log(F) + X**

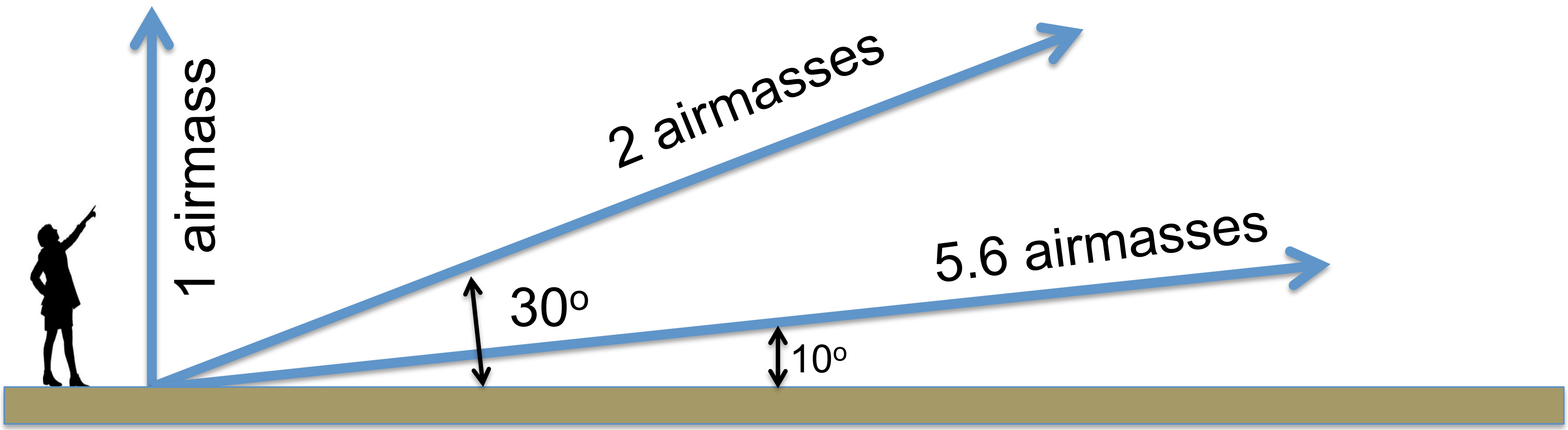
For a good calibration to a photometric system, we need many standard stars covering a range of colors and observed at different airmasses

Atmospheric extinction

airmass = sec z = (senϕ senδ + cosϕ cosδ cosH)$^{-1}$

H = ST - α

1 airmass = mass of air *overhead* (zenith)



Extinction coefficient ***k***: magnitudes/airmass

Example, *k* = 0,16 mag/airmass & m_{obs}(zenith) = 10,06

→ star outside the atmosphere: m_0 = 10,06 - 0,16 = 9,90

Bouguer's law: $m_z = m_0 + k \sec z$

m_0 : outside the atmosphere

m_z : *magnitude at zenithal distance z*

k : extinction coefficient

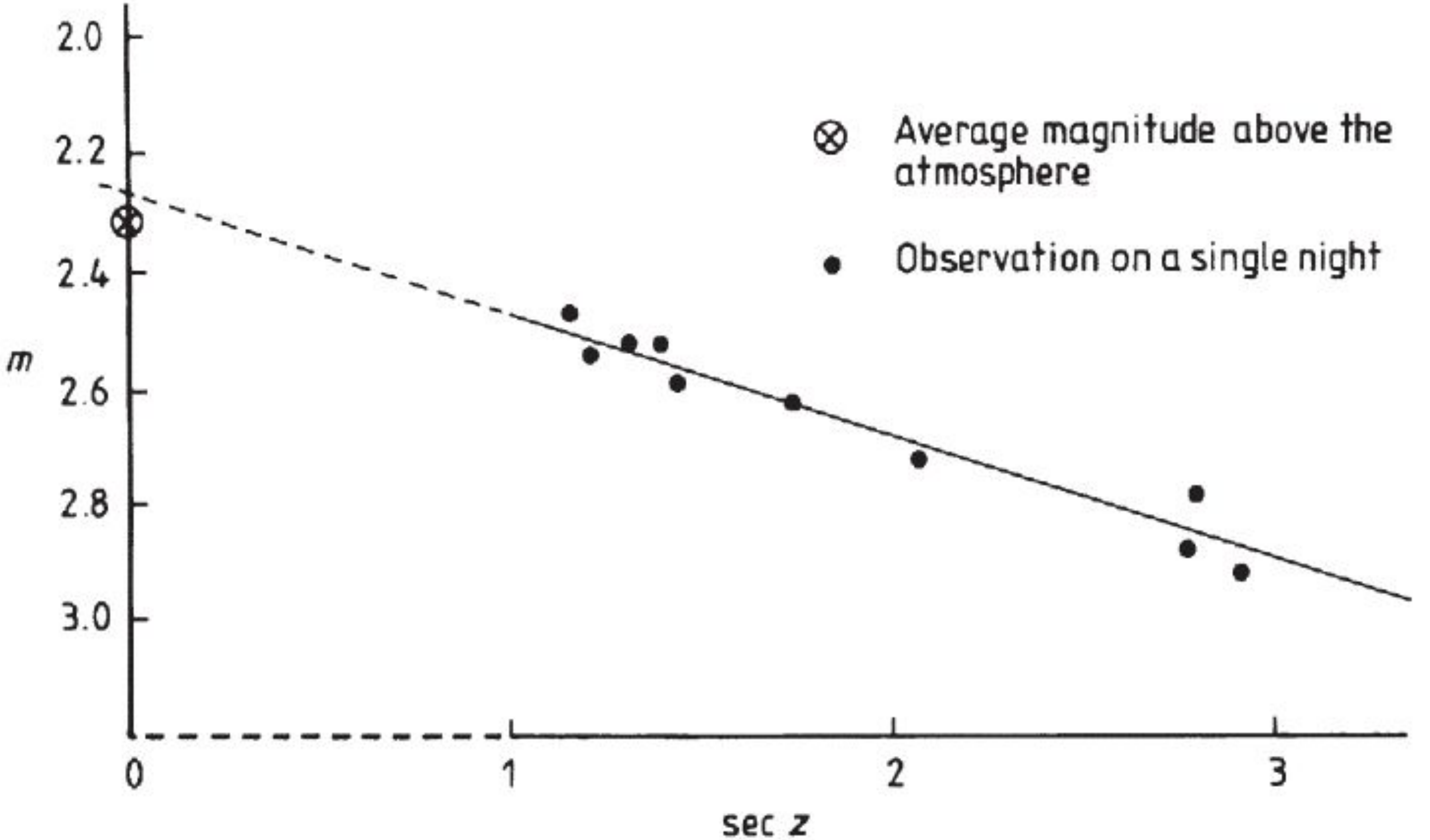


Figure 3.2.5. Schematic variation in magnitude of a standard star with zenith distance

Example of extinction k at OPD

$$m_z = m_0 + k \sec z$$

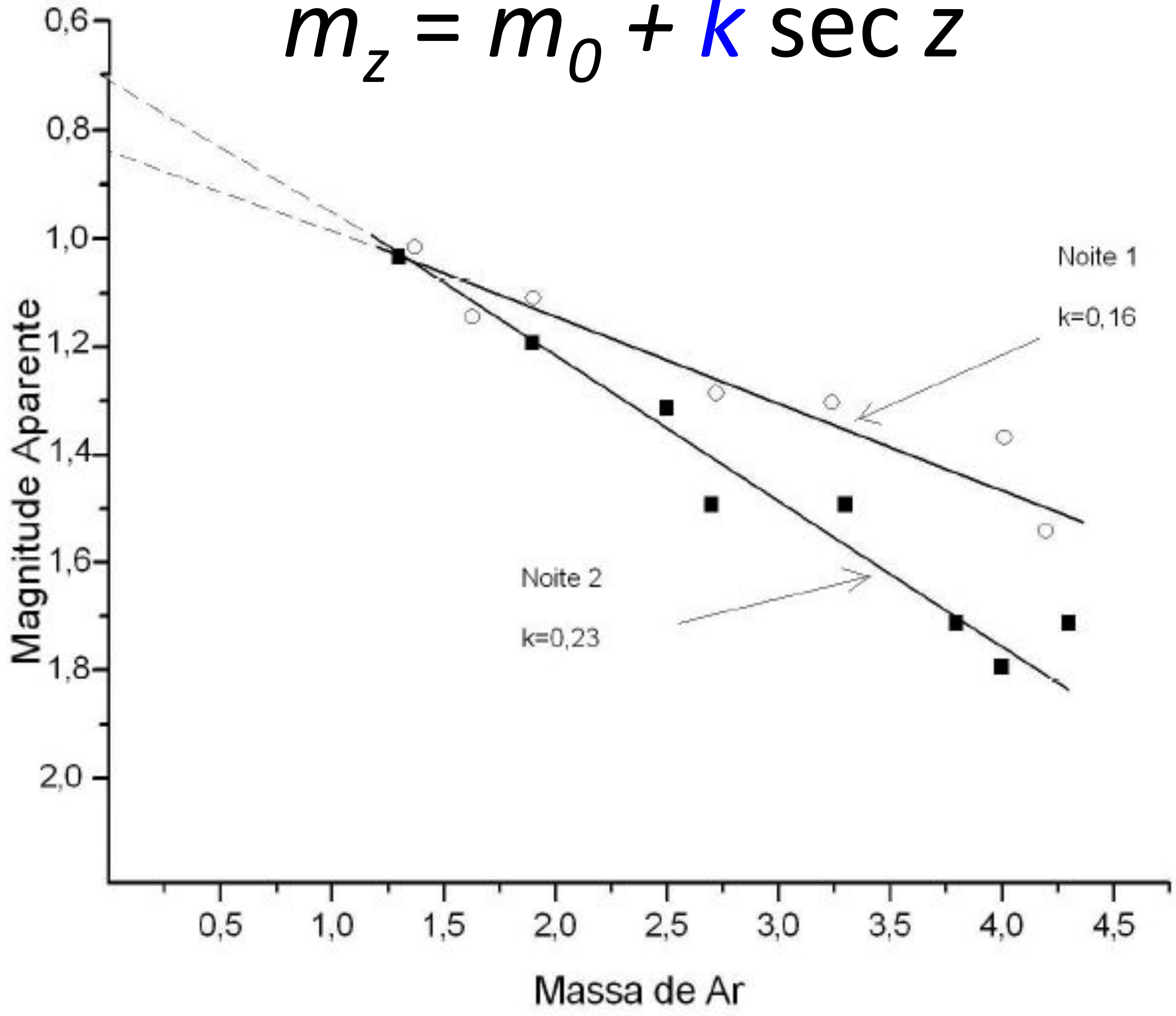
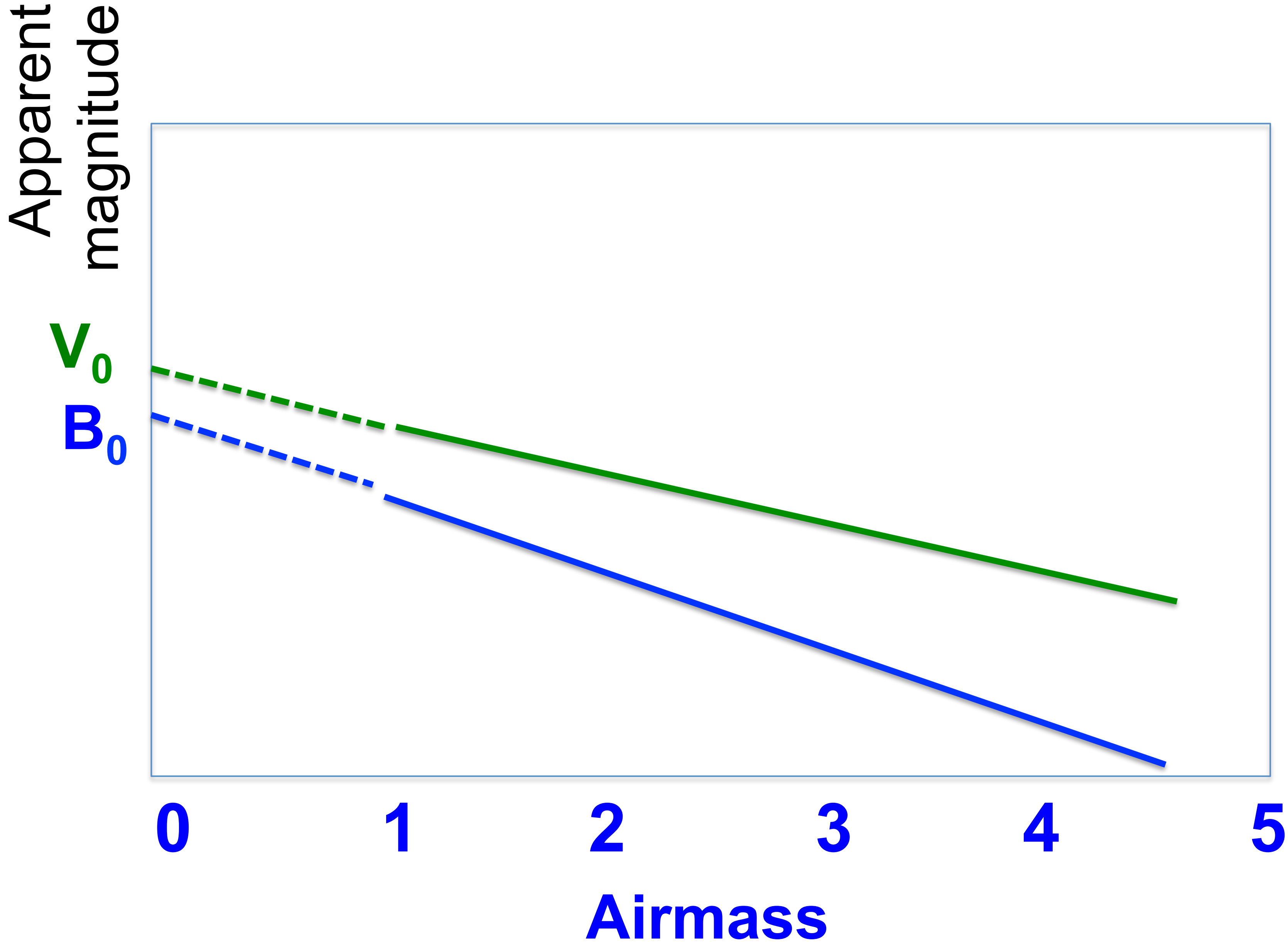


Gráfico 1 - Exemplo de curva de extinção
Fonte: Elaboração própria.

Atmospheric extinction: *Wavelength dependence*



Atmospheric extinction: *Wavelength dependence*

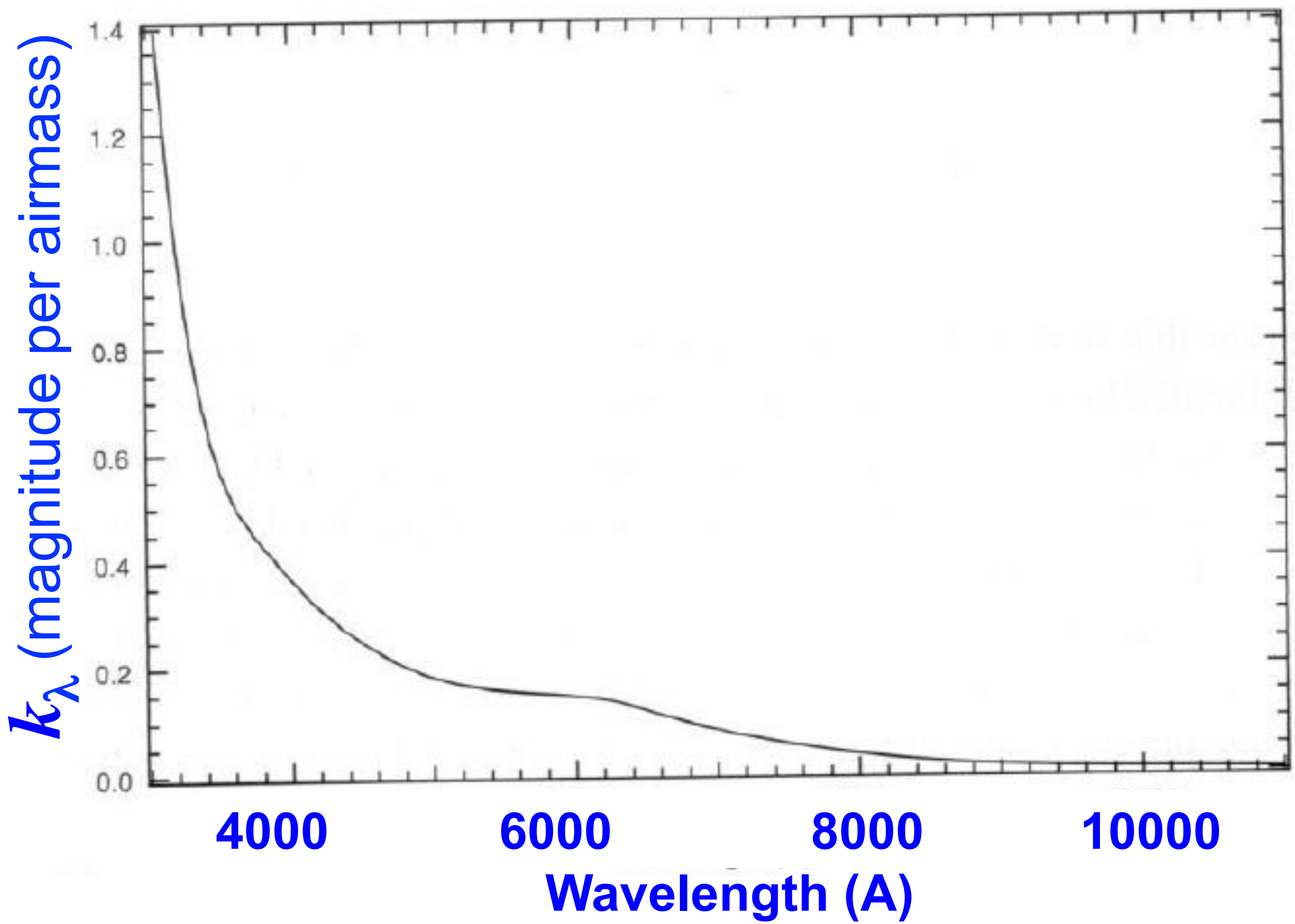


Figure 7.5. Variation of extinction with wavelength. The data are from the Cerro Tololo Interamerican Observatory in Chile (see Stritziger *et al.*, 2005).

Atmospheric extinction

Dependence with Wavelength

Atmospheric extinction at the OPD observatory

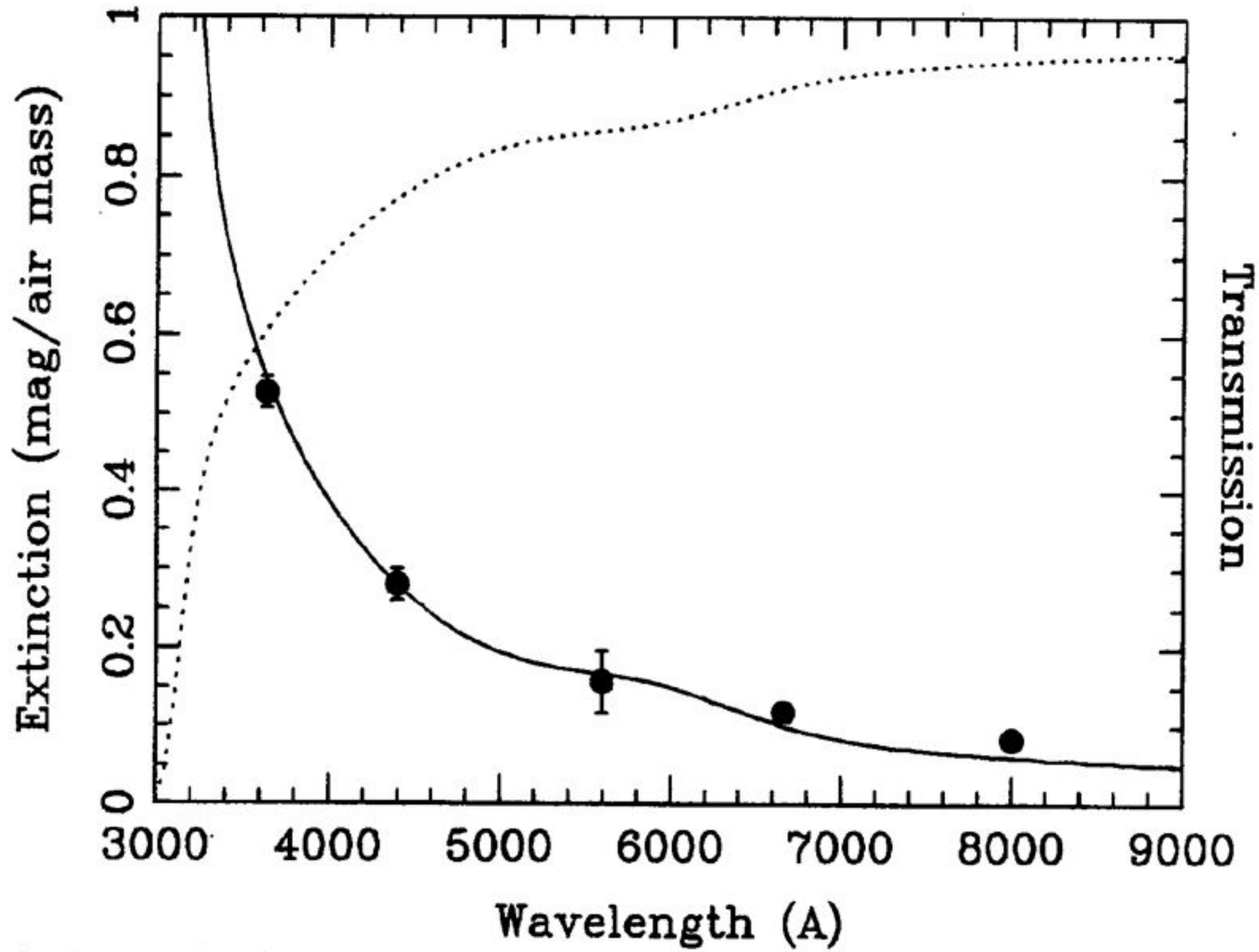


FIG. 5—The atmospheric extinction in the *UBVRI* bands as measured with FOTRAP at LNA (1864 m above sea level). The continuous curve is the semiempirical model of Bessell (1990) and Hayes and Latham (1975) for the extinction. The dotted line is the corresponding transmission. This curve is used to obtain the *UX* and *BX* passbands of Table 3 and Fig. 3.

Atmospheric extinction

Second-order extinction (color term)

$$k_{\mathrm{V}} = k'_{\mathrm{V}} + k''_{\mathrm{V,BV}} \cdot (B - V)$$

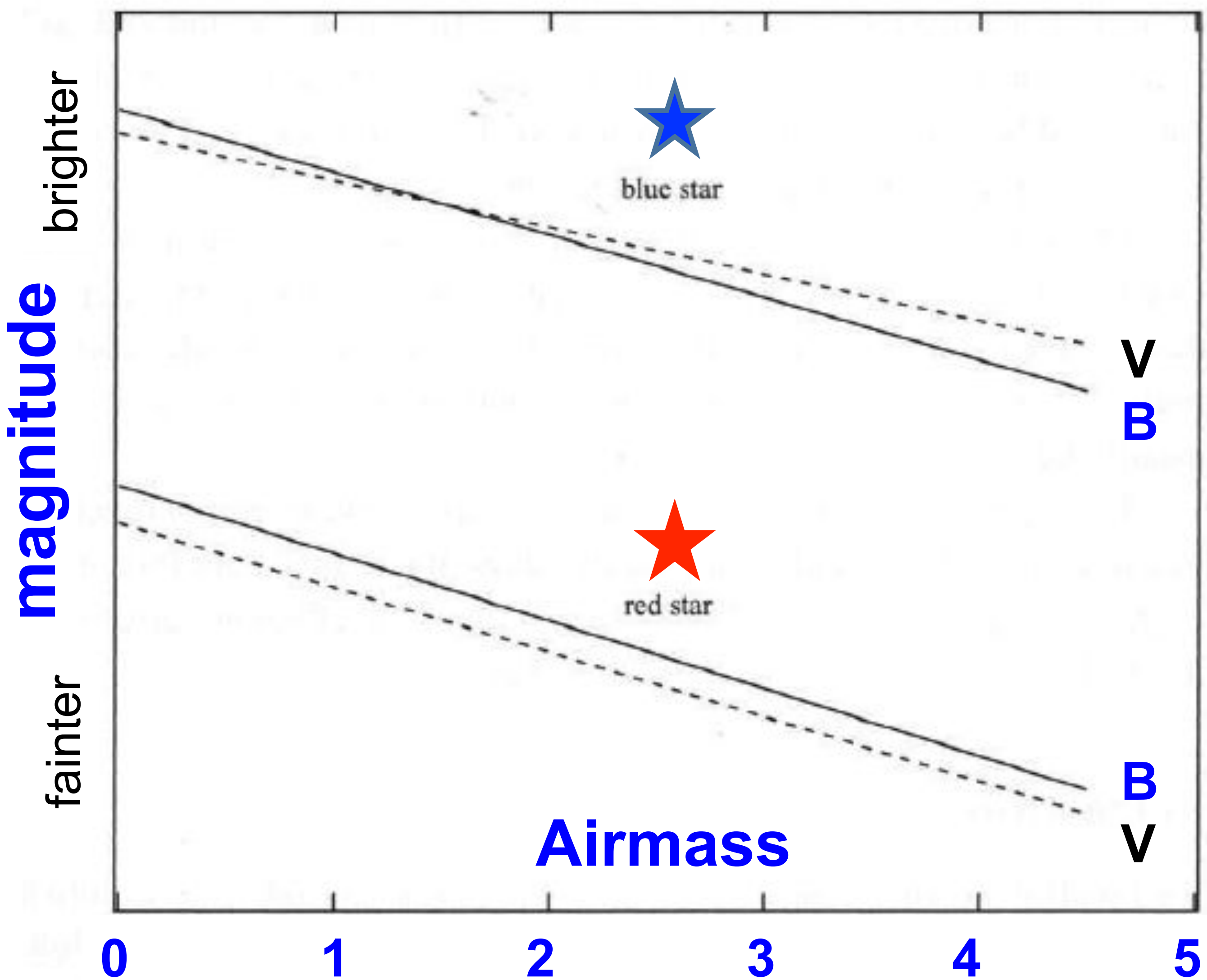


Figure 7.6. The extinction coefficient depends on the color of the star. The solid lines are for blue magnitudes and the dashed lines are for visual magnitudes.

$$F = \frac{\int_0^\infty f(\lambda) s(\lambda) d\lambda}{\int_0^\infty s(\lambda) d\lambda}$$

Correcting for atmospheric extinction

Once we determine the extinction coefficient k, we can obtain the magnitudes:

$$m_0 = m_z - k \sec z$$

$$m_0 = m_z - k \text{ airmass}$$

z: zenithal distance

m_z: magnitude observed at zenithal distance z

m_0: magnitude outside Earth's atmosphere

After the instrumental magnitudes have been corrected for atmospheric extinction …

Conversion to an standard system

Observed instrumental *magnitudes of standards:* $\boldsymbol{b_0}$, $\boldsymbol{v_0}$, $\boldsymbol{r_0}$, $\boldsymbol{i_0}$

Magnitudes of standard stars in the $BV(RI)_C$ system: ***B , V , R , I***

Most simple transforming relations:

The transformation coefficients are obtained by relating the standard and extinction-corrected magnitudes as follows

$$B - V = \phi_{bv} + \mu_{bv}(b - v)_0$$

$$V = v_0 + \phi_v + \varepsilon(B - V)$$

$$V - R = \phi_{vr} + \mu_{vr}(v - r)_0$$

$$R - I = \phi_{ri} + \mu_{ri}(r - i)_0$$

Transformation coefficients

Standard stars (e.g. Landolt)

Table 10.1. *Landolt Standard Area 110 standard and instrumental magnitudes*

Star	V	B – V	V – R	R – I	v_0	$(b-v)_0$	$(v-r)_0$	$(r-i)_0$
496	13.004	1.040	0.607	0.681	−8.830	1.815	0.772	0.288
499	11.737	0.987	0.600	0.674	−10.097	1.695	0.792	0.121
502	12.330	2.326	1.373	1.250	−9.589	3.030	1.512	0.799
503	11.773	0.671	0.373	0.436	−10.044	1.375	0.537	−0.003
504	14.022	1.248	0.797	0.683	−7.848	2.070	0.928	0.225
506	11.312	0.568	0.335	0.312	−10.506	1.247	0.489	−0.135
507	12.440	1.141	0.633	0.579	−9.391	1.839	0.781	0.120

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doi:10.1088/0004-6256/137

UBVRI PHOTOMETRIC STANDARD STARS AROUND THE CELESTIAL EQUATOR: UPDATES AND ADDITIONS

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Received 2008 November 10; accepted 2008 December 24; published 2009 April 2

ABSTRACT

New broadband *UBVRI* photoelectric observations on the Johnson–Kron–Cousins photometric system have been made of 202 stars around the sky, and centered at the celestial equator. These stars constitute both an update of and additions to a previously published list of equatorial photometric standard stars. The list is capable of providing, for both celestial hemispheres, an internally consistent homogeneous broadband standard photometric system around the sky. When these new measurements are included with those previously published by Landolt (1992), the entire list of standard stars in this paper encompasses the magnitude range $8.90 < V < 16.30$, and the color index range $-0.35 < (B - V) < +2.30$.

Table 2
UBVRI Photometry of Standard Stars

											Mean Error of the Mean					
Star (1)	α (J2000.0) (2)	δ (J2000.0) (3)	V (4)	$B-V$ (5)	$U-B$ (6)	$V-R$ (7)	$R-I$ (8)	$V-I$ (9)	n (10)	m (11)	V (12)	$B-V$ (13)	$U-B$ (14)	$V-R$ (15)	$R-I$ (16)	$V-I$ (17)
TPhe I	00 30 04.593	−46 28 10.17	14.820	+0.764	+0.338	+0.422	+0.395	+0.817	25	13	0.0026	0.0032	0.0072	0.0036	0.0098	0.0110
TPhe A	00 30 09.594	−46 31 28.91	14.651	+0.793	+0.380	+0.435	+0.405	+0.841	29	12	0.0028	0.0046	0.0071	0.0019	0.0035	0.0032
TPhe H	00 30 09.683	−46 27 24.30	14.942	+0.740	+0.225	+0.425	+0.425	+0.851	23	12	0.0029	0.0029	0.0071	0.0035	0.0077	0.0098
TPhe B	00 30 16.313	−46 27 58.57	12.334	+0.405	+0.156	+0.262	+0.271	+0.535	29	17	0.0115	0.0026	0.0039	0.0020	0.0019	0.0035
TPhe C	00 30 16.98	−46 32 21.4	14.376	−0.298	−1.217	−0.148	−0.211	−0.360	39	23	0.0022	0.0024	0.0043	0.0038	0.0133	0.0149
TPhe D	00 30 18.342	−46 31 19.85	13.118	+1.551	+1.871	+0.849	+0.810	+1.663	37	23	0.0033	0.0030	0.0118	0.0015	0.0023	0.0030
TPhe E	00 30 19.768	−46 24 35.60	11.631	+0.443	−0.103	+0.276	+0.283	+0.564	38	10	0.0017	0.0013	0.0025	0.0007	0.0016	0.0020
TPhe J	00 30 23.02	−46 23 51.6	13.434	+1.465	+1.229	+0.980	+1.063	+2.043	28	15	0.0023	0.0043	0.0059	0.0011	0.0015	0.0011
TPhe F	00 30 49.820	−46 33 24.07	12.475	+0.853	+0.534	+0.492	+0.437	+0.929	19	10	0.0008	0.0024	0.0095	0.0005	0.0014	0.0029
TPhe K	00 30 56.315	−46 23 26.04	12.935	+0.806	+0.402	+0.473	+0.429	+0.909	2	2	0.0007	0.0007	0.0163	0.0007	0.0001	0.0007

Photometric standards of Landolt in field around the Mira variable **T Phe**

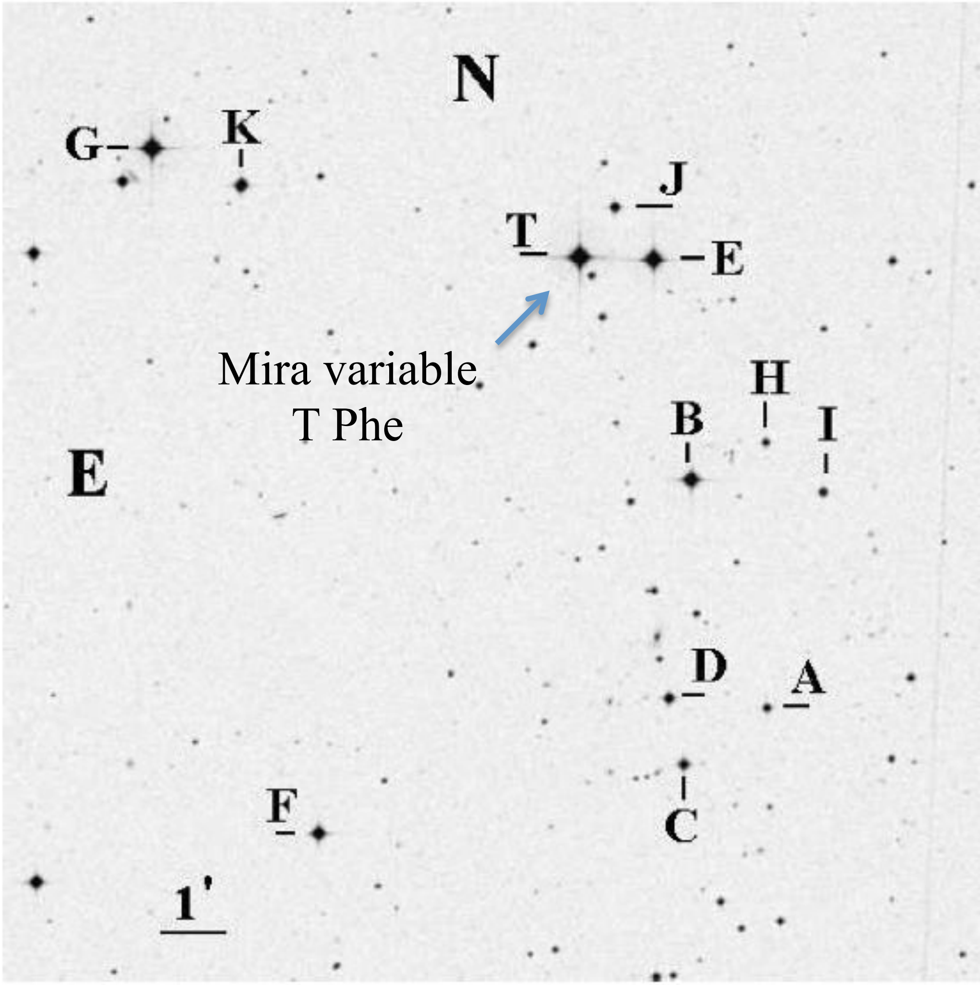


Figure 1. Field, 15′ on a side, of the sequence in the vicinity of the Mira variable star T Phe, marked as "T" in the figure.

Table 2
UBVRI Photometry of Standard Stars

Star (1)	α (J2000.0) (2)	δ (J2000.0) (3)	*V* (4)	*B−V* (5)	*U−B* (6)	*V−R* (7)	*R−I* (8)	*V−I* (9)	*n* (10)	*m* (11)	Mean Error of the Mean: *V* (12)	*B−V* (13)	*U−B* (14)	*V−R* (15)	*R−I* (16)	*V−I* (17)
TPhe I	00 30 04.593	−46 28 10.17	14.820	+0.764	+0.338	+0.422	+0.395	+0.817	25	13	0.0026	0.0032	0.0072	0.0036	0.0098	0.0110
TPhe A	00 30 09.594	−46 31 28.91	14.651	+0.793	+0.380	+0.435	+0.405	+0.841	29	12	0.0028	0.0046	0.0071	0.0019	0.0035	0.0032
TPhe H	00 30 09.683	−46 27 24.30	14.942	+0.740	+0.225	+0.425	+0.425	+0.851	23	12	0.0029	0.0029	0.0071	0.0035	0.0077	0.0098
TPhe B	00 30 16.313	−46 27 58.57	12.334	+0.405	+0.156	+0.262	+0.271	+0.535	29	17	0.0115	0.0026	0.0039	0.0020	0.0019	0.0035
TPhe C	00 30 16.98	−46 32 21.4	14.376	−0.298	−1.217	−0.148	−0.211	−0.360	39	23	0.0022	0.0024	0.0043	0.0038	0.0133	0.0149
TPhe D	00 30 18.342	−46 31 19.85	13.118	+1.551	+1.871	+0.849	+0.810	+1.663	37	23	0.0033	0.0030	0.0118	0.0015	0.0023	0.0030
TPhe E	00 30 19.768	−46 24 35.60	11.631	+0.443	−0.103	+0.276	+0.283	+0.564	38	10	0.0017	0.0013	0.0025	0.0007	0.0016	0.0020
TPhe J	00 30 23.02	−46 23 51.6	13.434	+1.465	+1.229	+0.980	+1.063	+2.043	28	15	0.0023	0.0043	0.0059	0.0011	0.0015	0.0011
TPhe F	00 30 49.820	−46 33 24.07	12.475	+0.853	+0.534	+0.492	+0.437	+0.929	19	10	0.0008	0.0024	0.0095	0.0005	0.0014	0.0029
TPhe K	00 30 56.315	−46 23 26.04	12.935	+0.806	+0.402	+0.473	+0.429	+0.909	2	2	0.0007	0.0007	0.0163	0.0007	0.0001	0.0007

Conversion to a standard system

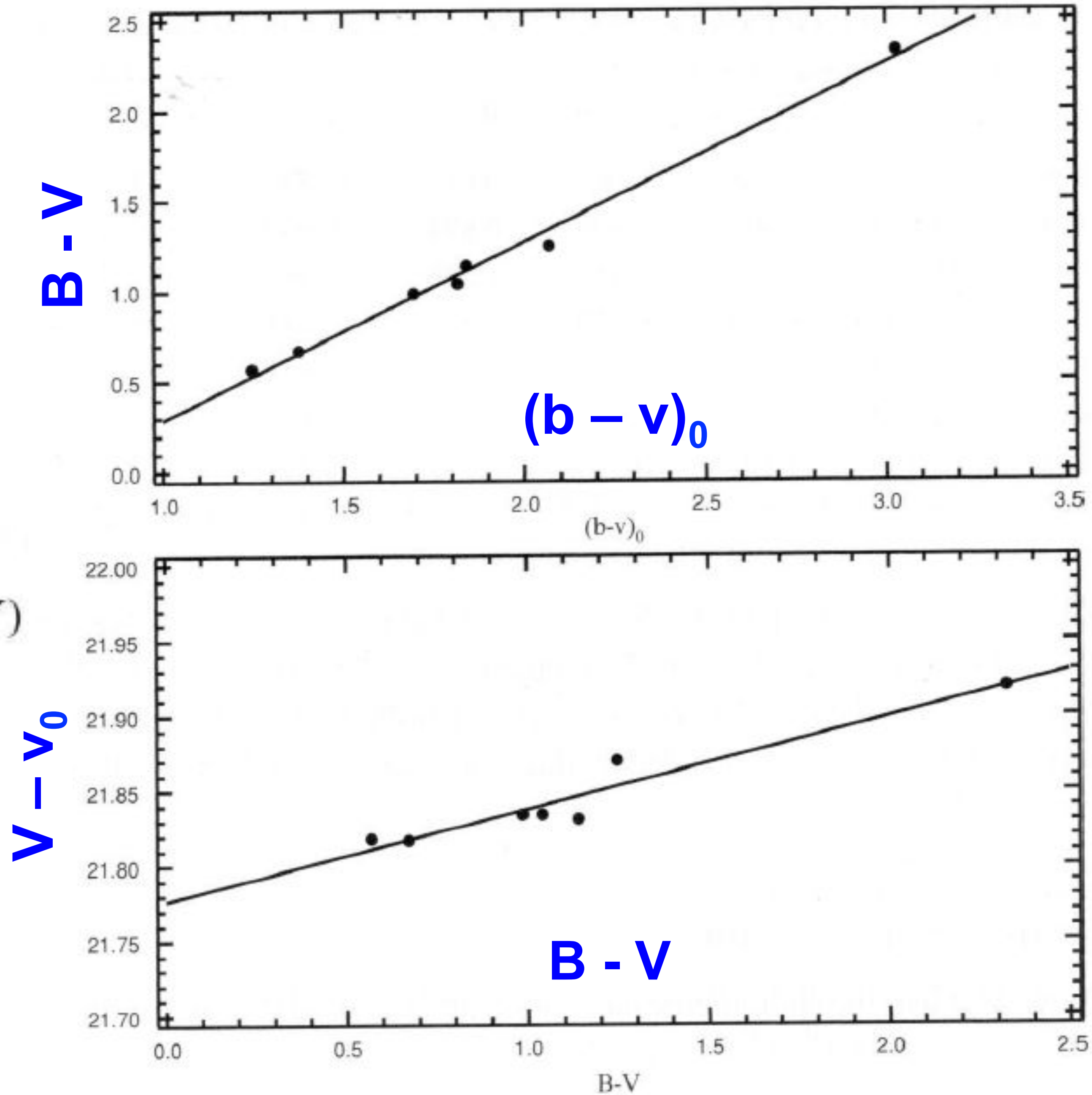
Figure 10.3. Transformation coefficient examples. Top: standard B–V magnitudes are plotted against instrumental magnitudes. Bottom: difference between standard and instrumental visual magnitudes are plotted against B–V. The data are from Table 10.1. The straight lines are least-squares fits to the data.

$$B - V = \phi_{bv} + \mu_{bv}(b - v)_0$$

$$V = v_0 + \phi_v + \varepsilon(B - V)$$

$$V - R = \phi_{vr} + \mu_{vr}(v - r)_0$$

$$R - I = \phi_{ri} + \mu_{ri}(r - i)_0$$



Another option: simultaneously solve for extinction and transformation coefficients

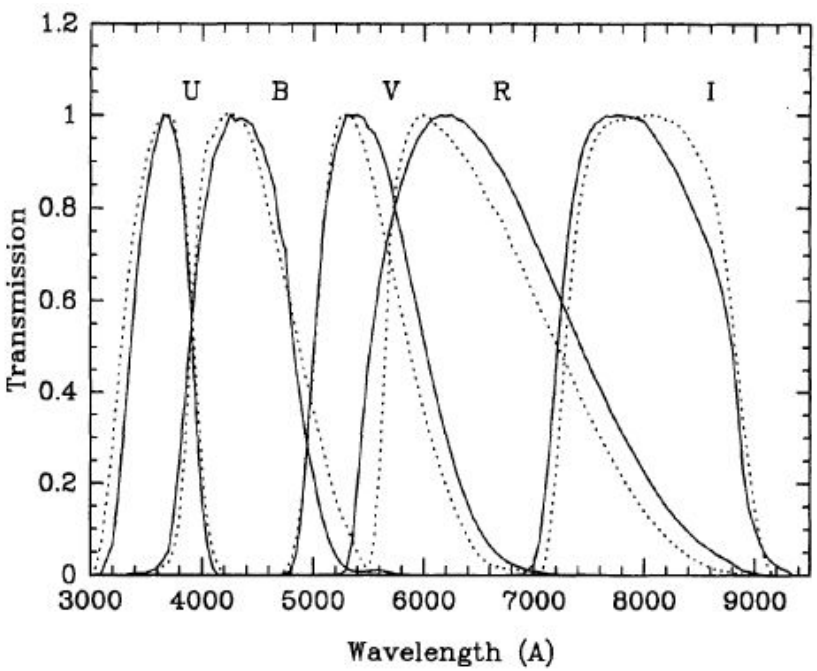


FIG. 3—The FOTRAP passbands (continuous curves) compared to the standard recipe (Bessell 1990; dotted curves). FOTRAP has a slightly narrower *U* but wider *V* and *R* responses with respect to the standard system. The *U* and *B* passbands shown here take into account the effect of the transparency of the atmosphere at one airmass (the *UX* and *BX* bands in Table 3).

X: airmass

Jablonski et al. 1994 PASP 106, 1172

The reduction program implements the prescriptions of Harris, Fitzgerald, and Reed (1981) to solve simultaneously for extinction and transformation coefficients. For each standard star the *V* magnitude and color indices can be written as

$$v-V=a_1+a_2X+a_3(B-V)+a_4X(B-V)+a_5(B-V)^2, \quad (1)$$

$$u-b=b_1+b_2X+b_3(U-B)+b_4X(U-B)+b_5(U-B)^2, \quad (2)$$

$$b-v=c_1+c_2X+c_3(B-V)+c_4X(B-V)+c_5(B-V)^2, \quad (3)$$

$$v-r=d_1+d_2X+d_3(V-R)+d_4X(V-R)+d_5(V-R)^2, \quad (4)$$

$$r-i=e_1+e_2X+e_3(R-I)+e_4X(R-I)+e_5(R-I)^2, \quad (5)$$

where the left-hand terms correspond to instrumental values and the capital symbols in the right hand are used to denote catalog values. X is the airmass. In the simultaneous least-squares solution each star's measurement is weighted by an error estimate calculated at acquisition time (which takes into account the contributions of photon noise, scintillation, misguiding, etc.). An adapted version of the subroutine LFIT in Press et al. (1986) was used for the simultaneous least-squares fit.

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Colors of the Sun including data from Brazil (OPD), Mexico & Africa

THE $UBV(RI)_C$ COLORS OF THE SUN

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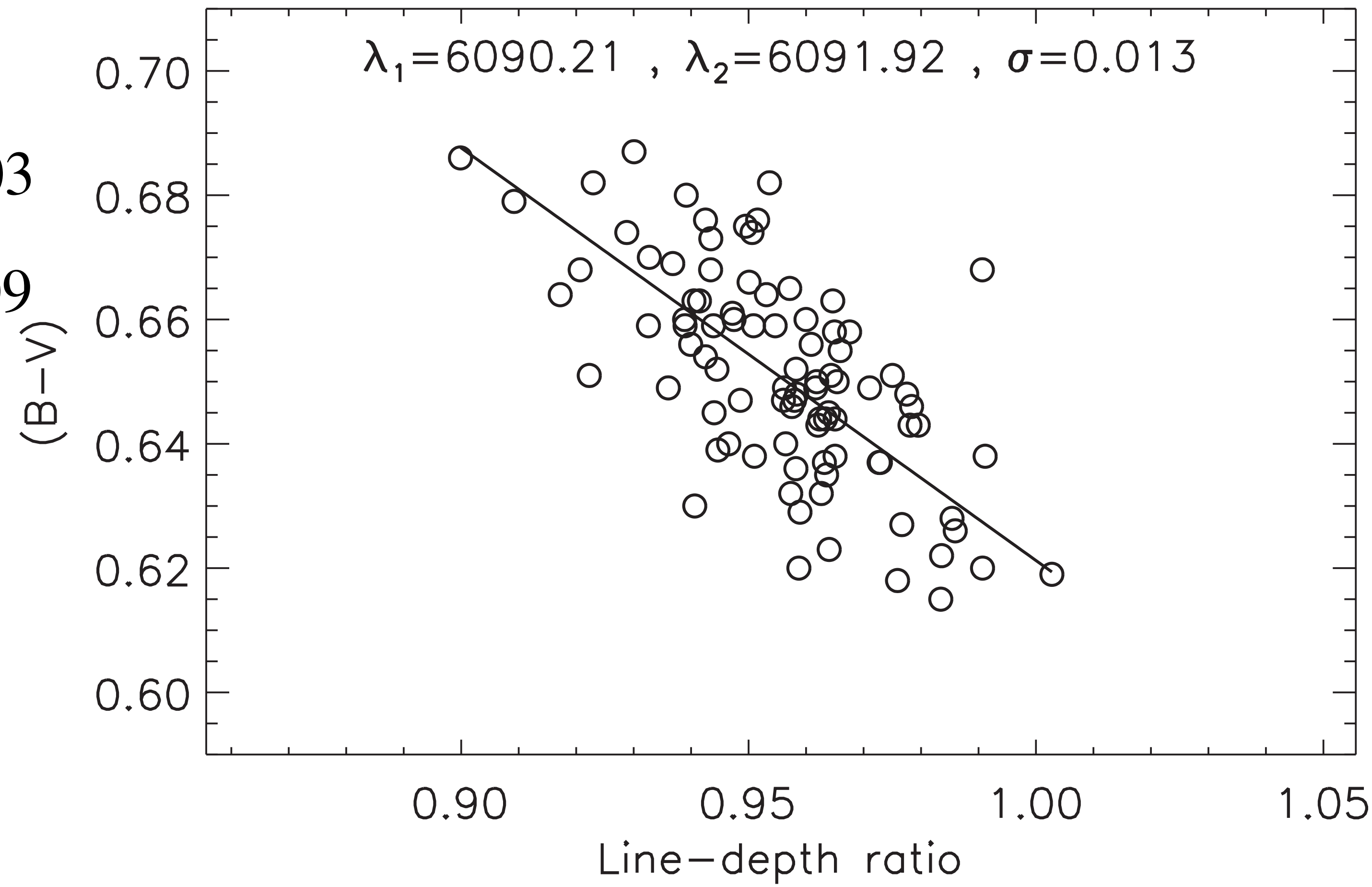
$$(B-V)_\odot = 0.653 \pm 0.003$$

$$(U-B)_\odot = 0.158 \pm 0.009$$

$$(V-R)_\odot = 0.356 \pm 0.003$$

$$(V-I)_\odot = 0.701 \pm 0.003$$

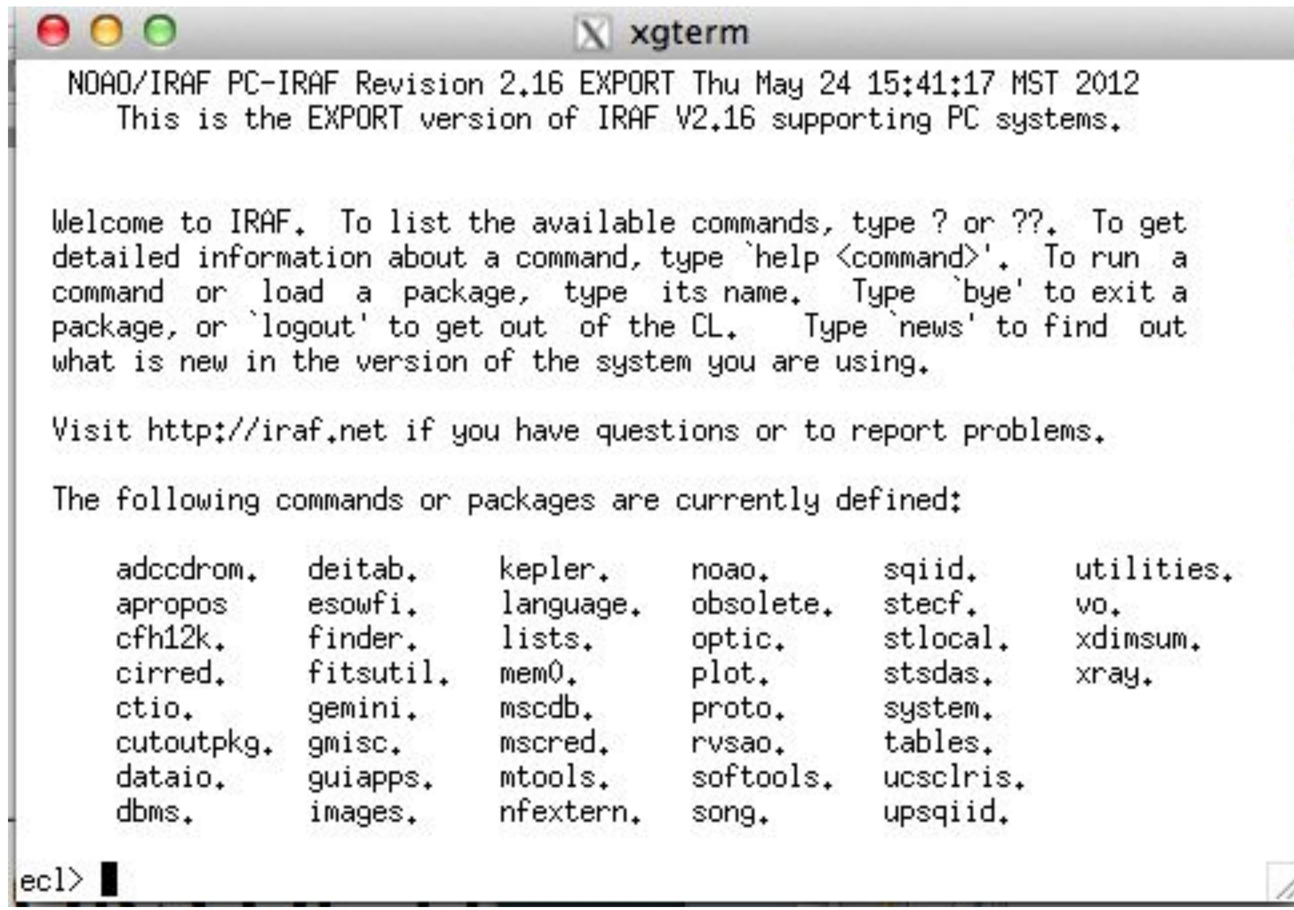


Basic photometry with IRAF

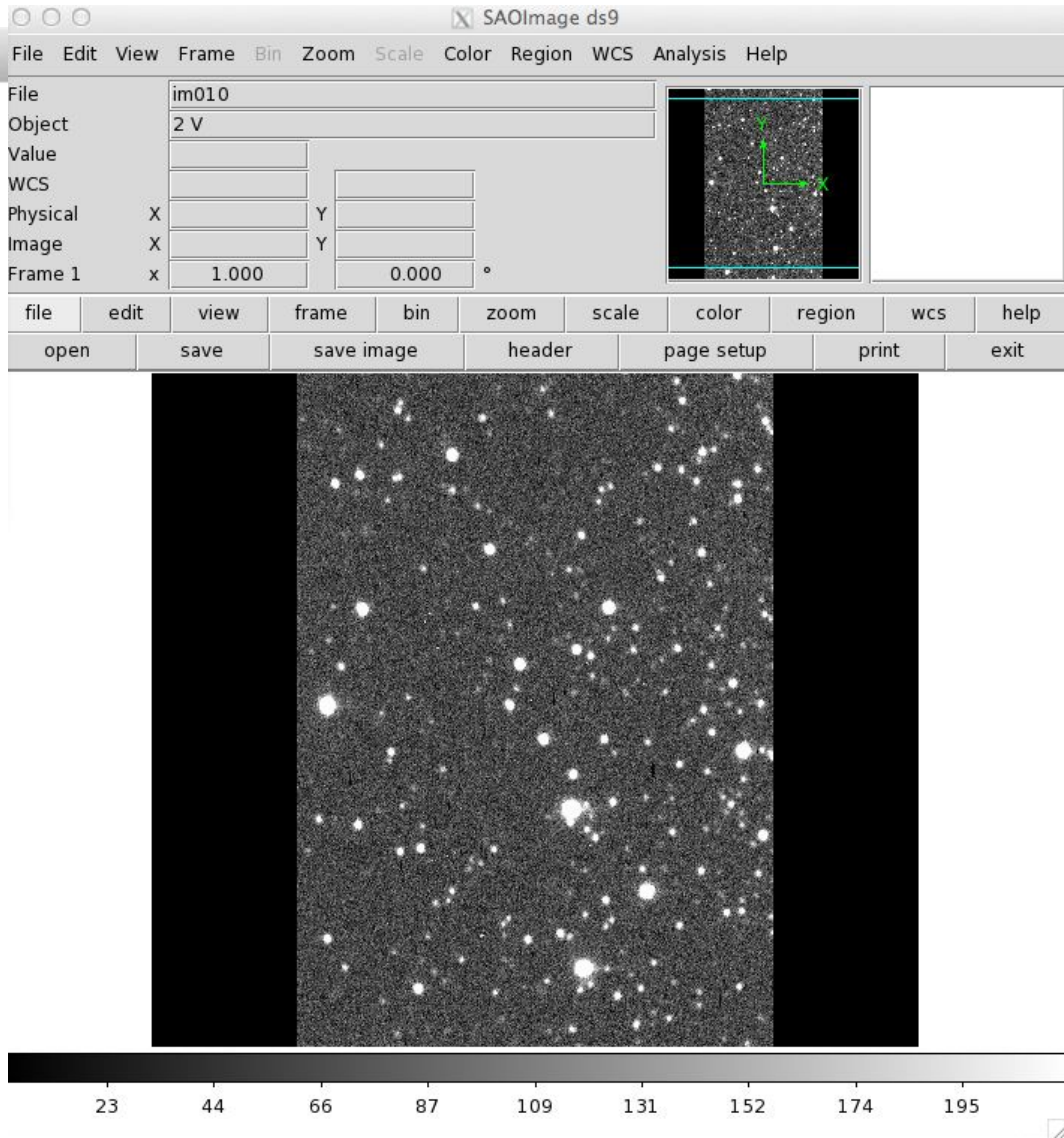
- Example using the images of M92 from basic IRAF tutorial (see readme and intro.tar)
- im010.fits
- im011.fits
- Call iraf (type *cl*)

in a xgterm window

in the directory iraf



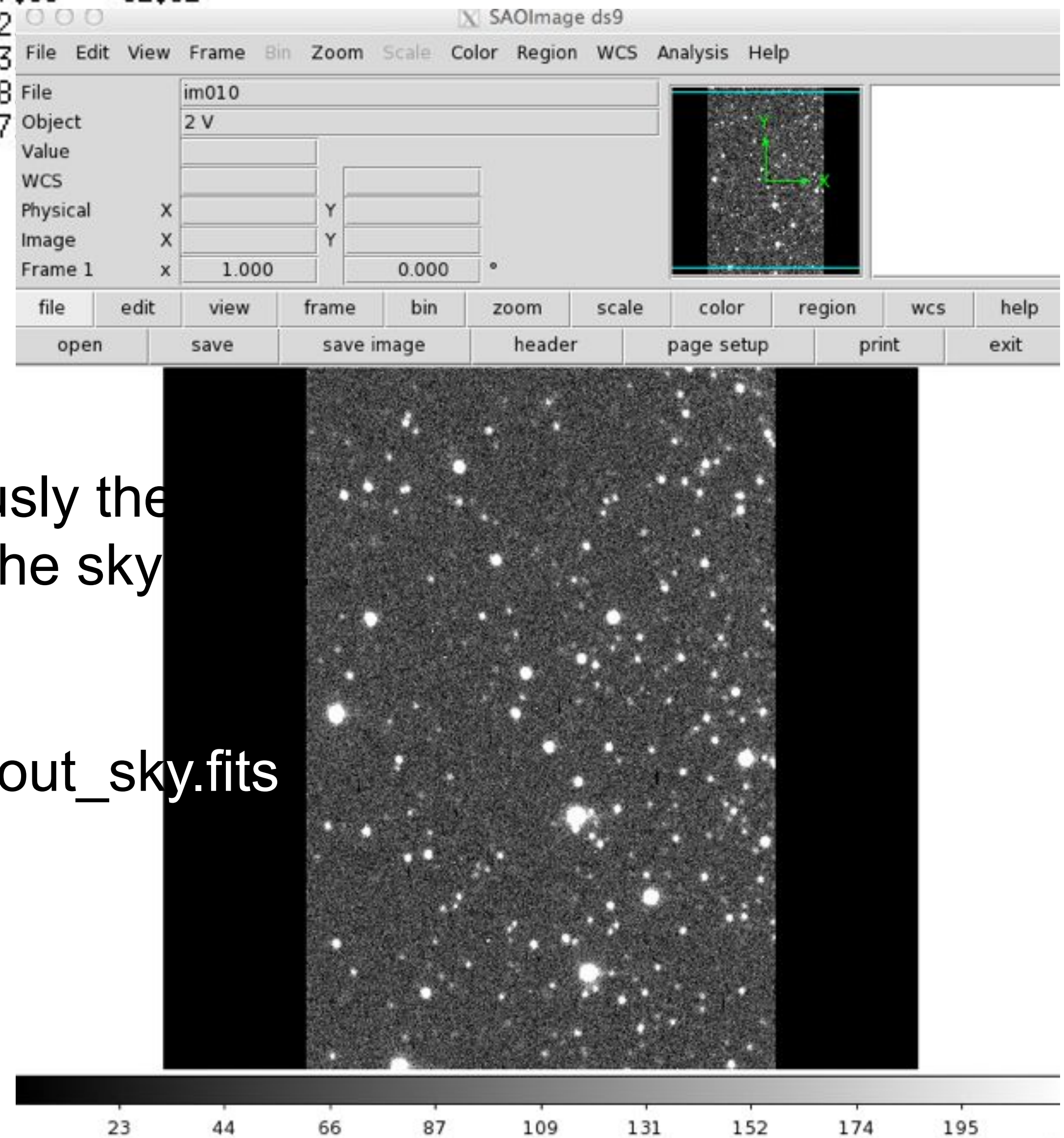
```
ecl> pwd
/Users/jorge/iraf
ecl> cd intro
ecl> ls *.fits
im010.fits        im011.fits
ecl> !ds9 &
ecl> display im010 1
z1=23.29314 z2=86.1793
ecl>
```



Imexam to estimate the sky (m)

ecl> imexam

# SECTION	NPIX	MEAN	MEDIAN	STDDEV	MIN	MAX
[153:157,415:419]	25	40.6	41.32	6.68	27.25	55.06
[60:64,358:362]	25	40.36	39.05	6.935	28.6	52.28
[62:66,301:305]	25	40.2	39.38	9.008	23.54	58.13
[26:30,214:218]	25	39.5	38.84	5.543	27.12	47.9
[128:132,195:199]	25	38.6	39.48	8.176	17.55	52.31
[223:227,174:178]	25	42.13	38.29	8.028	32	
[104:108,107:111]	25	40.54	41.	8.078	23	
[145:149,52:56]	25	42.65	41.12	6.715	28	
[47:51,135:139]	25	41.07	40.49	8.399	27	



It is not necessary to subtract previously the
because the photometry talks will fit the sky
However, in a first approximation:

imarith imagem.fits – sky image_without_sky.fits
In the example above, sky ~ 40.

xgterm

```
ecl> epar imexamine
```

epar: edit parameters

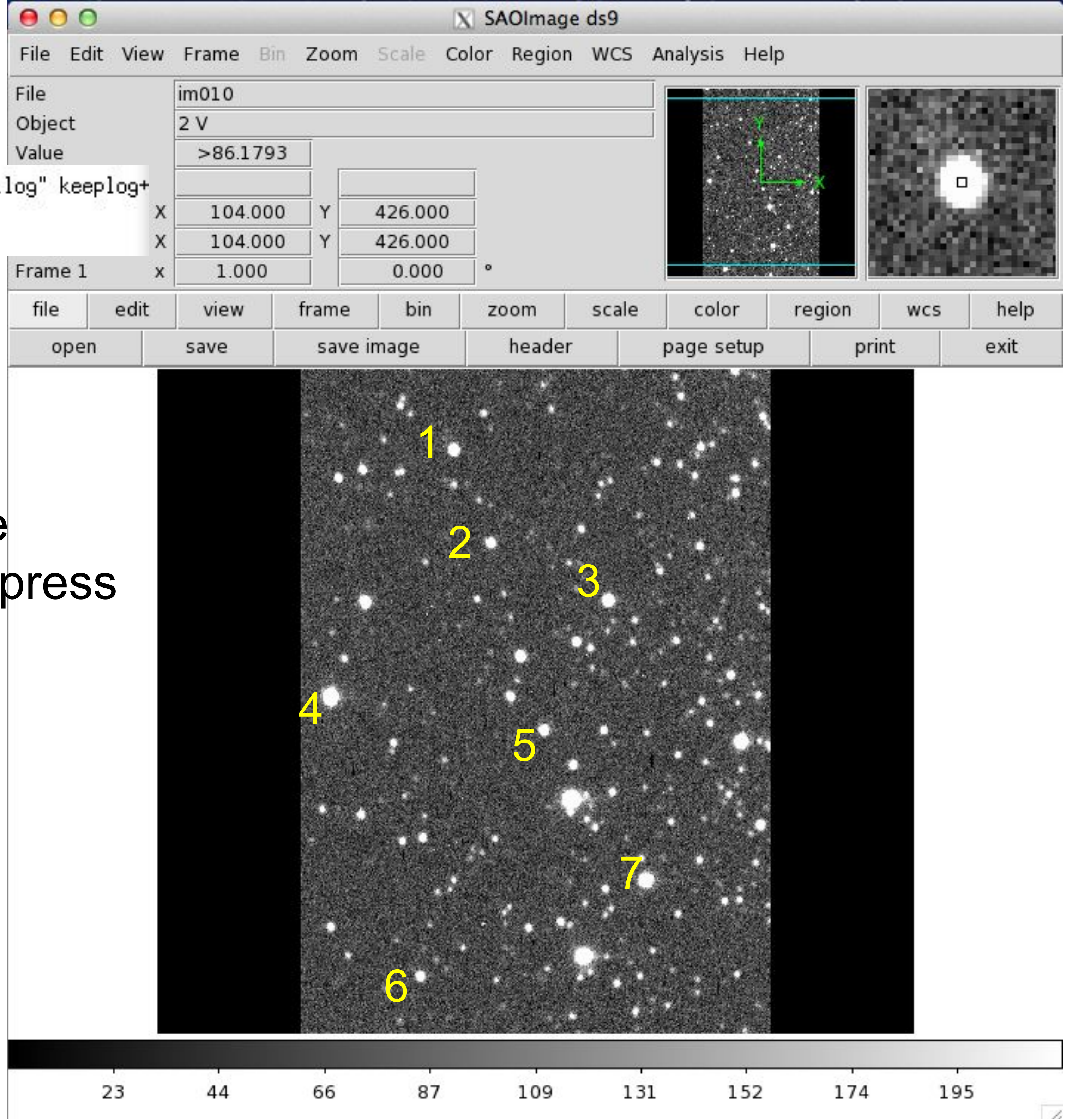
xgterm

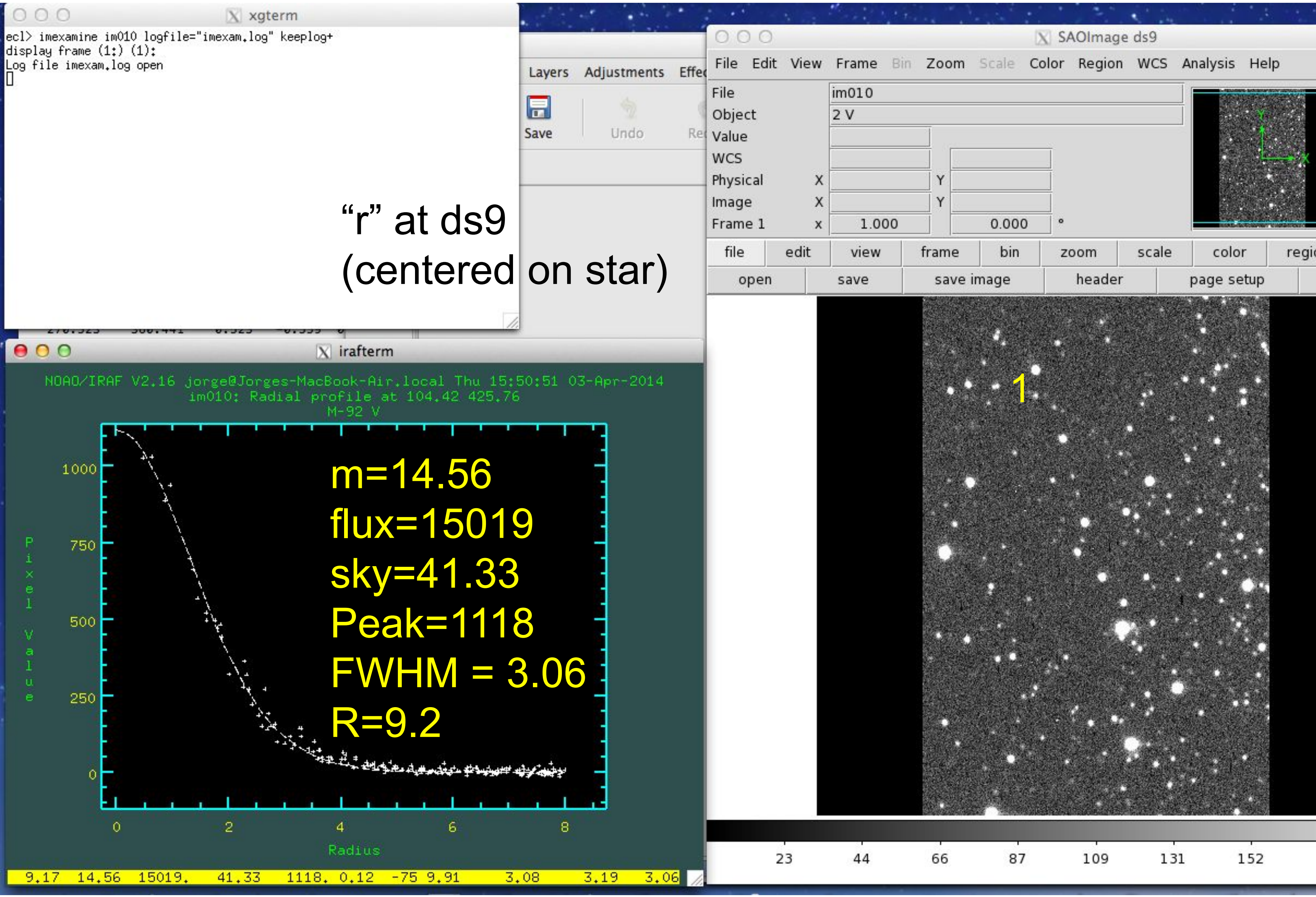
```
                              I R A F
                 Image Reduction and Analysis Facility
PACKAGE = tv
   TASK = imexamine

input   =                               images to be examined
(output =                             ) output root image name
(ncoutpu=                          101) Number of columns in image output
(nloutpu=                          101) Number of lines in image output
frame   =                            1  display frame
image   =                               image name
(logfile=                             ) logfile
(keeplog=                           no) log output results
(defkey =                            a) default key for cursor list input
(autored=                          yes) automatically redraw graph
(allfram=                          yes) use all frames for displaying new images
(nframes=                            0) number of display frames (0 to autosense)
(ncstat =                            5) number of columns for statistics
(nlstat =                            5) number of lines for statistics
(graphcu=                             ) graphics cursor input
(imagecu=                             ) image display cursor input
(wcs    =                      logical) Coordinate system
More
ecl> imexamine im010 logfile="imexam.log" keeplog+
```

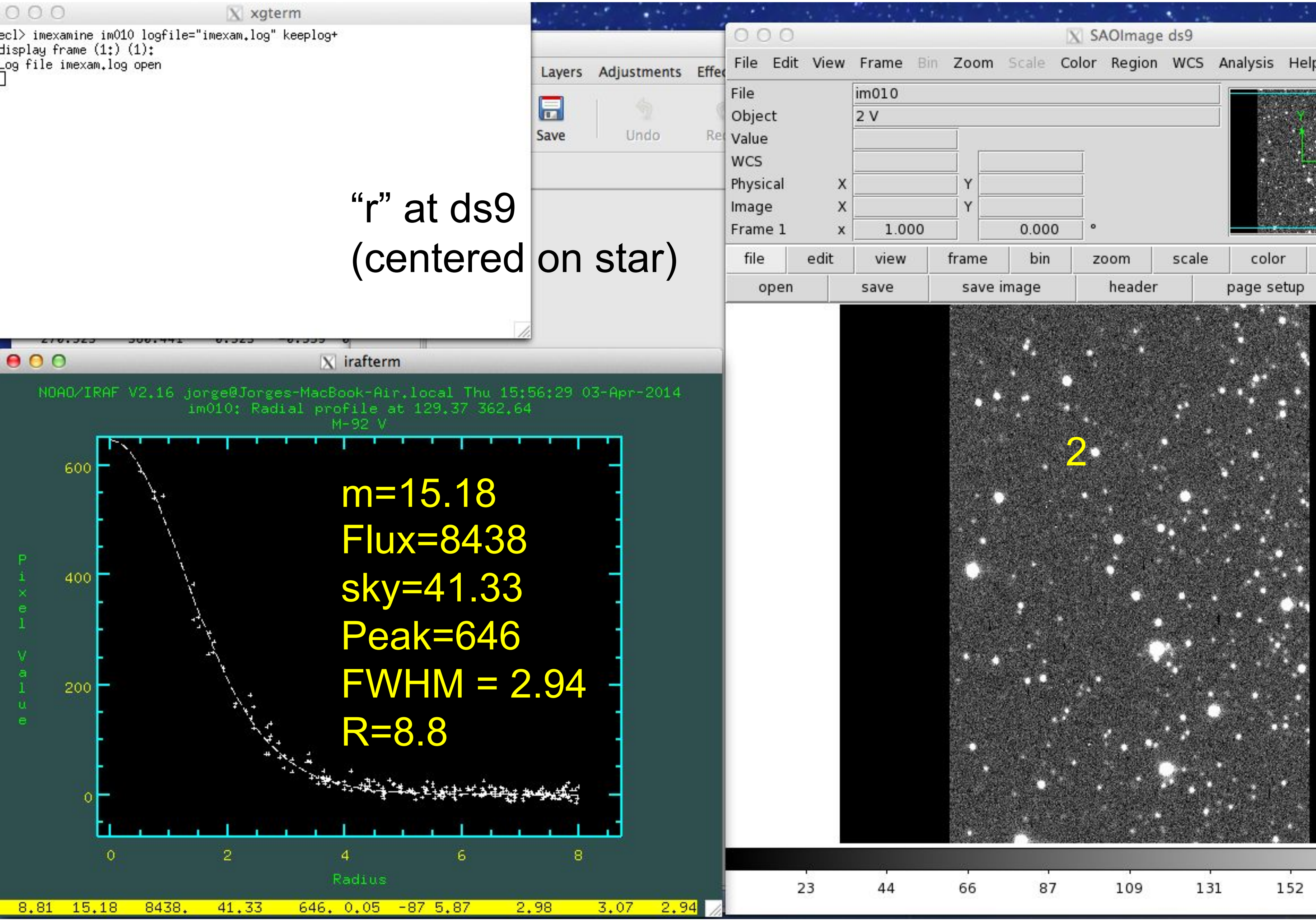
To exit: CTRL-D

```
ecl> imexamine im010 logfile="imexam.log" keeplog+
display frame (1:) (1):
Log file imexam.log open
```

Put cursor on the labeled star and press “r” (radial profile)




xgterm
ecl> imexamine im010 logfile="imexam.log" keeplog+
display frame (1:) (1):
Log file imexam.log open
"r" at ds9
(centered on star)
Layers
Adjustments
Save
Undo
irafterm
NOAO/IRAF V2.16 jorge@Jorges-MacBook-Air.local Thu 15:50:51 03-Apr-2014
im010: Radial profile at 104.42 425.76
M-92 V
Pixel Value
1000
750
500
250
0
0
2
4
6
8
Radius
m=14.56
flux=15019
sky=41.33
Peak=1118
FWHM = 3.06
R=9.2
9.17 14.56 15019. 41.33 1118. 0.12 -75 9.91 3.08 3.19 3.06
SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File im010
Object 2 V
Value
WCS
Physical X Y
Image X Y
Frame 1 x 1.000 0.000 °
file edit view frame bin zoom scale color
open save save image header page setup
1
23 44 66 87 109 131 152



xgterm
ecl> imexamine im010 logfile="imexam.log" keeplog+
display frame (1:) (1):
Log file imexam.log open
“r” at ds9
(centered on star)
irafterm
NOAO/IRAF V2.16 jorge@Jorges-MacBook-Air.local Thu 15:56:29 03-Apr-2014
im010: Radial profile at 129.37 362.64
M-92 V
Pixel Value
Radius
m=15.18
Flux=8438
sky=41.33
Peak=646
FWHM = 2.94
R=8.8
8.81 15.18 8438. 41.33 646. 0.05 -87 5.87 2.98 3.07 2.94
SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File im010
Object 2 V
Value
WCS
Physical X Y
Image X Y
Frame 1 x 1.000 0.000 °
file edit view frame bin zoom scale color
open save save image header page setup
2
23 44 66 87 109 131 152

cl>!gedit imexam.log (for linux)

or

cl> !open –a textedit imexam.log (for mac)

imexam.log

```
# [1] im010 - M-92 V
#    COL     LINE    COORDINATES       R      MAG     FLUX      SKY     PEAK    E    PA BETA ENCLOSED   MOFFAT DIRECT
  104.42  425.76 104.42 425.76     9.17   14.56   15019.    41.33    1118. 0.12  -75 9.91      3.08     3.19   3.06
#    COL     LINE    COORDINATES       R      MAG     FLUX      SKY     PEAK    E    PA BETA ENCLOSED   MOFFAT DIRECT
  129.37  362.64 129.37 362.64     8.81   15.18    8438.    41.33     646. 0.05  -87 5.87      2.98     3.07   2.94
```

Some additional tips

http://www.astronomy.pomona.edu/astro101/iraf.phot.html

- For a more complete photometry of a sample of stars you could use the package digiphot

cl> digiphot

apphot. daophot. photcal. ptools.

Usar o sub-pacote apphot

- **di> apphot**
- aptest findpars@ pconvert polymark psort center fitpsf pdump polypars@ qphot centerpars@ fitsky pexamine polyphot radprof daofind fitskypars@ phot prenumber wphot datapars@ pcalc photpars@ pselect

and perform photometry with the task phot

To create lists of stars use the task daofind

To extract photometry from the magnitude files you can use the task txdump

Surface brightness

- For extended objects the brightness is not necessarily homogeneous
- We can define the surface brightness as the brightness observed by solid angle Ω:

$$\mu(\vec{R}) \propto -2,5 \log I(\vec{R}) \;\; ; \quad I(\vec{R}) = \frac{\text{fluxo}}{\Omega}(\vec{R})$$

Units: [mag/arcsec^{2}]

Conversion of magnitude to surface brightness μ

For an object of magnitude m and with an area on the sky A (em arcsec^2), the surface brightness μ:

$$\mu = m + 2.5 \log_{10} A$$

Some values of surface brightness μ

Sky at night

- New Moon: $\mu_B = 22.7$, $\mu_R = 20.9$, $\mu_H = 13.7$ [mag/”^{2}]
- Full Moon: $\mu_B = 19.5$, $\mu_R = 19.9$, $\mu_H = 13.7$ [mag/”^{2}]

Sky at day: $\mu_V \sim 3$ [mag/”^{2}]

Sky is brighter in the IR. Moon affects more the optical

The relation between μ & I: $I_{object}/I_{sky} = 10^{(2/5)(\mu_{sky}-\mu_{object})}$

For example, $\mu = 25$ mag/”^{2} R band → $I_{object} \sim 14\% \; I_{sky}$

Adopting μ_R (sky) ~ 20,4

From counts/pixel → mag/"^{2}

$\mu_0 = \mu_{fit} - \mu_{zero}$

μ_{zero}: photometric calibration

Comparison of field stars with known magnitudes and the number of counts/pixel

μ [mag/"^{2}] = mag_{ref} -2.5 log[counts/$counts_{ref}$] + 2.5logpix^2

pix = in arcsec

mag_{ref} = magnitude of reference star

$counts_{ref}$ = total counts of reference star