Astro 500

Techniques of Modern Observational Astrophysics

Matthew Bershady

University of Wisconsin

Lecture Outline

- Photometry
  - General comments
  - Aperture photometry
  - Curves of growth
  - Profiles
  - Profile fitting
  - Crowded fields & DOAPHOT
  - Photometric calibration
  - Surface photometry
  - Ellipse fitting
  - Star-galaxy separation: size and shape (moments)
  - Source Extractor and moments of the light profile
  - Other methods: profile-fitting, the η function
  - S/N and curves of growth: random vs sys. error
  - Photometric calibration (revisited)

Stellar photometry (Aperture photometry through Photometric calibration)

Extended-source photometry (Surface photometry through Photometric calibration (revisited))

General comments

- Stellar photometry is well defined and therefore relatively easy because the light-profile is well-defined, or at least self-similar.
- Extended source photometry is not well-defined and therefore difficult because the light-profile is not known *a priori* and not self-similar.
- For extended sources there are always trades between random vs systematic errors. For stellar sources, this can be finessed.

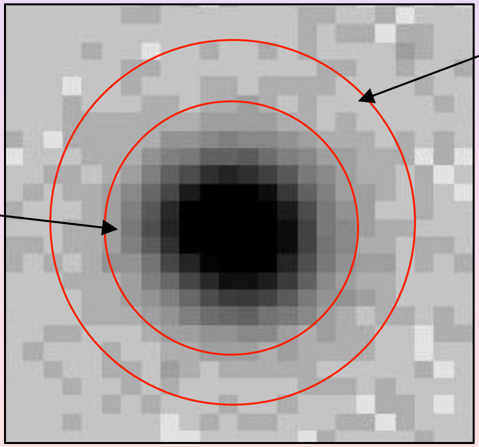
- Calibration: important to differentiate relative vs absolute. Absolute photometry is difficult, particularly for extended sources.

- Sky forefrounds represent sources of random and systematic error:
  - Random errors from photon counts
  - Random and systematic errors from sky-level determinations
- Determining an accurate sky level is the limiting factor for extended source photometry.

Stellar Photometry

- Aperture Photometry
  - DaCosta, 1992, ASP Conf Ser 23
  - Stetson, 1987, PASP, 99, 191
  - Stetson, 1990, PASP, 102, 932

Sum counts in all pixels in aperture



Determine sky in annulus, subtract off sky/pixel in central aperture

Much of what is discussed here is applicable to extended-source photometry, with caveats about accuracy and precision. *Why is this?*

Aperture Photometry

$$I = \sum_{ij} I_{ij} - n_{pix} \times \text{sky/pixel}$$

Total counts in aperture from source

Number of pixels in aperture

Counts in each pixel in aperture

$$m = c_0 - 2.5\log(I)$$

Aperture Photometry

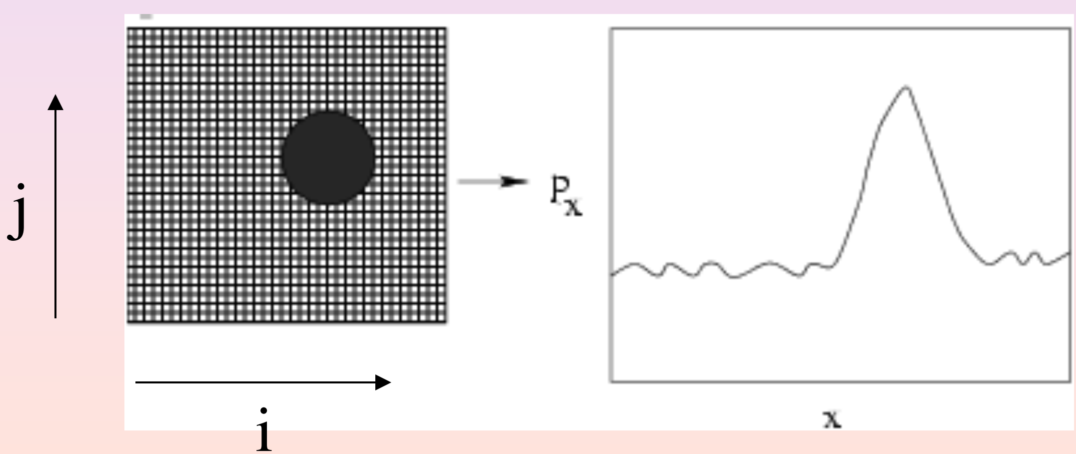
- What do you need?
  - Source center
  - Sky value
  - Aperture radius, or more generally, boundary*

*e.g., boundary could be based on a more complicated geometry, or on isophotes.

Centers

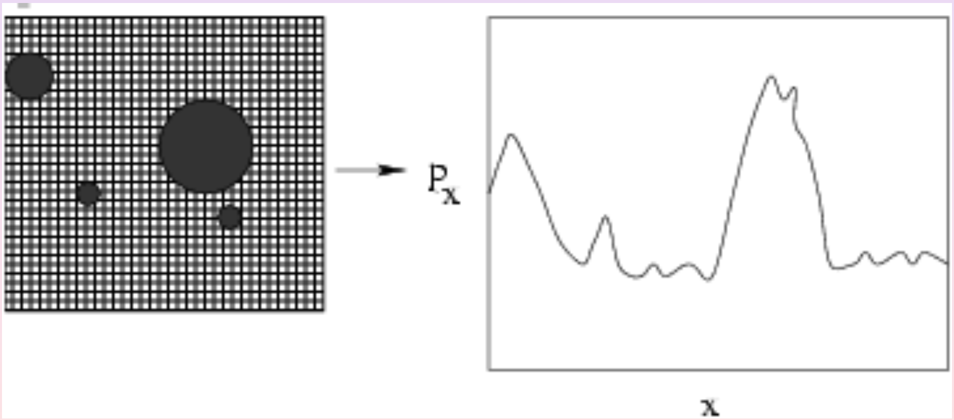
- The usual approach is to use "marginal sums''.

$$\rho_{x_i} = \sum_j I_{ij} \qquad \text{: Sum along columns}$$



Marginal Sums

- With noise and multiple sources you have to decide what is a source and to isolate sources.



Robust Marginal Sums

- Find peaks: use $\partial\rho_x/\partial x$ zeros
- Isolate peaks: use "symmetry cleaning''

1. Find peak
2. Compare pairs of points equidistant from center
3. If $I_{left} >> I_{right}$, set $I_{left} = I_{right}$

- Finding centers: Intensity-weighted centroid

$$x_{center} = \frac{\sum_i \rho_{x_i} x_i}{\sum_i \rho_{x_i}}$$

✓ok

$$\sigma^2 = \frac{\sum_i \rho_i x_i^2}{\sum_i \rho_i} - x_i^2$$

hmmm…

Recall: (lecture 4)

$$\bar{x}_w = \frac{\sum_{i=1}^{N}(w_i x_i)}{\sum_{i=1}^{N} w_i}$$

$$\sigma_w^2 = \frac{N}{N-1}\frac{\sum_{i=1}^{N}\left[w_i(x_i - \bar{x})^2\right]}{\sum_{i=1}^{N} w_i}$$

Centering alternative: Profile fitting

- Alternative for centers: Gaussian fit to ρ:

$$\rho_i = \text{background} + h \bullet e^{\left[-\left((x_i - x_c)/\sigma\right)^2/2\right]}$$

Height of peak

Solving for center

- DAOPHOT FIND algorithm uses marginal sums in subrasters, symmetry cleaning, reraster and Gaussian fit.

Will this work for extended sources?

Why stop at centering?

Sky

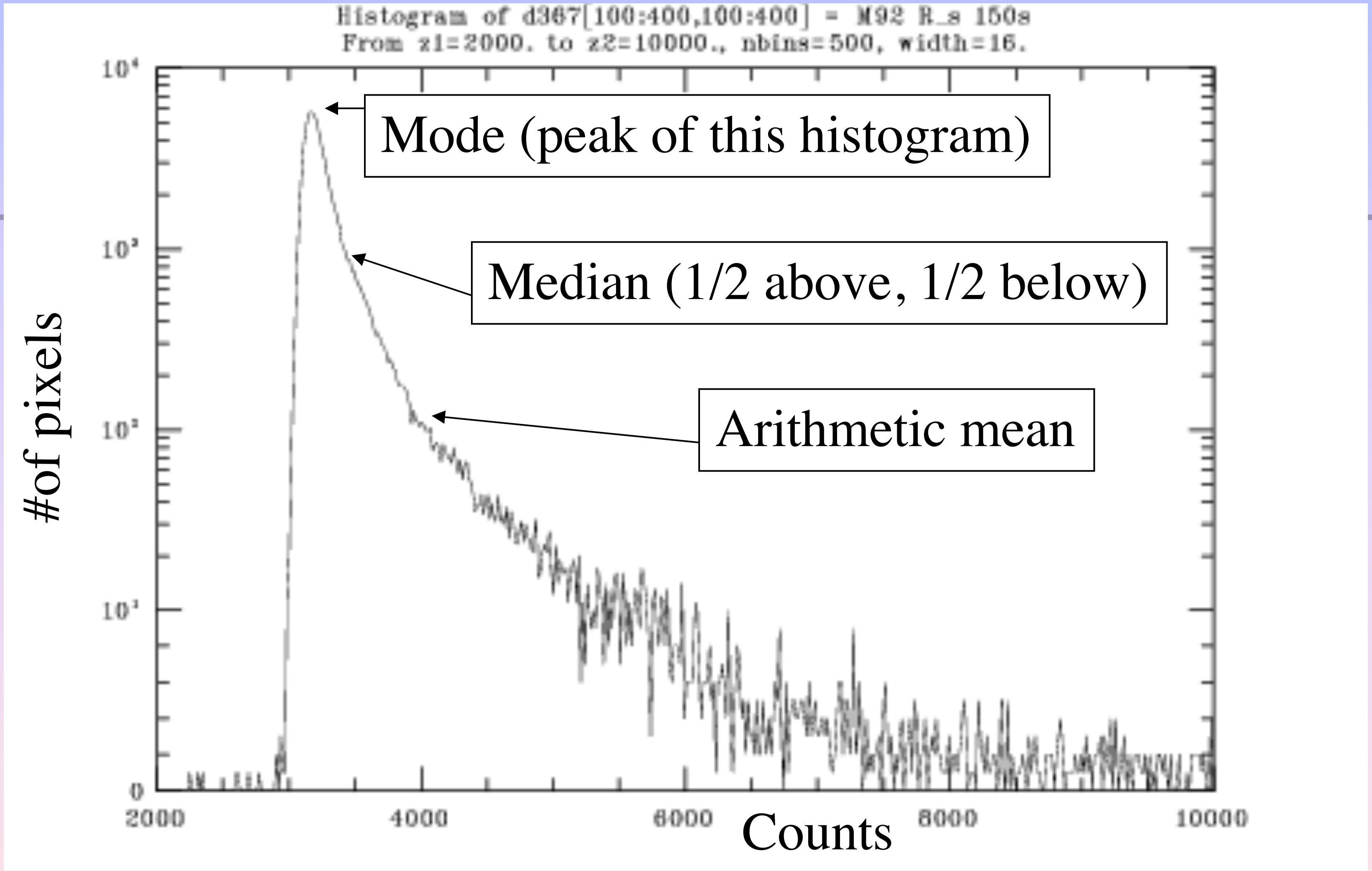
- To determine the sky, typically use a *local* annulus, evaluate the distribution of counts in pixels in a way to reject the bias toward higher-than-background values.
- Remember the 3 Ms (next slide)
- Answer these 3 questions:

systematics

1. Why local?
2. How local?
3. How big should the sky annulus be?

Think in terms of S/N in the background-limit, and consider error propogation.
Revisit the formulation considering $S_{object} = S_{observed} - S_{sky}$.

.



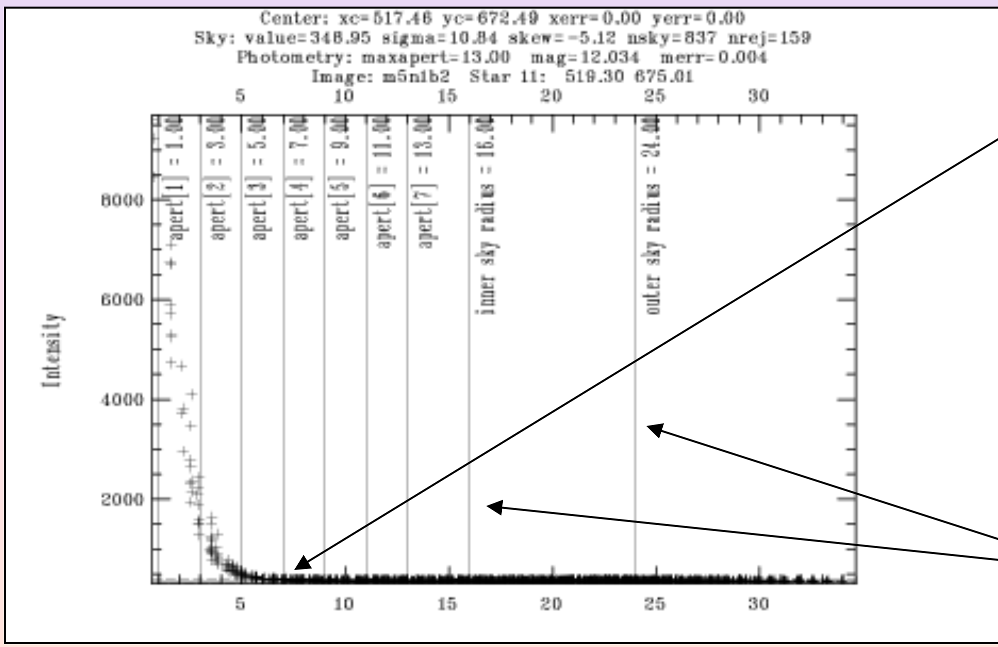
Because essentially all deviations from the sky are positive counts (stars and galaxies), the mode is the best approximation to the sky foreground but (a) it is noisy, and (b) it is not necessarily what you want to subtract (e.g., what about faint sources?).

Some Critical Details…

- … **that pack a big bite:**
- Pixels are square. What about the partial pixels at a given radius? Usual approach is to assume uniform brightness throughout pixel and calculate fraction within *r* of the aperture center.
- How good is your photometry code at dealing with (counting) fractional pixels in the aperture? Most code uses approximations when radius is small. IRAF's code is very bad for radius < 3 pixels.
- What about aperture size?

Aperture size and growth curves

- First, it is VERY hard to measure the *total* light as some light is scattered to very large radius.



Radius from center in pixels

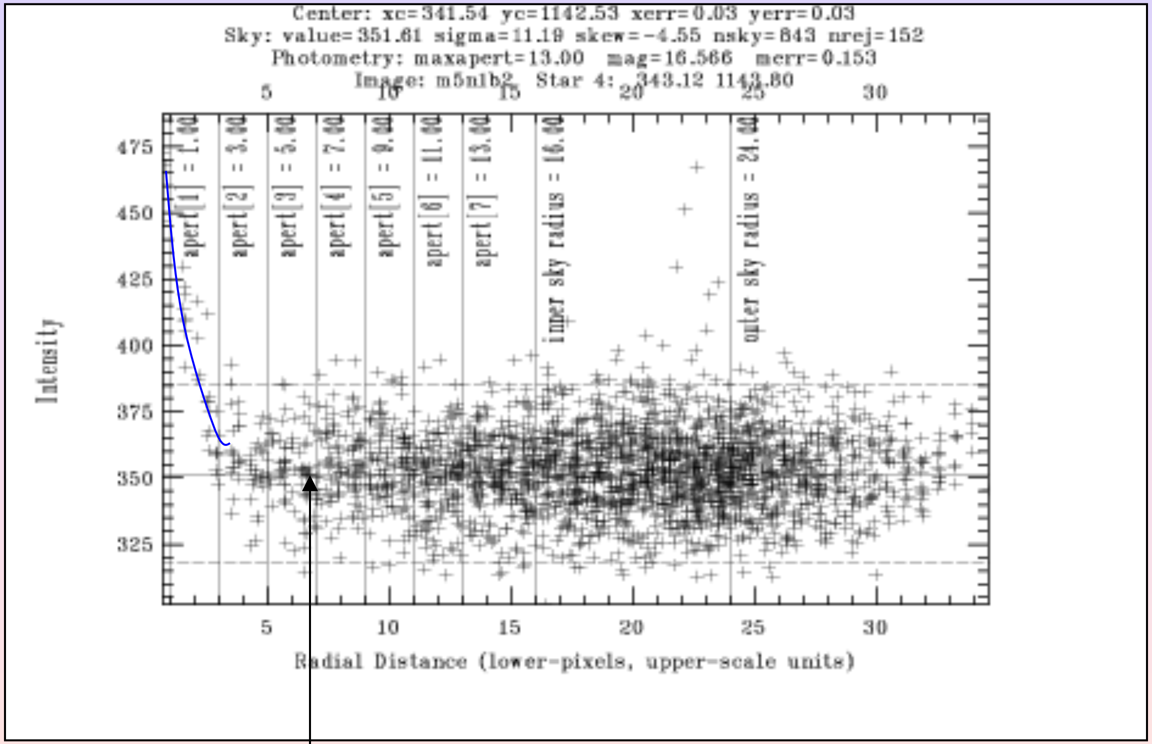
Perhaps you have most of the light within this radius

Radial intensity distribution for a bright, isolated star.

Inner/outer sky radii

Radial intensity distribution for a faint star

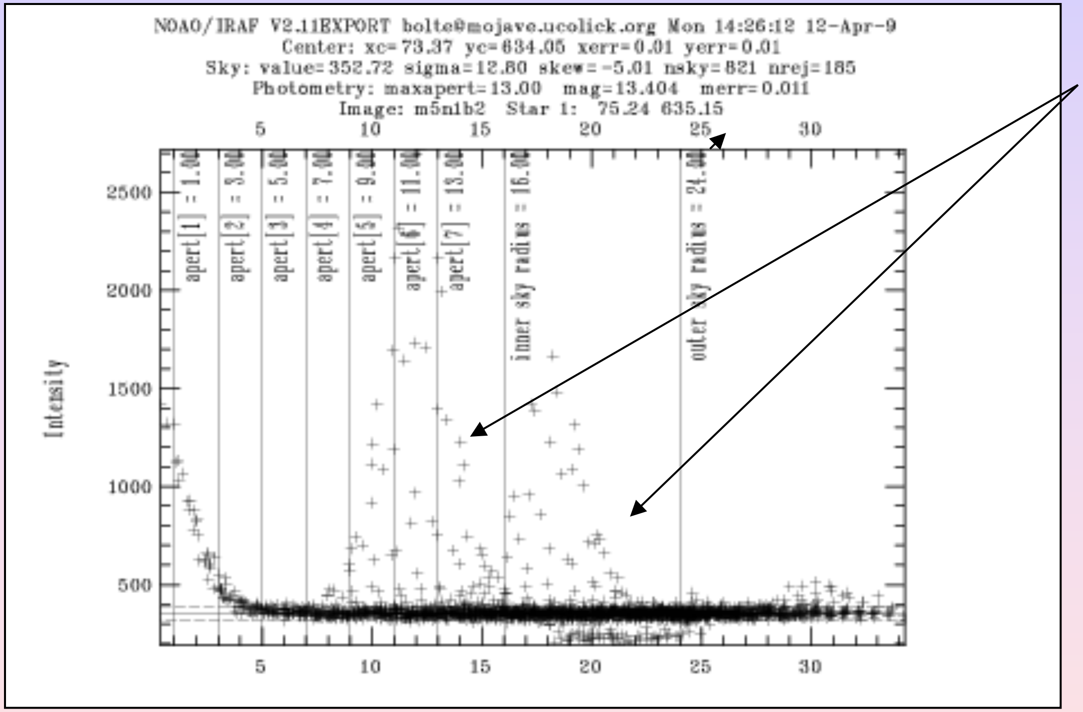
Same frames as previous example



The wings of a faint star are lost to sky noise at a different radius than the wings of a bright star.

Bright star aperture

Radial profile with neighbors

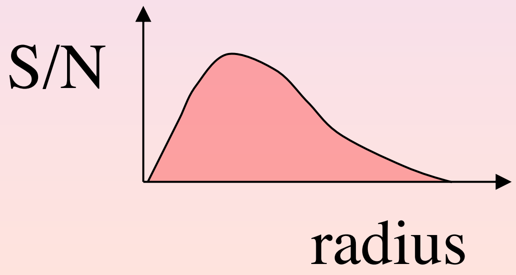


Neighbors OK in sky annulus (mode), trouble in star apertures

Growth Curves

- Idea is to use a small aperture (highest S against background and smaller chance of contamination) for everything and determine a correction to larger radii based on several relatively isolates, relatively bright stars in a frame.
- Note! This assumes a linear response so that all point sources have the same *fraction* of light within a given radius.
- Howell, 1989, PASP, 101, 616

Think in terms of S/N

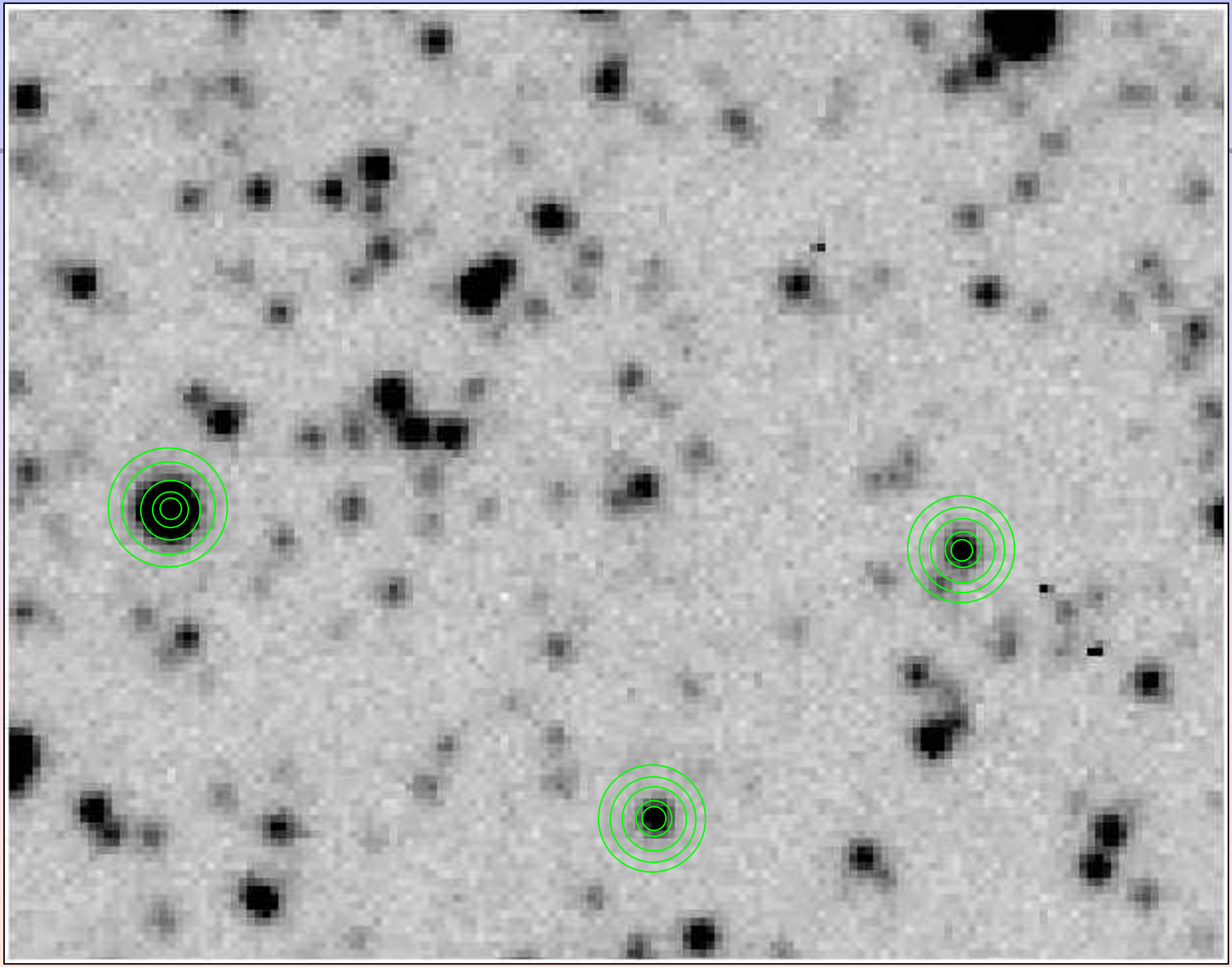


What happens if:

(a) PSF varies across image?

(b) From frame to frame?

(c) All sources do not have same shape?



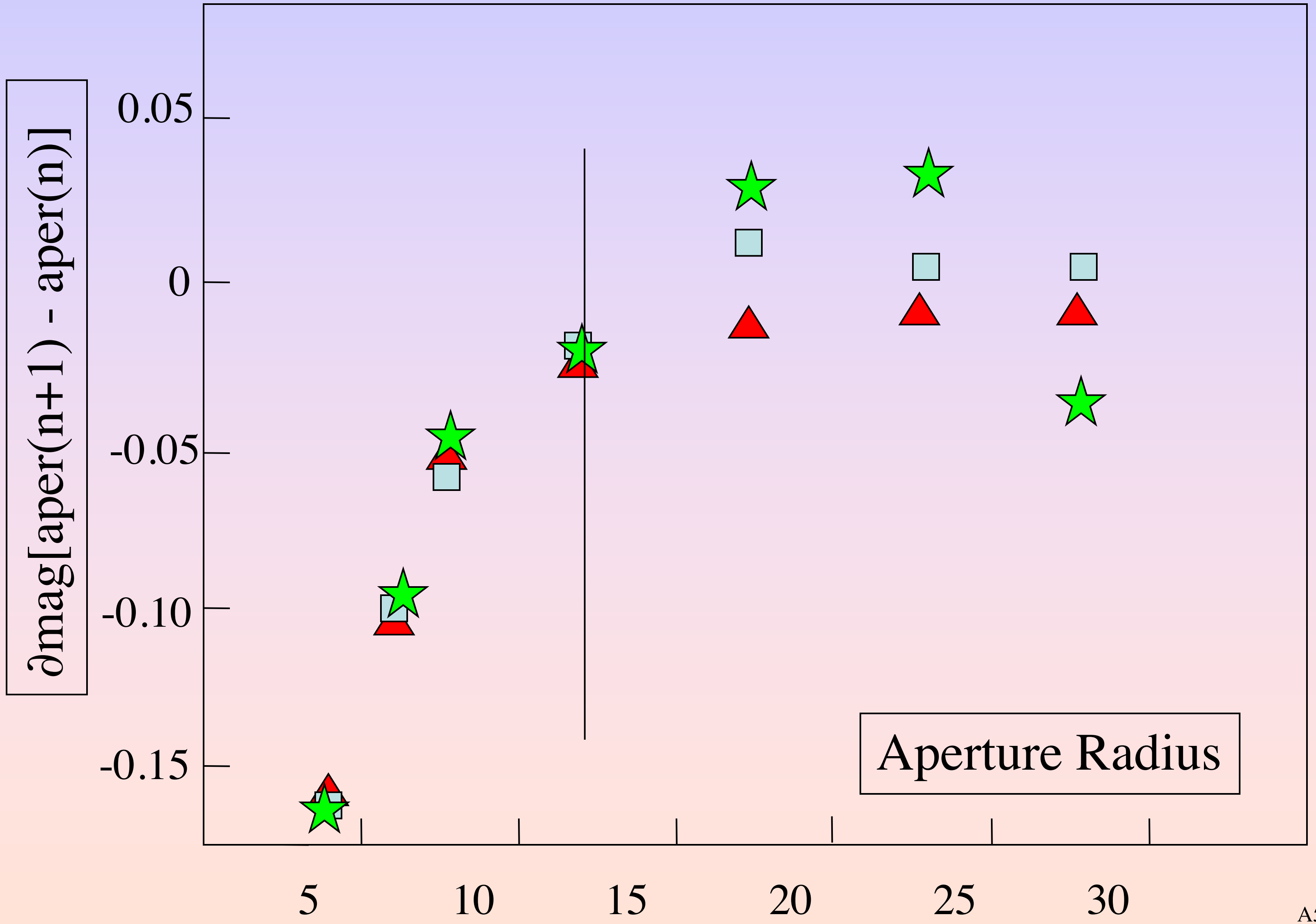
Stellar Growth Curves

Table. ∂mag for apertures n-1, n

Aperture	2	3	4	5	6	7	8
Star#1	0.43	0.31	0.17	0.09	0.05	0.02	0.00
Star#2	0.42	0.33	0.19	0.08	0.21	0.11	0.04
Star#3	0.43	0.32	0.18	0.10	0.06	0.02	-0.01
Star#4	0.44	0.33	0.18	0.22	0.14	0.12	0.14
Star#5	0.42	0.32	0.18	0.09	0.19	0.21	0.19
Star#6	0.41	0.33	0.19	0.10	0.05	0.30	0.12
cMean	0.430	0.324	0.184	0.094	0.057	0.02	0.00

Sum of these is the total aperture correction to be added to magnitude measured in aperture 1

Curves of Growth



DAOGROW

- Software: (in IRAF)
- Stetson, 1990, PASP, 102, 932 presented a fitting function for growth curves.
- Gaussian core + exponential + inverse power law for large radius

This is a general profile-fitting concept that can and has been applied to galaxies (see Dressler & Gunn 1992).
If model is correct, highest precision results, but risk of systematic error (wrong model).

Aperture Photometry Summary

1. Identify brightness peaks

2. $$\sum_{xy} I_{xy} - (\text{sky} \bullet \text{aperture area})$$

Use small aperture

3. Add in "aperture correction" determined from bright, isolated stars

Easy, fast, works well except* for the case of overlapping images

*…*and extended sources*

Crowded-field Photometry

- As was assumed for aperture corrections, all point sources have the same PSF (linear detector).
- Various codes have been written that:
  1. Automatic star finding
  2. Construction of PSF
  3. Fitting of PSF to (multiple) stars
- DAOPHOT, ROMAPHOT, DOPHOT, STARMAN
- Will spend some time on the use of DAOPHOT

DAOPHOT

- Stetson, 1987, PASP, 99, 191
- Stetson, DAOPHOT Users' Manual
- Main subroutines:
  - FIND
  - PHOT
  - PSF
  - ALLSTAR (DAOPHOT II)
- Couple of parameter files:
  - daophot.opt
  - photo.opt

in IRAF

- daophot.opt

HI=65635 (in counts)
LO=5 (in standard deviations: sky-5σ)
GA=3.9 (gain in e-/dn)
RE=2.05 (readout noise in units of DN)
FI=3 (PSF fitting radius)
PS=12 (PSF radius)
TH=3.5 (threshold in units of sky standard deviations)
AN=-6 (analytical form of PSF)
WA=-2 (`watch' - level of verbosity for feedback)
VA=2 (spatial variability of PSF)

- photo.opt

A1=3 (1st aperture radius=3 pixels)
A2=0 (if a zero is encountered, DAOPHOT ignores the rest of the apertures)
Etc
A9=19
AA=22
AB=25
AC=29
IS=35 (inner sky radius)
OS=45 (outer sky radius)

DAOPHOT FIND

- Needs gain, RN, HIBAD, LOBAD, FWHM
- Find convolves the frame with a gaussian with σ = FWHM/2.35. This improves the S/N for objects with a point-source PSF.
- For subrasters, constructs marginal sums and uses derivative zeros to isolate objects
- Fits two 1-D gaussian in x and y
- Calculates ``sharpness'' and ``roundness''
- Writes a .coo file with: n,x,y,mag,sharp,round

- Determine the right threshold with a couple easy tests:
    1. Plot #stars found vs threshold level
    2. Use IRAF *fields* and *tvmark* to put dots at the x,y positions in the .coo file
- Output file default name is framename.coo
- First time through a frame, the strong blends will not be properly parsed into individual centroids.

PHOT

- Requires photo.opt file in directory to define apertures and sky annulus
- Requires input .coo file
- Calculates sky-subtracted magnitude for each aperture (usually only one)
- Determines the sky value for each object
- Output: framename.ap

PSF - 1

- PSF uses stars on the frame to create a PSF. DAOPHOT uses an analytical core plus a 2-D lookup table.
  - For any star: m=c_0-2.5log(psf scaling factor)
- DAOPHOT options are variants on bivariate:

$$I(r) \propto e^{-r^2/2\alpha^2} \qquad \text{Gaussian}$$

$$\propto \frac{1}{1+\left(r^2/\alpha^2\right)^{\beta}} \qquad \text{Moffet}$$

Fitting radius: ~FWHM; PSF radius: ~ 4 x FWHM

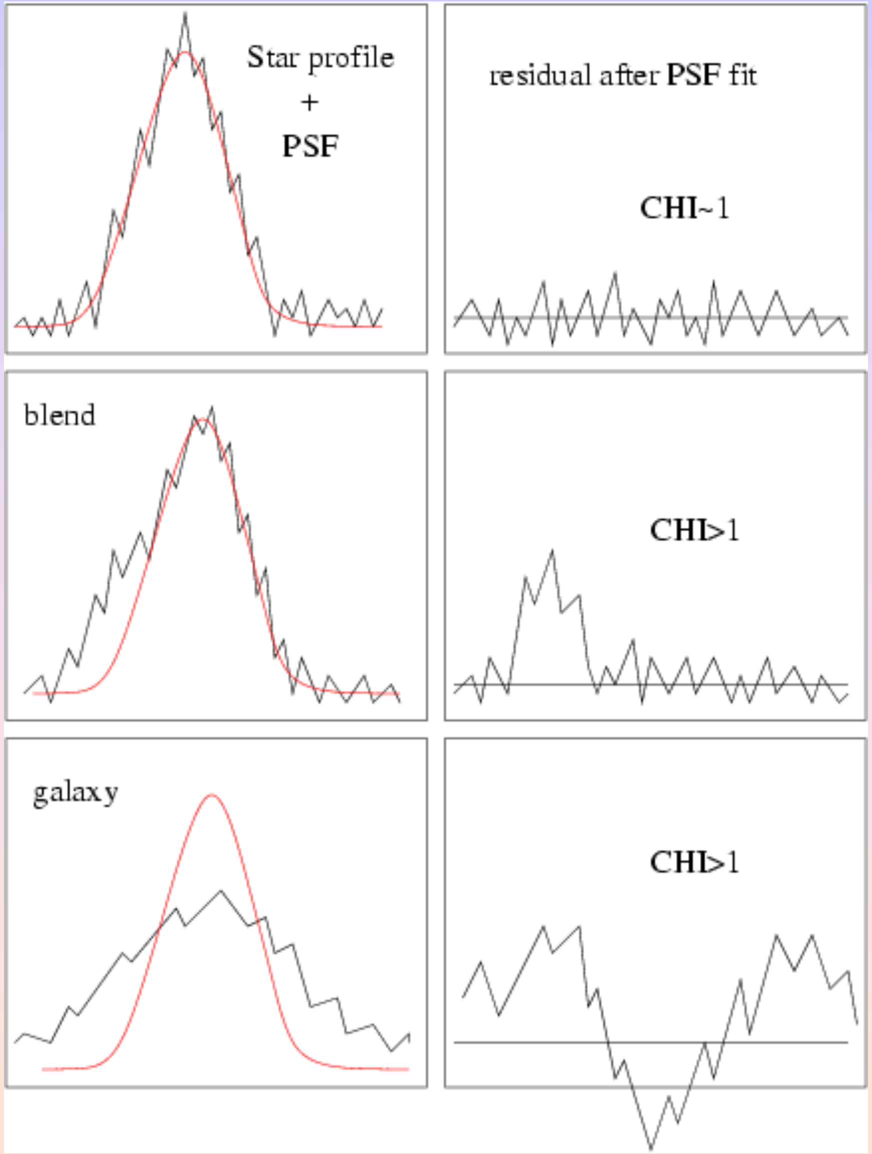
PSF - 2

- To construct a PSF
  1. Choose unsaturated, relatively isolated stars
  2. If PSF varies over the frame, sample the full field
  3. Make 1st iteration of the PSF
  4. Subtract psf-star neighbors
  5. Make another PSF
- Output of PSF routine is a framename.psf which has a header containing the parameters defining the analytical function and an encoded look up table of residuals.

Allstar (DAOPHOT II)

- Use the .ap file and .psf as input (x,y,sky for every object)
- Based on PSF radius, group objects into sets that need to be simultaneously fitted with PSFs
- Fit PSFs to groups
- Return: framename.als
  - x, y, mag, ∂mag, chi

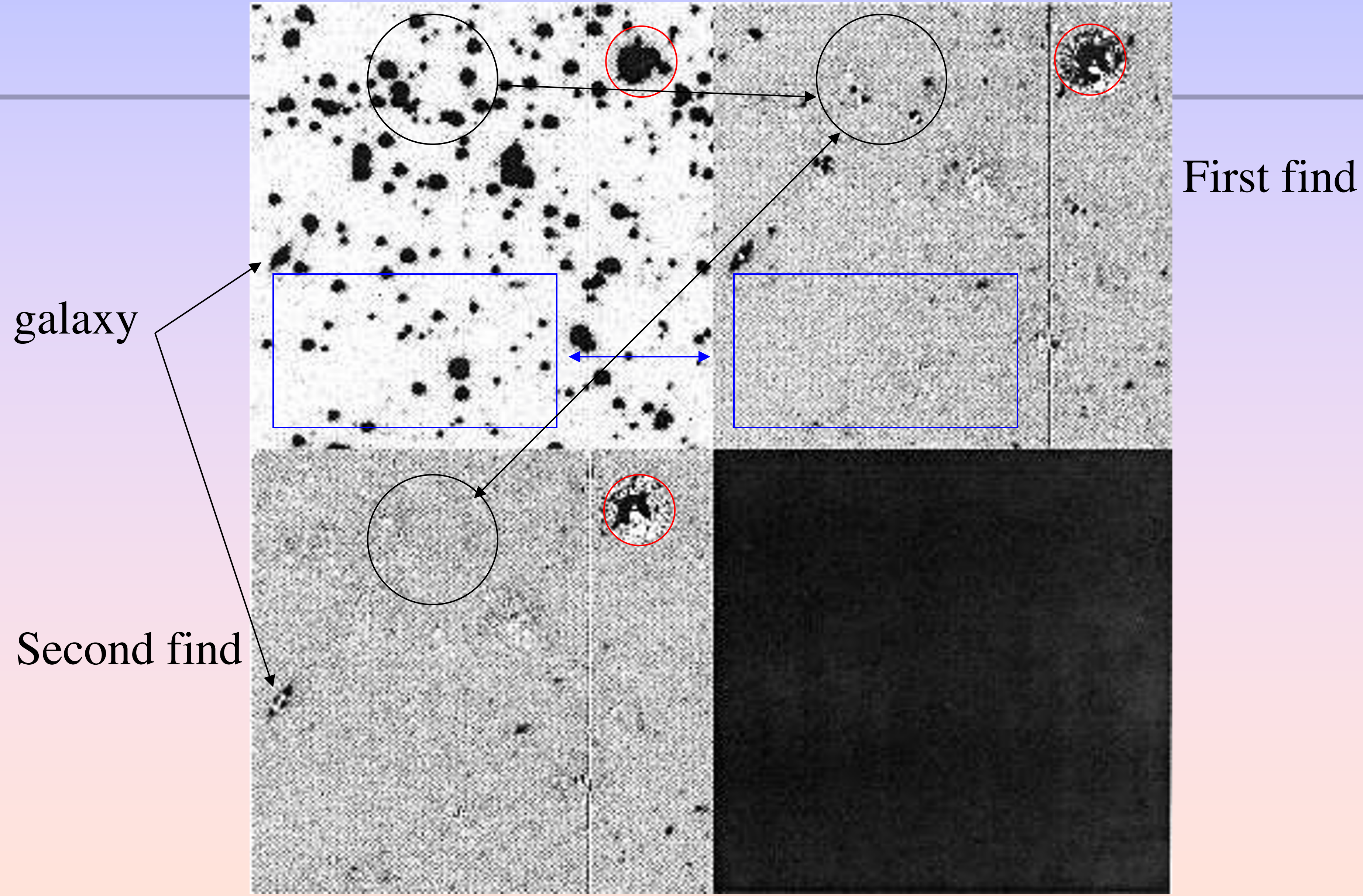
Scaling factor — ratio of actual psf fit to how well it should have fit


Star profile
+
PSF
residual after PSF fit
CHI~1
blend
CHI>1
galaxy
CHI>1

DAOPHOT run

1. Attach frame
2. find (frame.coo)
3. phot (frame.ap)
4. PSF loop (frame.psf)
5. Allstar (frame.als, frames.fits)
6. Attach subtracted frame
7. Find (frames.coo)
8. Phot (frames.ap)
9. Merge two lists
10. allstar

Star-subtracted frame


First find
galaxy
Second find

Post-DAOPHOT

- You usually want to combine photometry in each filter and match up stars in different filters to determine colors.
- First, need to determine the coordinate transformation between frames. You can do this and combine *photometry* or *images*.
- In IRAF, use a list of a matched stars and *geotrans* and *geomap*.
- There are standalone Stetson programs to combine DAOPHOT-format photometry files

DAOMATCH

- DAOMATCH uses the Method of Matching Triangles. Triangle side length ratios are invariant under rotation, translation, scale change and ``flip''. Groth, 1986, AJ, 91, 1244. (note: #triangles goes like n!/[3!(n-3)!])
- Check bright stars in two files, identify matching triangles, solve for coefficients in:

$$x_1 = A + Cx_2 + Dy_2$$

$$y_1 = B + Ex_2 + Fy_2$$

DAOMATCH

- For dithered frames:
  - A,B - x,y offsets
  - C,F ~ 1 (scale changes in x and y)
  - D,E ~ 0 (cross-terms are non-zero for rotations)
- Use this with .als files and produce a .mch file with the coordinate transformations. This is usually used as the first guess, to be fed into DAOMASTER

DAOMASTER

- DAOMASTER takes the DAOMATCH .mch files with transformations and a list of .als files and (1) refines the transformations using all matched stars, (2) derives robust photometric offsets between frames and (3) *correctly* averages measurements (remember to never average magnitudes!)

Photometric Calibration

- The photometric standard systems have tended to be zero-pointed arbitrarily. Vega is the most widely used and was original defined with V≈ 0 and all colors = 0.
- Hayes & Latham (1975, ApJ, 197, 587) put the Vega scale on an absolute scale.
- The AB scale (Oke, 1974, ApJS, 27, 21) is a physical-unit-based scale with:

$$m(AB) = -2.5\log(f) - 48.60$$

where f is monochromatic flux is in units of erg/sec/cm^2/Hz. Objects with constant flux/unit frequency interval have zero color on this scale

Photometric calibration-II

1. *Instrumental* magnitudes

Counts/sec → I

$$m = c_0 - 2.5\log(I \bullet t)$$

$$= c_0 - 2.5\log(I) - 2.5\log(t)$$

$\underbrace{c_0 - 2.5\log(I)}_{m_{instrumental}}$

Photometric Calibration-III

- To convert to a *standard* magnitude you need to observe some standard stars and solve for the constants in an equation like:

$$m_{inst} = M + c_0 + c_1 X + c_2(\text{color}) + c_3(\text{UT}) + c_4(\text{color})^2 + \ldots$$

Stnd mag

zpt

airmass

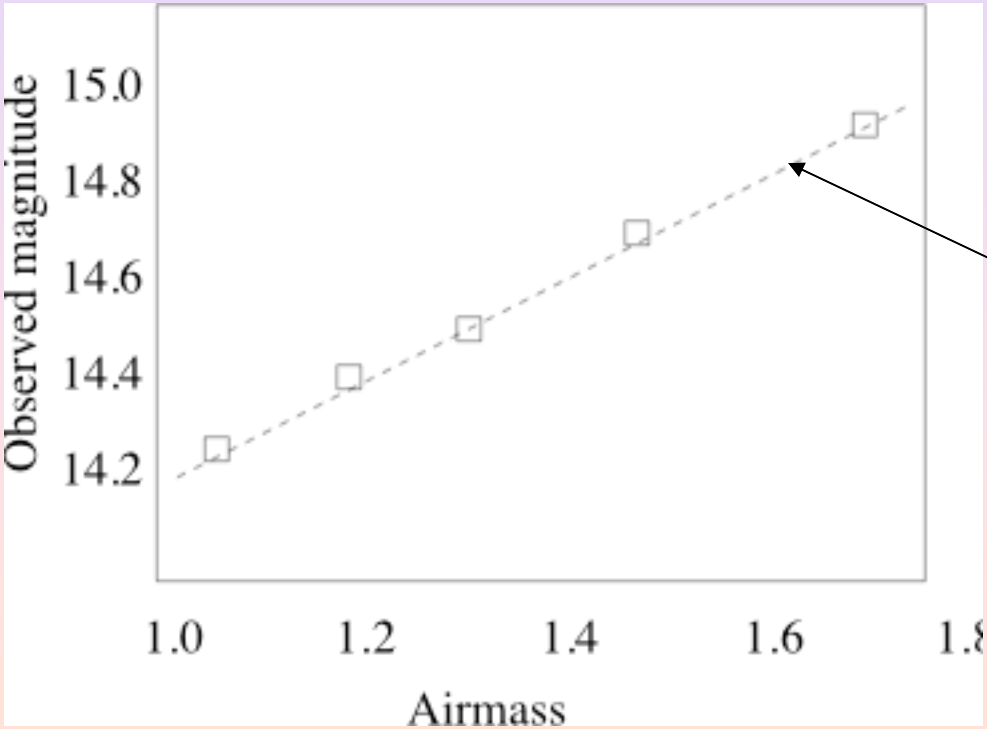
Color term

Instr mag

Extinction coeff (mag/airmass)

Extinction Coefficients

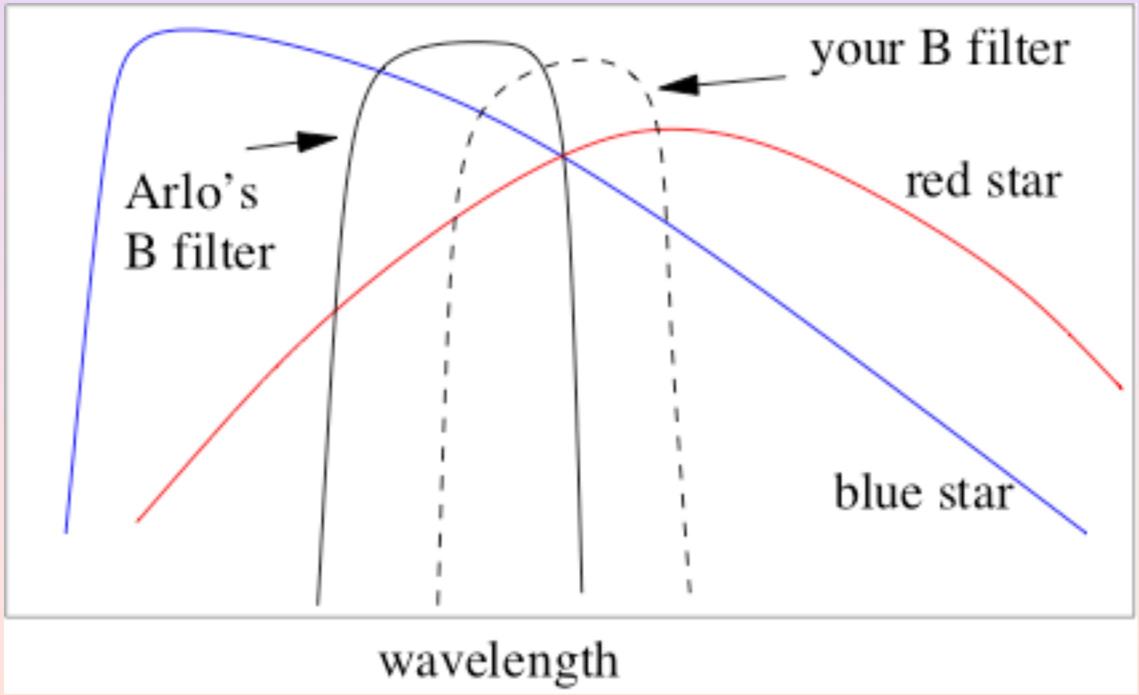
- Extinction coefficients:
  - Increase with decreasing wavelength
  - Can vary by 50% over time and by some amount during a night
  - Are measured by observing standards at a range of airmass during the night

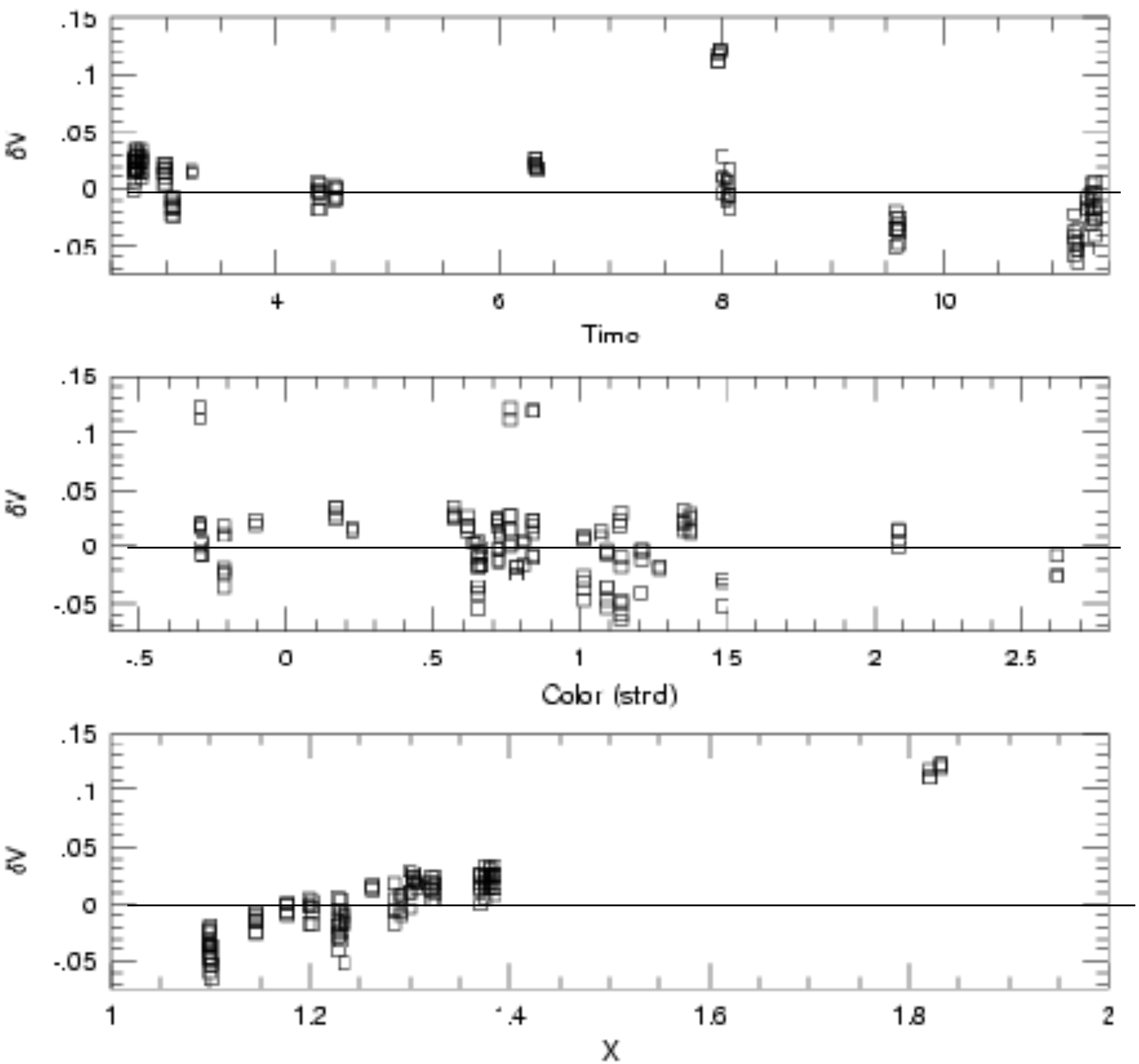


Slope of this line is c_1

Color Terms

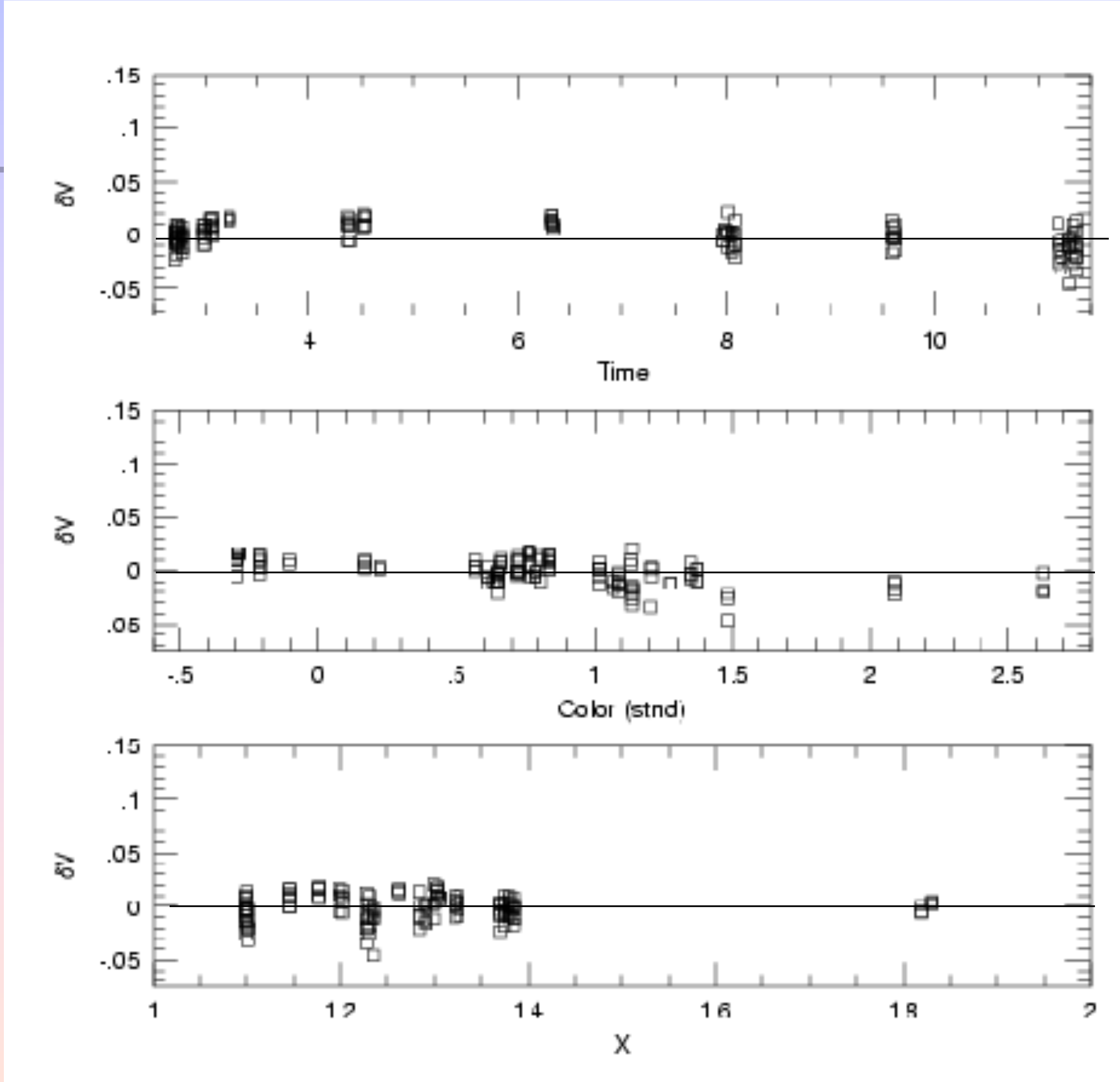
- The *color terms* come about through mismatches between the effective bandpasses of your filter system and those of the standard system. Objects with different spectral shapes have different offsets.





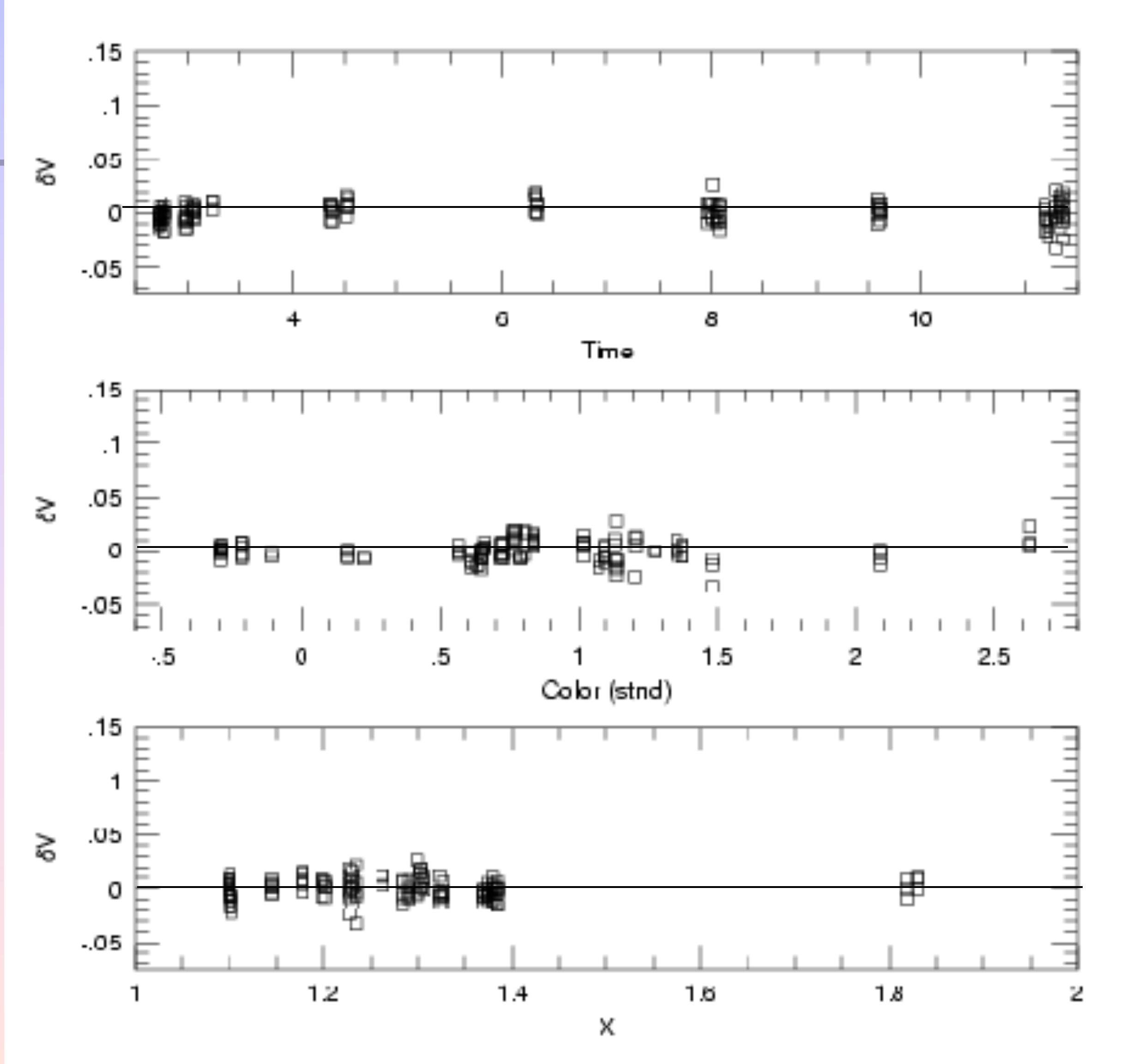
$V = v_1 + a_0$

RMS=0.055



$$V = v_{inst} + c_0 + c_1 X$$

RMS=0.032



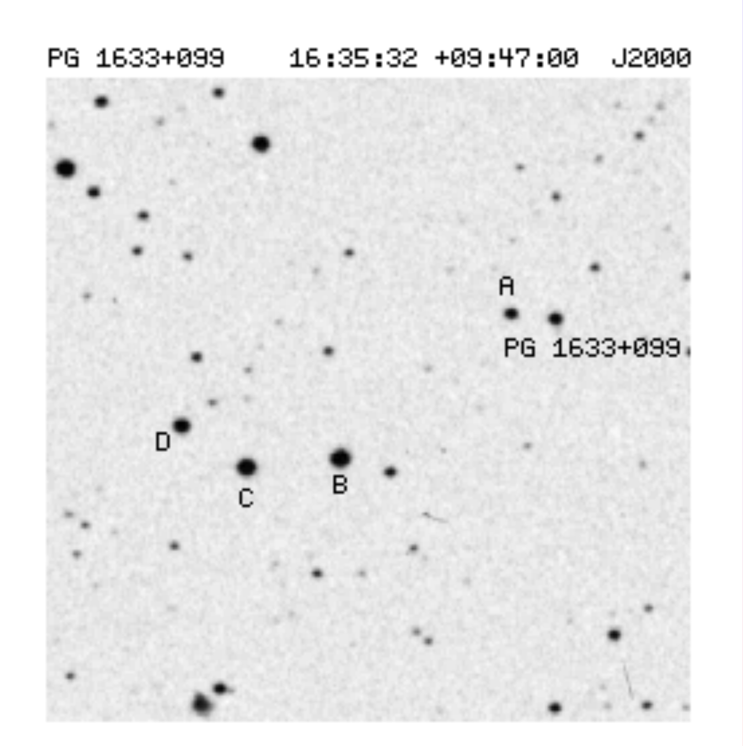
$V = v_{inst} + c_0 + c_1 X + c_2 (B-V)$

RMS=0.021

Photometric Standards

- Landolt (1992, AJ, 104, 336)
- Stetson (2000, PASP, 112, 995)
- Fields containing several well measured stars of similar brightness and a big range in color. The blue stars are the hard ones to find and several fields are center on PG sources.
- Measure the fields over at least the the airmass range of your program objects and intersperse standard field observations throughout the night.

Example Landolt Field



Standard Transformation

- Usually observe standard fields on a night
  ………………… program fields …………
  - Standards measured with growth-curve aperture photometry to estimate the `total' light
  - Program stars measured via frame-dependent PSF scaling factors
- For each program field you need to find the magnitude difference between the PSF and `total' light -- this is called the *aperture correction*

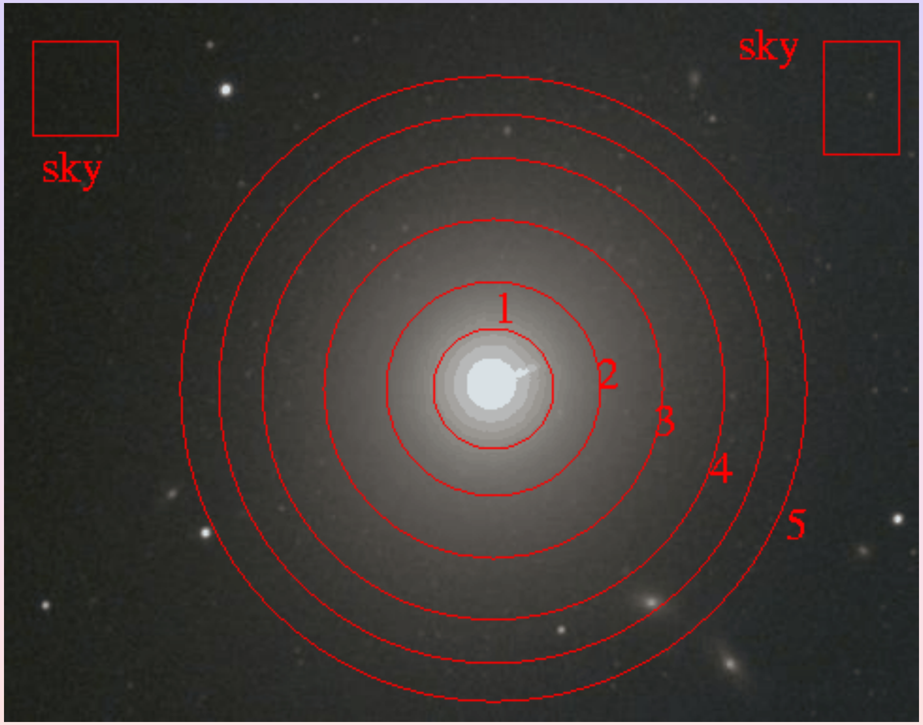
Aperture correction procedure

- After finding and PSF fitting stars on a frame, subtract the fitted PSFs for all but 20 or 30 relatively isolated objects (after the subtraction, they are hopefully very isolated)
- Do growth-curve photometry on the frame and find:

$$\overline{\Delta} = \sum_{1}^{n} (\mathrm{mag}_{\mathrm{PSF}} - \mathrm{mag}_{\mathrm{aperture}})/n$$

- This gets added to all the PSF-based magnitudes on the frame.
- Note: check for position-base trends

Surface Photometry

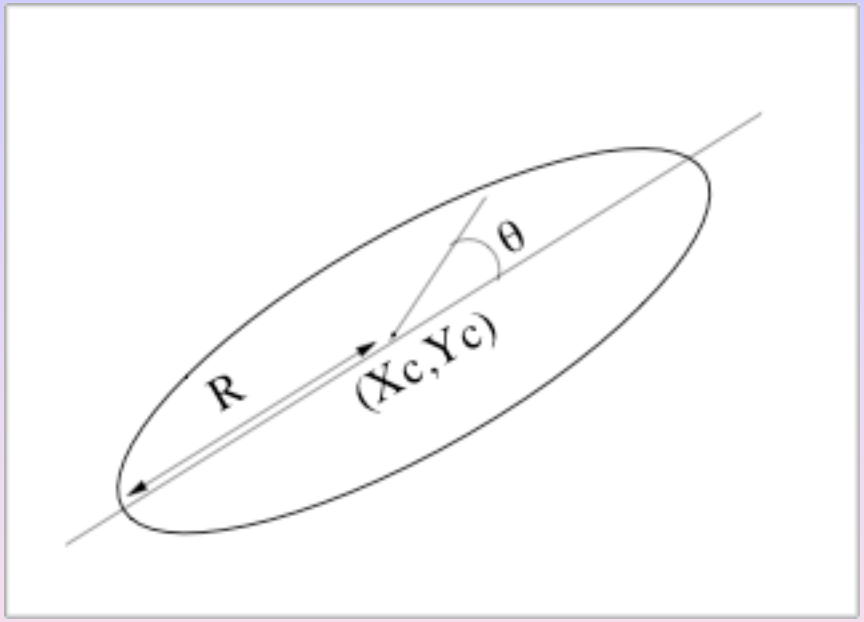


Simple approach of aperture photometry works OK for some purposes.

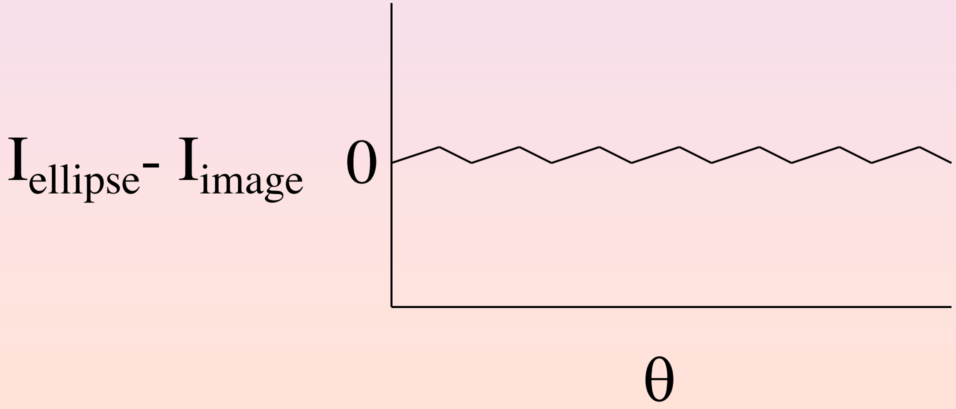
$mag = c_0 - 2.5(cnts_{aper} - \pi r^2 sky)$

Typically working with much larger apertures
- prone to contamination
- sky determination even more critical
- often want to know more than total brightness

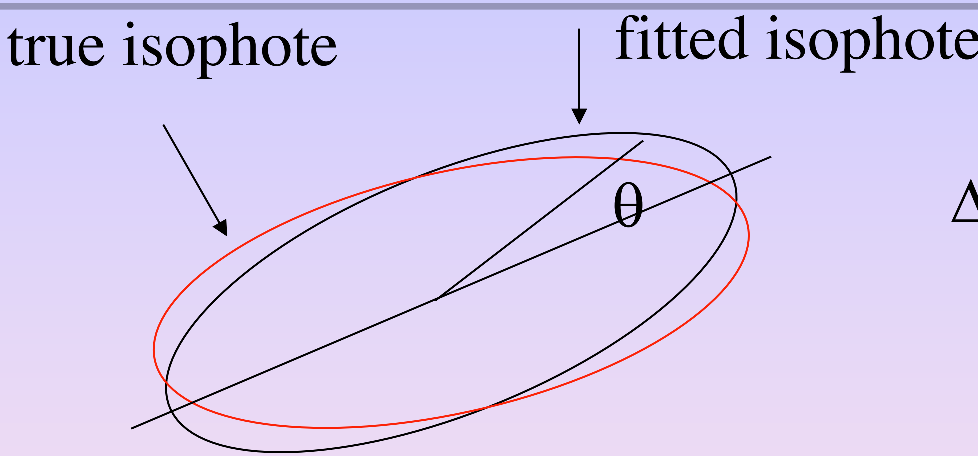
- There is a long history of surface photometry with CCDs:
  - GASP Davis et al., AJ, 90, 1985
  - Jedrzejewski, MNRAS, 226, 747, 1987
- Could fit (or find) *isophotes*, and the most common procedure is to fit elliptical isophotes.
- Parameters are: x_{center}, y_{center}, ellipticity (ε), R (semi-major axis) and position angle.

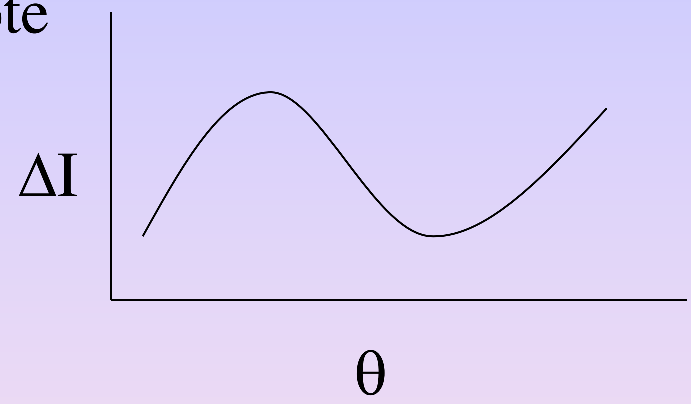


Start with guesses for x_c, y_c, R, ε and p.a., then compare the ellipse with real data all along the ellipse (all θ values)



Good isophote





Fit the ΔI - θ plot and iterate on x_c, y_c, p.a., and ε to minimize the coefficients in an expression like:

$$I(\theta)= I_0 + A_1\sin(\theta) + B_1\cos(\theta) + A_2\sin(2\,\theta) + B_2\cos(2\theta)$$

Changes to x_c and y_c mostly affect A_1, B_1,
p.a. " " A_2
ε " " B_2

- More specifically:

$$\Delta(\text{major axis center}) = \frac{-B_1}{I'}$$

$$\Delta(\text{minor axis center}) = \frac{-A_1(1-\varepsilon)}{I'}$$

$$\Delta(\varepsilon) = \frac{-2B_2(1-\varepsilon)}{a_0 I'}$$

$$\Delta(\text{p.a}) = \frac{2A_2(1-\varepsilon)}{a_0 I'[(1-\varepsilon)^2 - 1]}$$

where:

$$I' = \left.\frac{\partial I}{\partial R}\right|_{a_0}$$

← Position along the semi-major axis

- After finding the best-fitting elliptical isophotes, the residuals are often interesting. Fit:

$$I = I_0 + A_n \sin(n\theta) + B_n \cos(n\theta)$$

already minimized n=1 and n=2, n=3 is usually not significant, but:

B_4 is negative for ``Boxy'' isophotes

B_4 positive for ``disky'' isophotes

Surface Photometry Tools

- How do YOU carry out surface photometry measurements?
- For the class will use a Jedrxxxx-based set of algorithms available via IRAF in the STScI STSDAS set of packages.
- stsdas.analysis.isophote

Stsdas isophote tasks

bmodel	geompar@	isomap	magpar@
controlpar@	isoexam	isopall	samplepar@
ellipse	isoimap	isoplot	

Parameter files

Controlpar

```
PACKAGE = isophote
   TASK = controlpar

(conver =          0.05) convergency criterion (maximum harmonic amplitud
(minit  =            10) minimun no. of iterations at each sma
(maxit  =            50) maximun no. of iterations at each sma
(hcenter=            no) hold center fixed ?
(hellip =            no) hold ellipticity fixed ?
(hpa    =            no) hold position angle fixed ?
(wander =         INDEF) maximum wander in successive isophote centers
(maxgerr=           0.5) maximum acceptable gradient relative error
(olthres=            1.) object locator's k-sigma threshold
(soft   =            no) soft stop ?
(mode   =            al)
```

Geompar

PACKAGE = isophote
TASK = geompar

```
(x0     =          INDEF) initial isophote center X
(y0     =          INDEF) initial isophote center Y
(ellip0 =            0.2) initial ellipticity
(pa0    =            20.) initial position angle (degrees)
(sma0   =            10.) initial semi-major axis lenght
(minsma =             0.) minimum semi-major axis lenght
(maxsma =          INDEF) maximum semi-major axis lenght
(step   =            0.1) sma step between successive ellipses
(linear =             no) linear sma step ?
(maxrit =          INDEF) maximum sma lenght for iterative mode
(recente=            yes) allows finding routine to re-center x0-y0 ?
(xylearn=            yes) updates pset with new x0-y0 ?
(physica=            yes) physical coordinate system ?
```

Often it is a good idea to put in starting values

Samplepar

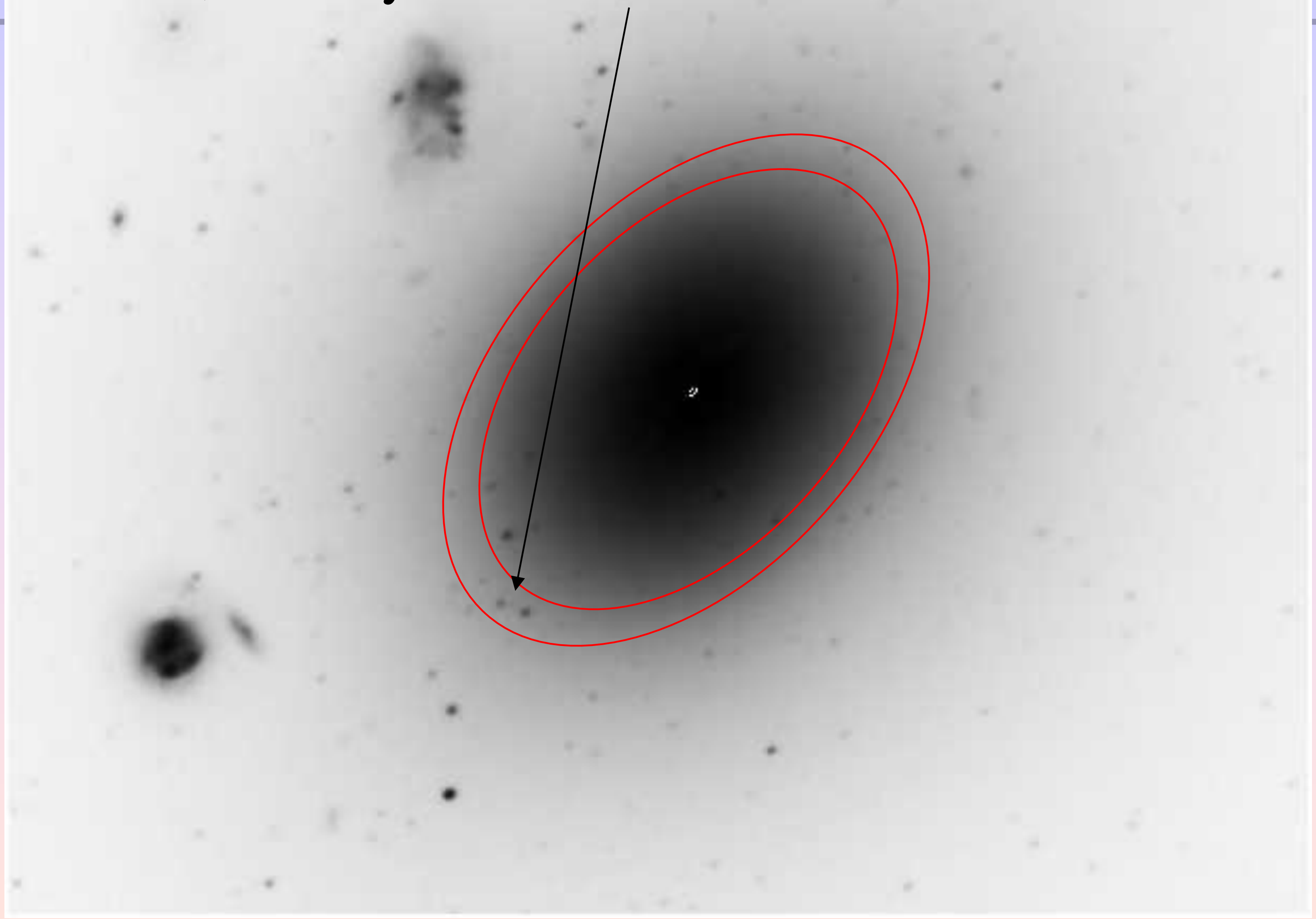
PACKAGE = isophote
TASK = samplepar

(integrm=	bi-linear) area integration mode	
(usclip =	3.) sigma-clip criterion for upper deviant points	Important!
(lsclip =	3.) sigma-clip criterion for lower deviant points	
(nclip =	0) number of sigma-clip iterations	
(fflag =	0.5) acceptable fraction of flagged data points	
(sdevice=	none) graphics device for ploting intensity samples	
(tsample=	none) tables with intensity samples	
(absangl=	yes) sample angles refer to image coord. system ?	
(harmoni=	none) optional harmonic numbers to fit	
(mode =	al)	

ellipse

- Use the σ-clipping option
  - Very common to pre-clean frames:
    - o Subtract point sources with DAOPHOT
    - o Mask saturated stars and CCD flaws
    - o Mask other galaxies
- Sometimes it is useful to input starting values

Calculate mean and RMS pixel intensity for annulus, toss any values above mean + nRMS



- Ellipse produces a Table (in STSDAS table format, ttools.tprint allows you to view this) with the parameters of the best fitting ellipses along the semi-major axis.
- Plotting $I_{ellipse}$ vs r gives the *surface brightness profile*

Photometry is the usual:

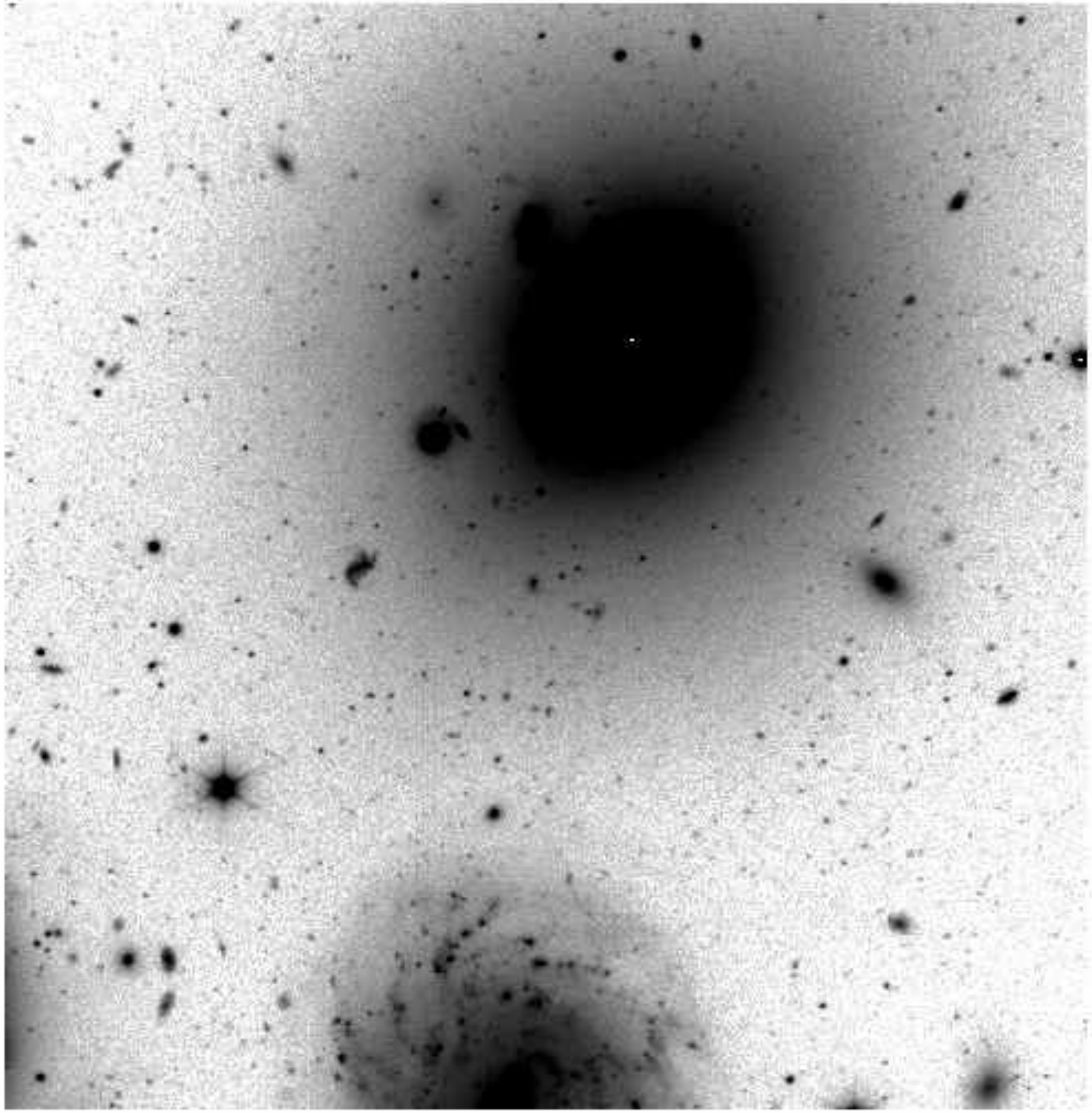
$$m = c_0 - 2.5\log(\sum(\text{pixels in } r+\Delta r) - (\text{npix} \bullet \text{sky})$$

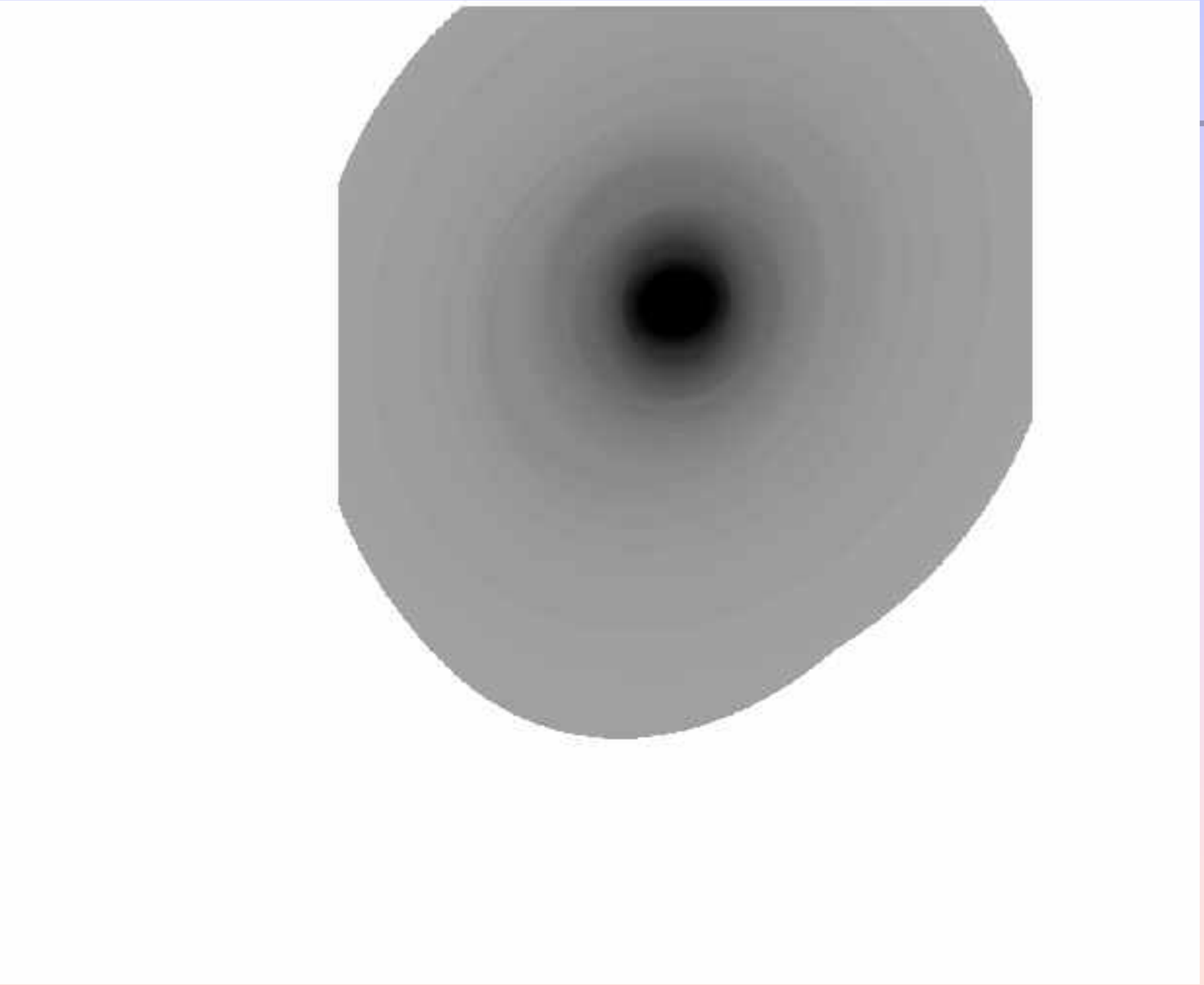
input image name (test3):
output table name (test3.tab):
Running object locator... Done.

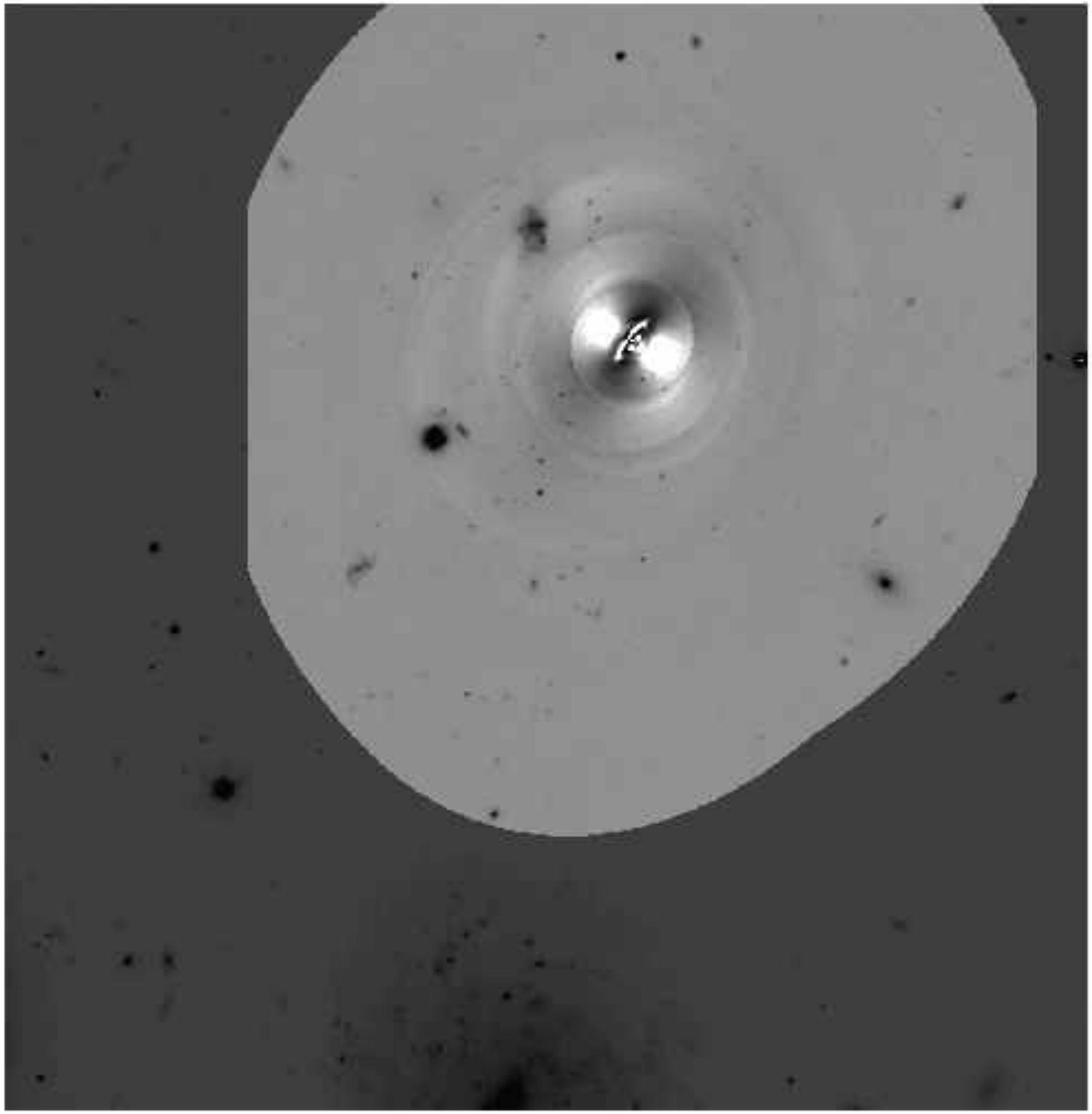
```
#
# Semi-    Isophote      Ellipticity     Position   Grad.  Data Flag Iter. Stop
# major      mean                          Angle      rel.               code
# axis     intensity                               error
#(pixel)                              (degree)
#
  40.00  4219.62(527.26) 0.123(0.002) -70.00( 0.54) 0.125  234   0    50    2
  44.00  3773.10(481.03) 0.123(0.002) -70.00( 0.59) 0.122  258   0    50    2
  48.40  3384.59(426.91) 0.123(0.002) -70.00( 0.52) 0.116  284   0    50    2
  53.24  3038.81(384.52) 0.123(0.002) -70.00( 0.47) 0.110  312   0    50    2
  58.56  2725.05(344.36) 0.123(0.002) -70.00( 0.56) 0.097  343   0    50    2
  64.42  2431.91(297.83) 0.123(0.002) -70.00( 0.38) 0.091  378   0    50    2

634.52   556.57(  7.44) 0.273(0.009) -18.68( 1.03) 0.101 2602 760    17    1
  36.36  4728.37(566.24) 0.123(0.003) -70.00( 0.70) 0.125  213   0    50    2
  33.06  5287.32(620.80) 0.123(0.005) -70.00( 1.36) 0.129  193   0    50    2


   0.73 51976.14(8482.2) 0.269(INDEF) -45.76(INDEF) 1.460   13  0    1   4
   0.66 53679.33(7585.3) 0.269(INDEF) -45.76(INDEF) 1.853   13  0    1   4
   0.60 55147.36(7006.2) 0.269(INDEF) -45.76(INDEF) 1.951   13  0    1   4
   0.55 56150.06(6355.0) 0.269(INDEF) -45.76(INDEF) 2.616   13  0    1   4
```

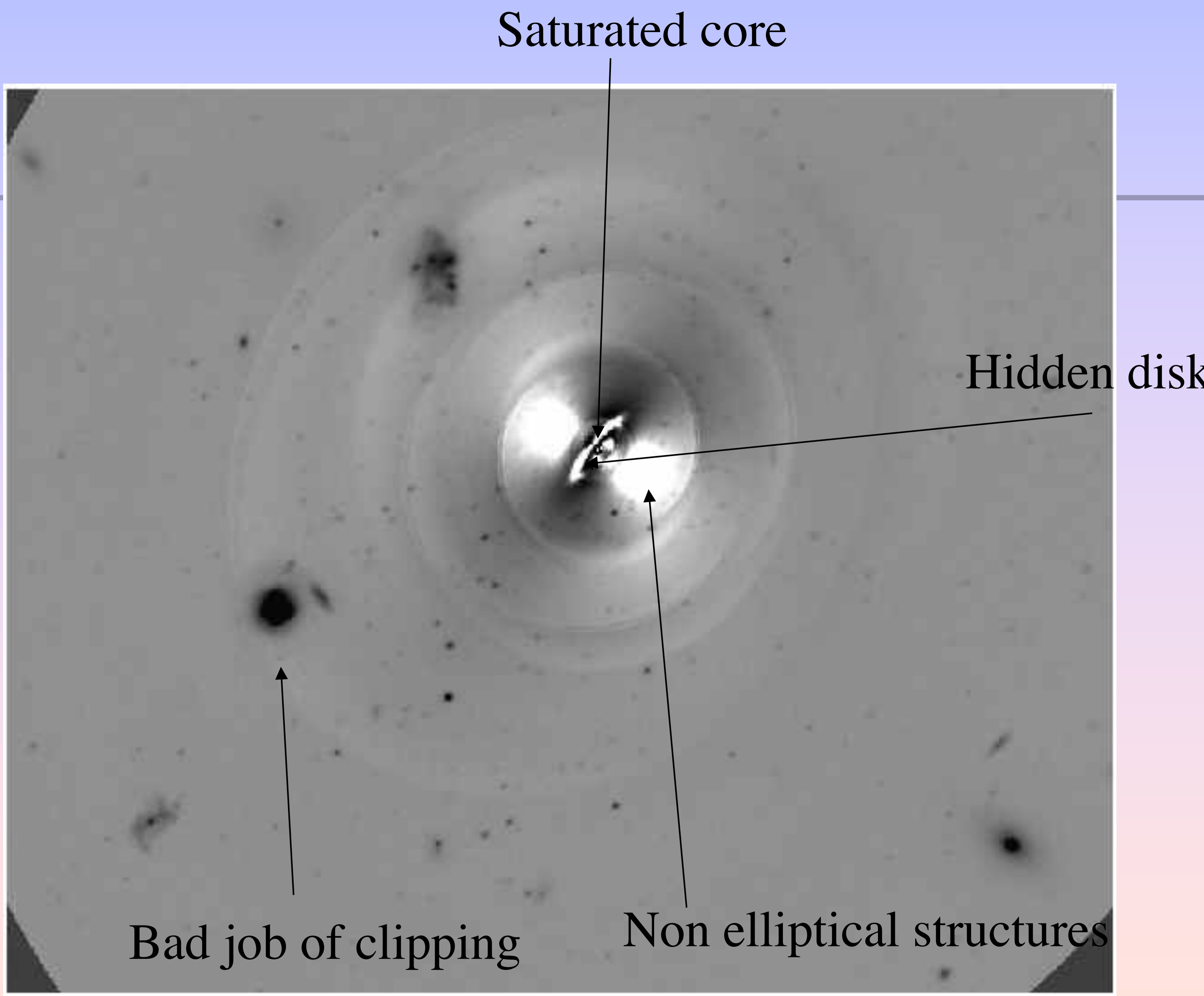
bmodel

- After you have run ellipse and produced a table. The task called *bmodel* will build a smooth image of the family of ellipses. Subtracting this from the original frame will tell you how good the fit is and will reveal non-axially symetric structures.



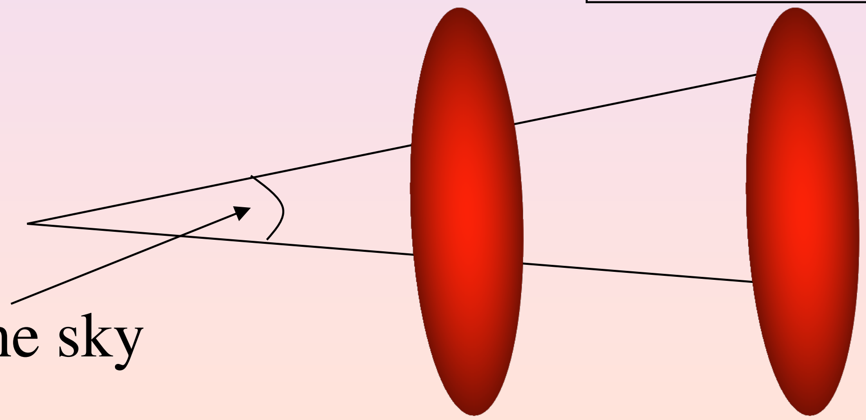





Saturated core
Hidden disk
Bad job of clipping
Non elliptical structures

- Last surface brightness note, in the near Universe, surface brightness is distant independent.
  - ➢S.B. $\propto$ I/(area of galaxy)

Brightness drop off with distance is exactly compensated by larger surface area of galaxy contributing



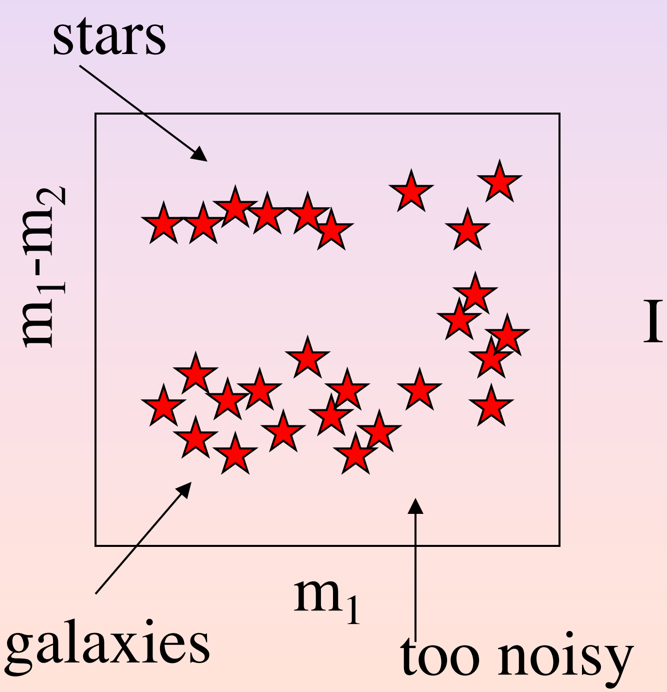
Fixed angle on the sky

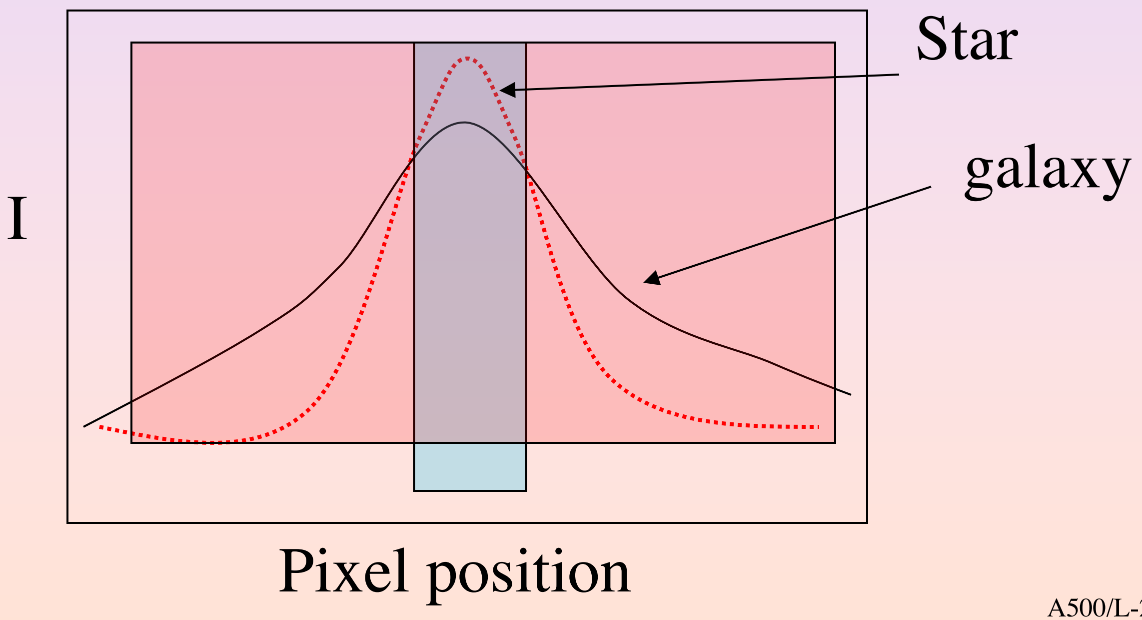
Small galaxies and classification

- Originally (starting with Kron in 1979) simple star-galaxy separation was the goal.
- These days packages do a lot more:
  - Deblending
  - Filtering
  - Photometry shape decomposition
    - FOCAS Jarvis & Tyson 1981, AJ 86, 476
    - PPP Yee 1991, PASP, 103 396
    - Source Extractor: Bertin & Arnouts 1996, A&AS, 117, 393

Star-Galaxy separation

- Galaxies are resolved, stars are not
- All methods use various approaches to comparing the amount of light at large and small radii.





Criteria:

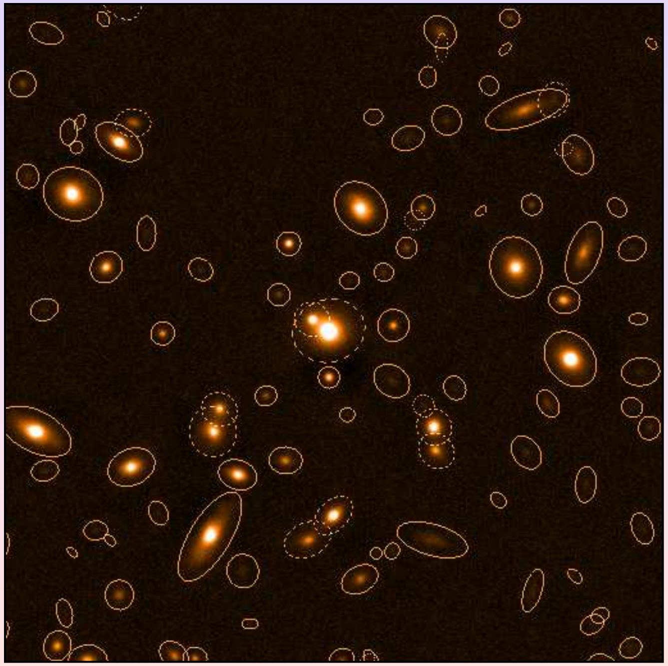
- $m_{\text{small r}}/m_{\text{large r}}$
- Total mag/peak count
- Mag/average surface brightness
- DAOPHOT CHI (PSF fit/predicted PSF fit)
- petroR50/petroR90 (SDSS)
- Often talk about *moment analysis*.

$$\frac{\sum_i \mathrm{I}_i \mathrm{x}_i^n}{\sum_i \mathrm{I}_i}$$

Same thing in y. n=1 is centroid, n=2 is variance etc.

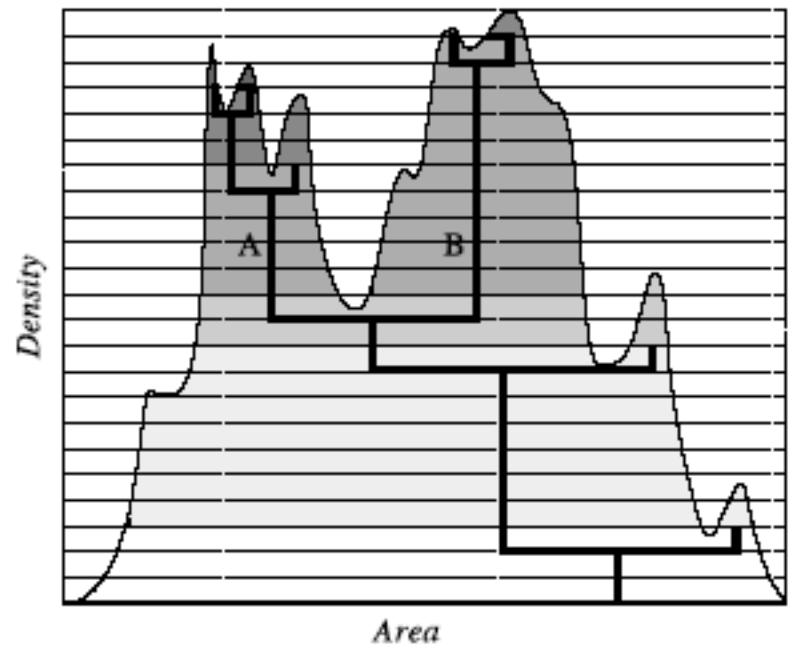
Note; ratio of second moments useful for ellipticity measurements

Source Extractor (*SE*)



- Most commonly used package these days is ***SE*** (although for pure star-galaxy separation it is hard to beat using the difference of two apertures).

- Bertin & Arnouts, 1996, A&AS, 117, 393
- User's Manual
- ***SE*** for Dummies v4
- Not for good surface photometry, but good for classification and rough photometric and structural parameter derivation for large fields.
  1. Background map (sky determination)
  2. Identification of objects (thresholding)
  3. Deblending
  4. Photometry
  5. Shape analysis



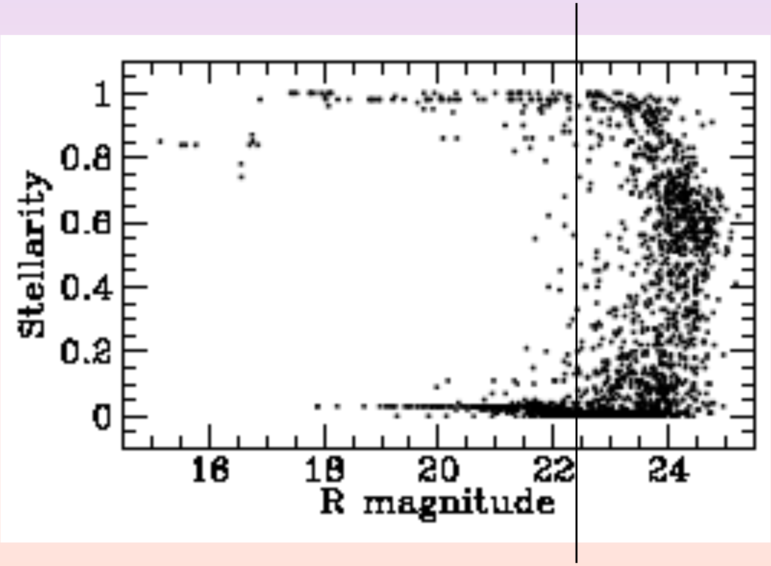
Thresholding is an alternative to *peak finding*. Look for contiguous pixels above a threshold value.

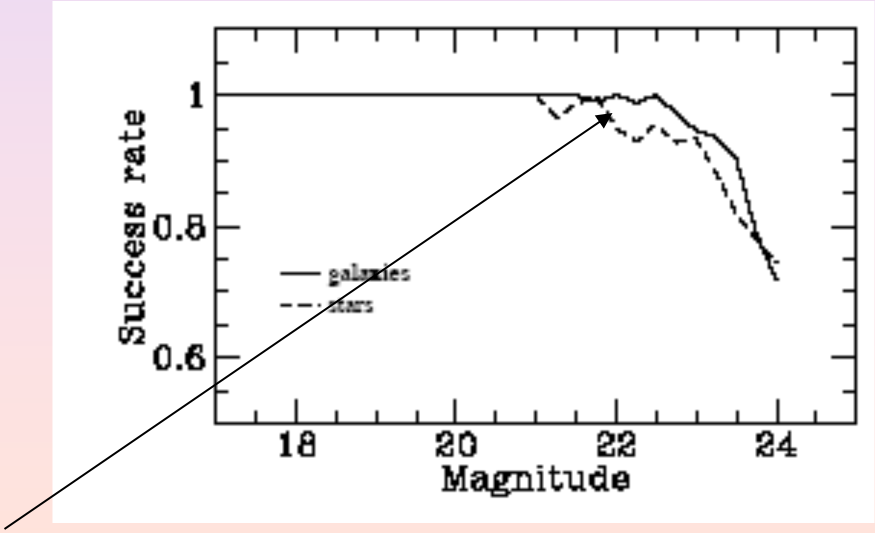
- User sets area, threshold value.
- Sometimes combine with a smoothing filter

Deblending based on multiple-pass thresholding

SE Star/Galaxy Separation

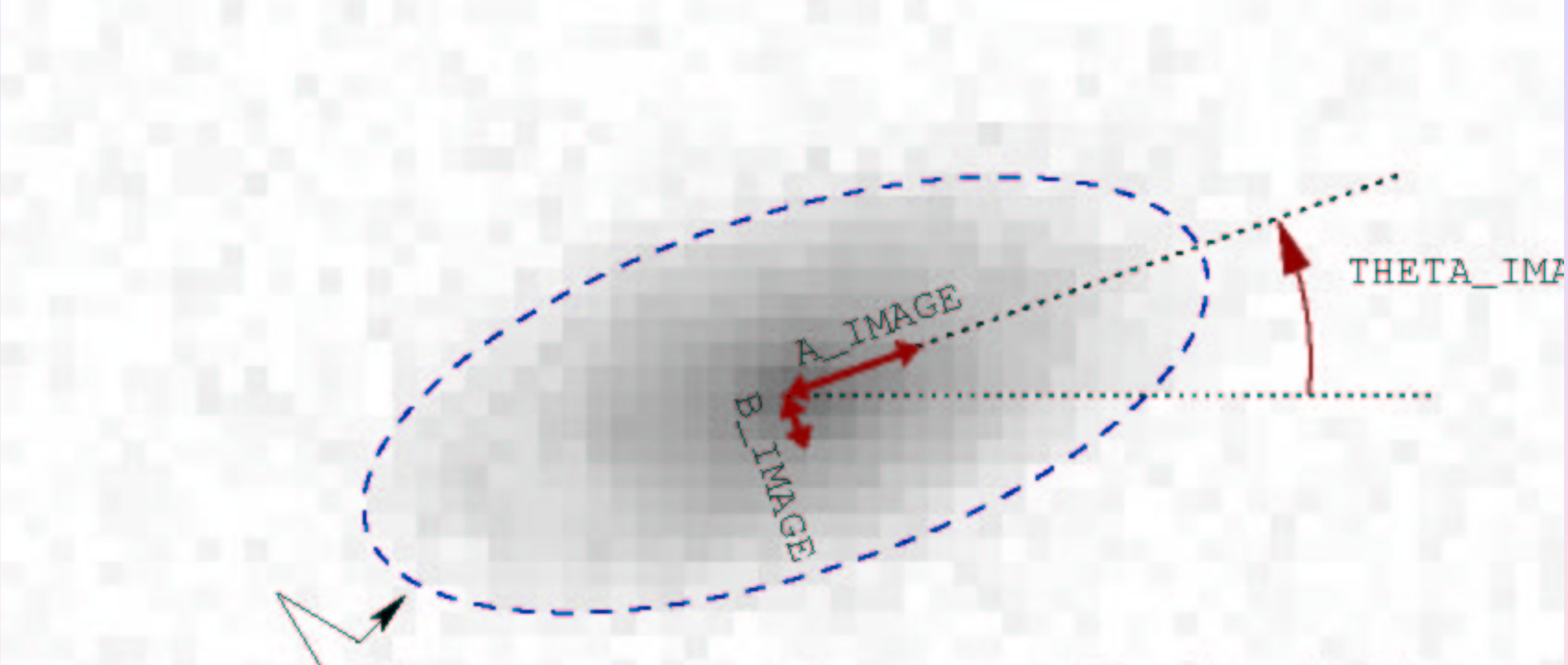
- Lots of talk about neural-net algorithms, but in the end it is a moment analysis.
- ``stellarity''. Typically test it with artificial stars and find it is very good to some limiting magnitude.



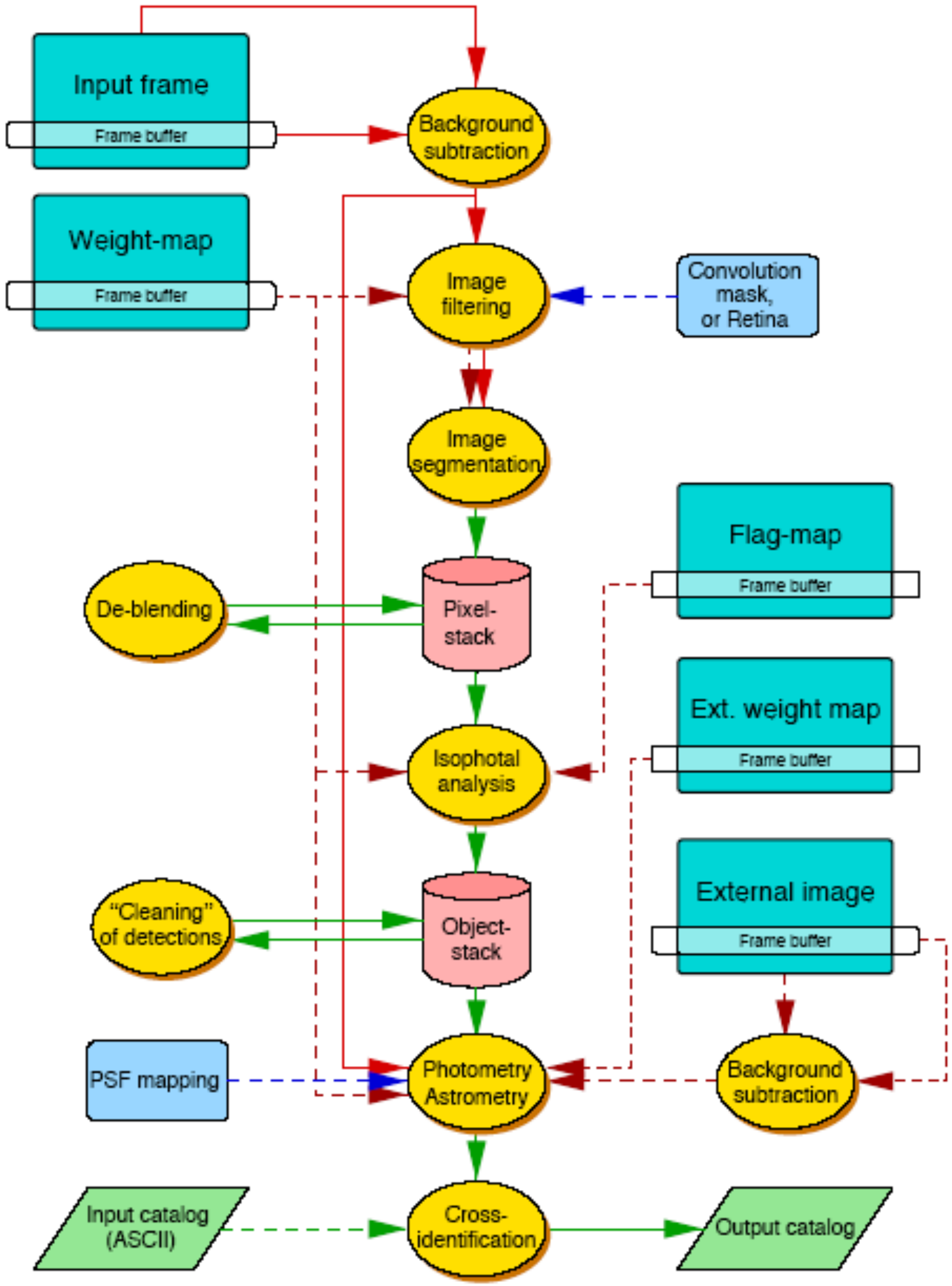


s-g going bad at R~22

Shapes



$$\text{CXX\_IMAGE}\times(x-\overline{x})^2+\text{CYY\_IMAGE}\times(y-\overline{y})^2+\text{CXY\_IMAGE}\times(x-\overline{x})(y-\overline{y}) = 3^2$$



Input frame
Frame buffer
Background subtraction
Weight-map
Frame buffer
Image filtering
Convolution mask, or Retina
Image segmentation
Flag-map
Frame buffer
De-blending
Pixel-stack
Ext. weight map
Frame buffer
Isophotal analysis
External image
Frame buffer
"Cleaning" of detections
Object-stack
PSF mapping
Photometry Astrometry
Background subtraction
Input catalog (ASCII)
Cross-identification
Output catalog

Extended source photometry

- Profiles: the Sersic function
- Total apertures: the need for size and shape info
- Curve of growth and S/N: random vs sys. Error
- Basic shape indicex: light concentration, *C*
- Moments r_1, r_{-2} – characteristic size and shape
- η-function – characteristic size and shape
- Total aperture schemes and calibration
- Other shape indices: A, S, Gini, M_{20}

Profiles

- $I(r,\theta)$ = surface-brightness distribution.
- Sersic (1968) proposed general function for radial light distribution of galaxies

$$I(r) = I_e \mathrm{d}\exp\{-b_n[(r/r_e)^{1/n} - 1]\}$$

- r_e, I_e are size and surface-brightness where half the total light is enclosed ("e" for effective); b_n, a constant tunes this condition.
- n = 1/2: Gaussian - stars and cores of all seeing-limited images.
- n = 1: Exponential - most disks, some bulges, dwarf-ellipticals (dE, dSph)
- n = 4: de Voucouleurs' $r^{1/4}$ -law - some bulges, some ellipticals. A range of n desribes the elliptical family (luminosity dependence).

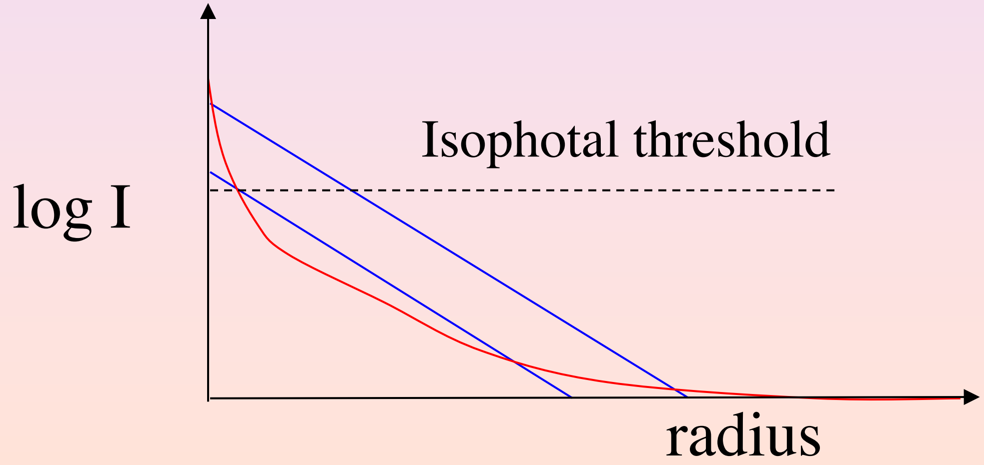
Size: r_e Surface-brightness: I_e Shape: n

Total Apertures

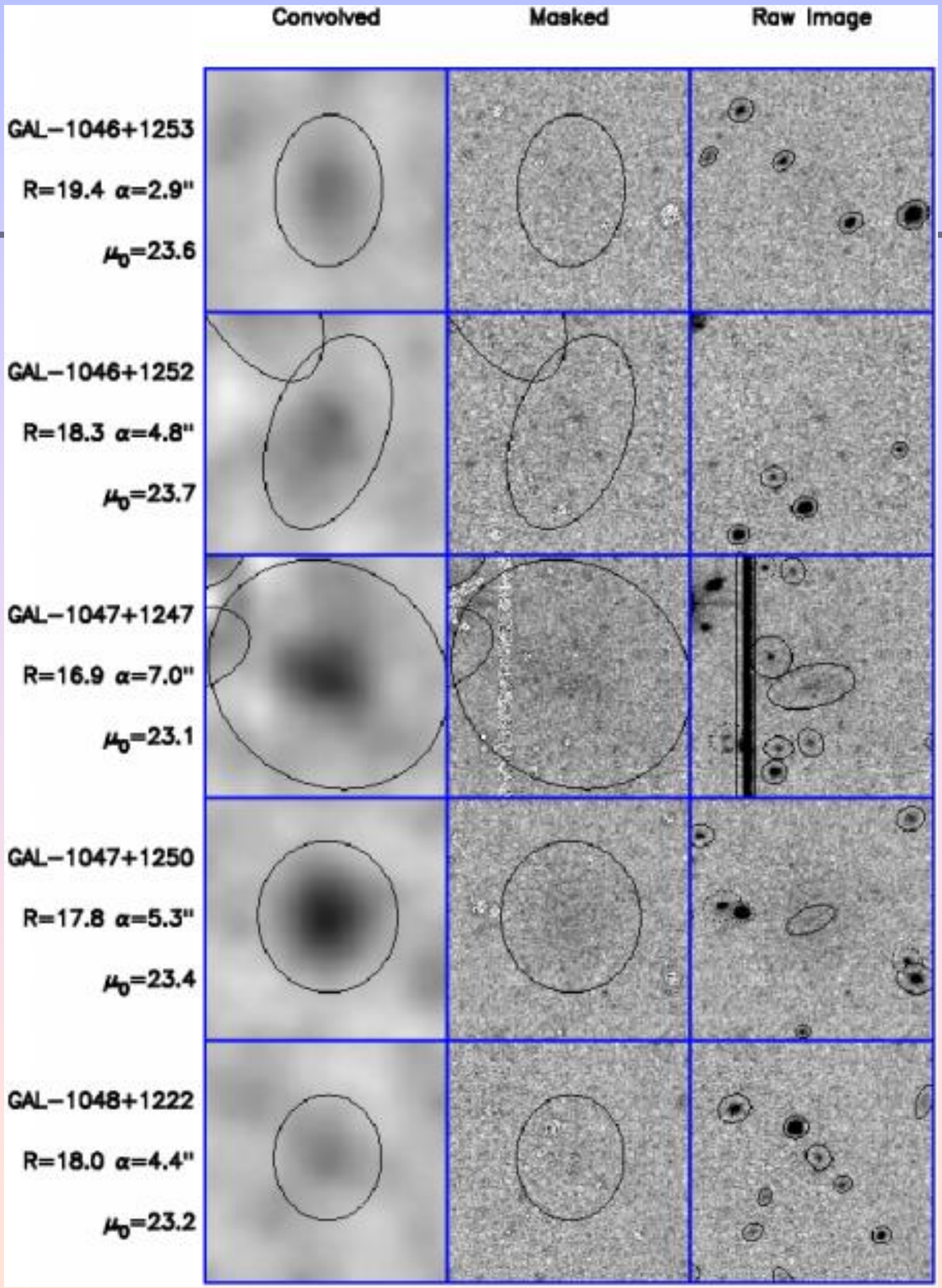
- Every galaxy has its own ***size*** and ***shape.***
- If you want to measure the total light, what do you do?
- Historical approach: use isophotes because the *isophotes* are well-defined and its what you can see on a per-pixel basis.
- True, the isophotal photometry is not meaningful.
- **Why isophotes are bad**: *the ice-berg effect*

  Galaxies have different I_e with the same size and shape

  For the same rest-frame I_e, redshift and k-corrections dim isophotes

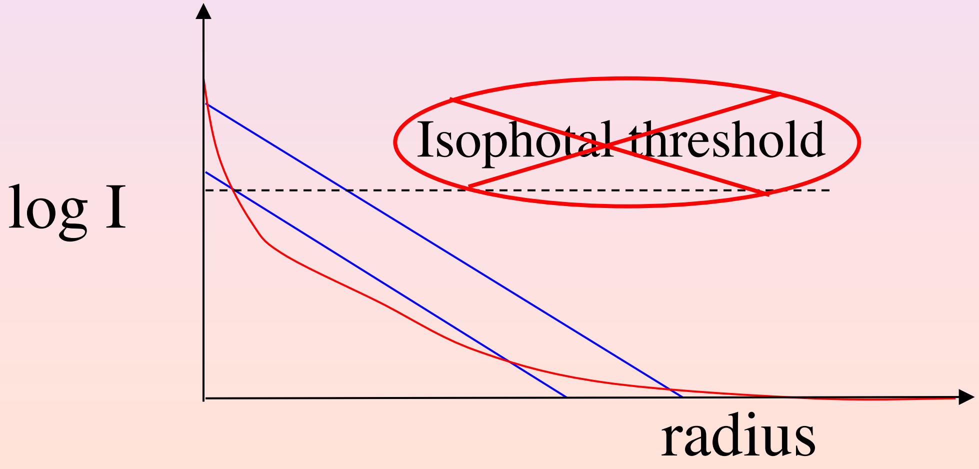


Avoid purely isophotal methods; Beware of data and results using such methods, particularly if probing to faint levels and/or high redshift.


Convolved
Masked
Raw Image
GAL−1046+1253
R=19.4 α=2.9"
μ0=23.6
GAL−1046+1252
R=18.3 α=4.8"
μ0=23.7
GAL−1047+1247
R=16.9 α=7.0"
μ0=23.1
GAL−1047+1250
R=17.8 α=5.3"
μ0=23.4
GAL−1048+1222
R=18.0 α=4.4"
μ0=23.2

Total Apertures

- Every galaxy has its own ***size*** and ***shape.***
- If you want to measure the total light, what do you do?
- Need to measure something about size which is not determined by the surface-brightness scale.
- Isophotes can still be useful to trace shape, but cannot be used to determined scale.

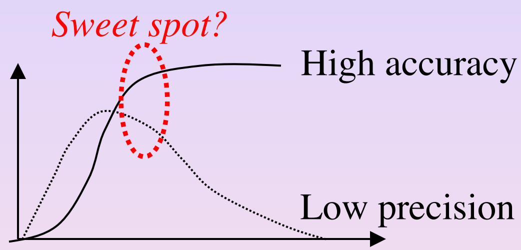


Curve of Growth and S/N

- *I(r, θ)* = surface-brightness distribution.
- g(r) is the curve of growth (c.o.g.) of the integrated light

$$g(r) = \int_0^{2\pi}\int_0^{r} I(r',\theta)\,r'\,dr'\,d\theta$$

g(r)

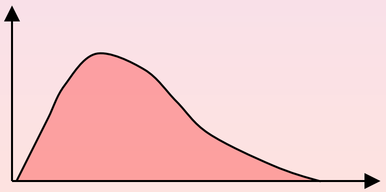


radius

- In background-limited regime, where g(r) is the signal,

$$S/N \propto g(r)/r$$

S/N

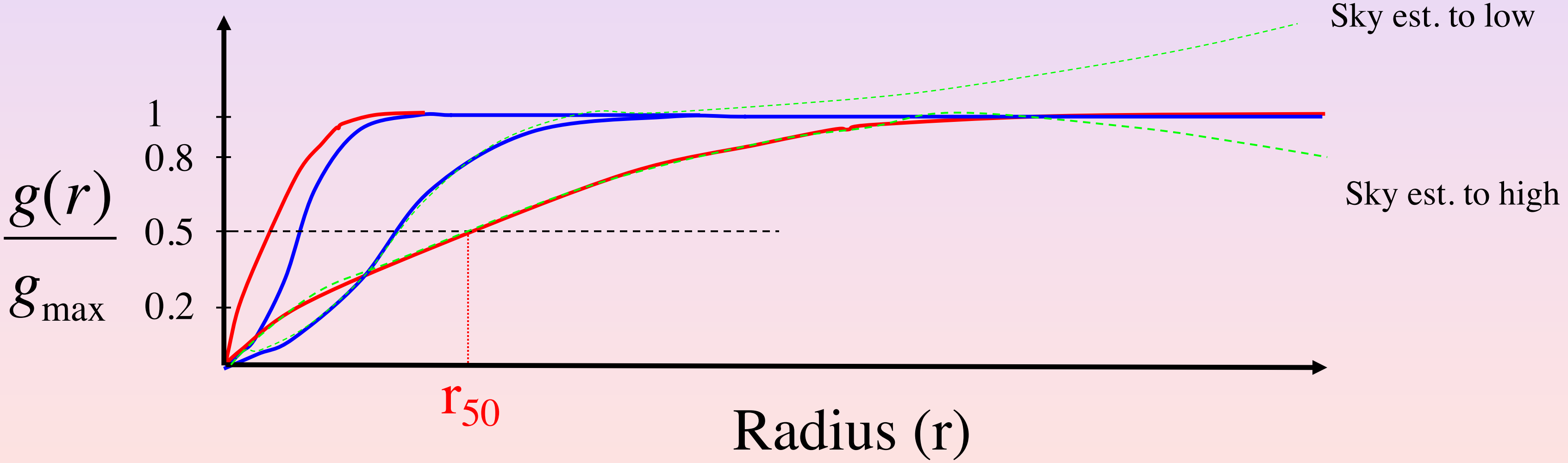


radius

Intrinsic trade: random vs sys. errors

Size based on g(r)

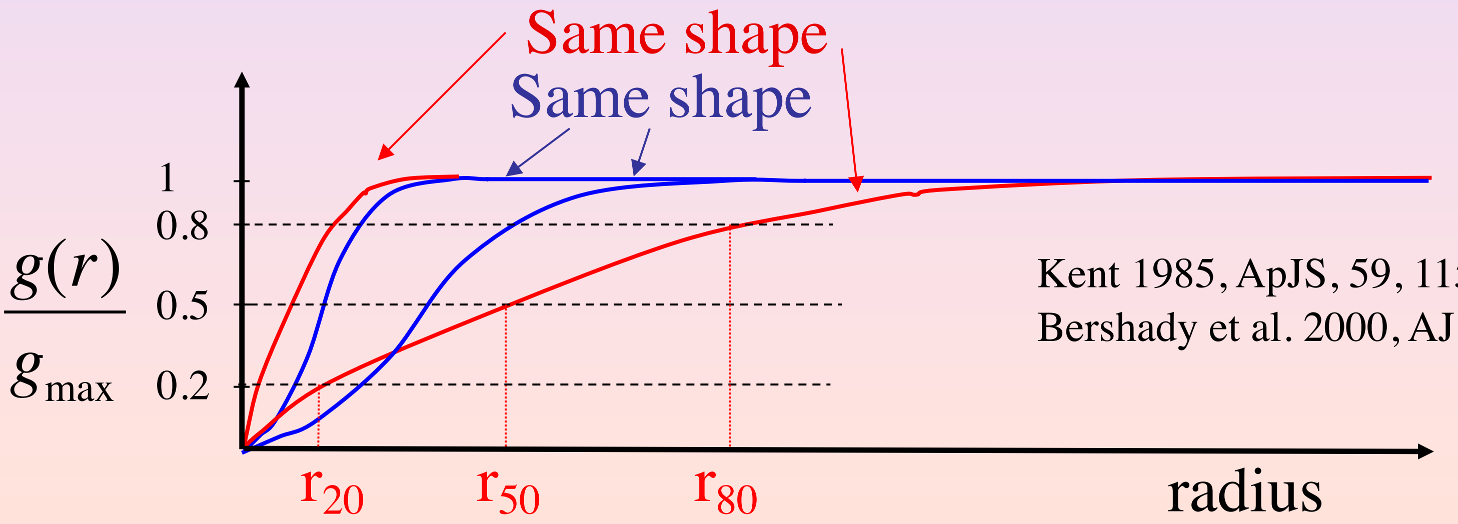
- Use g(r) to define characteristic size, e.g, r_{50}
- The S/N profile (g(r)/r) can also be used to define characteristic size, e.g., radius at which S/N peaks (r_{max})
- In general, $r_{max} \sim r_{50,}$ but this is only an approximation



Where do you determine g_{max}?
How good is your sky subtraction?

Shape based on g(r)

- Use g(r) to define charateristic radial shape, e.g., concentration index $C_{20:80} = 5 \log (r_{80}/r_{20})$.
- In general: $C = 5 \log r_{outer} / r_{inner}$
- Every profile shape has different C
- Different C definitions are better at distinguishing different types of profiles.



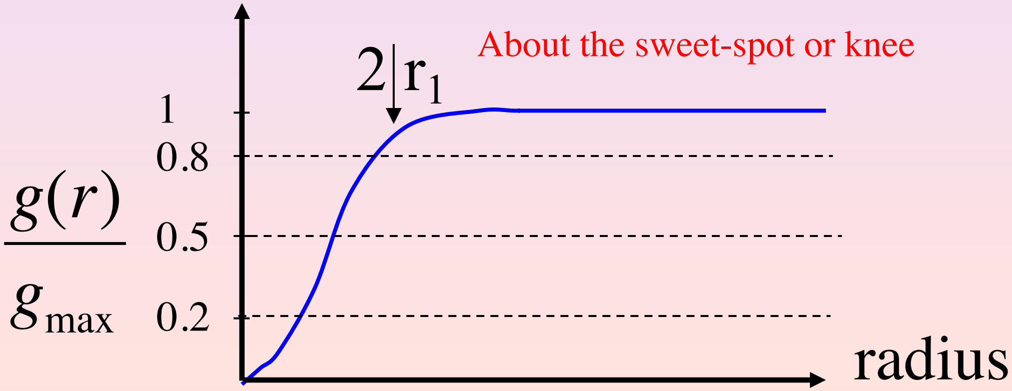
Kent 1985, ApJS, 59, 115
Bershady et al. 2000, AJ, 119, 2645

Moments based on g(r)

- Use g(r) moments to define charateristic radial size and shape, e.g., r_1 and r_{-2}
- r_1 is a good size-estimator
- 2 r_1 often close to total aperture *and* encloses *similar* fractions of total light for a range of profile shapes.
- r_{-2} is a good shape-estimator (star-galaxy)

$$r_1 = \frac{\int_0^{r_{max}} I(r) r^2 dr}{g(r)}$$

$$\left(\frac{1}{r_{-2}}\right)^2 = \frac{\int_{r_{min}}^{r_{max}} I(r) r^{-1} dr}{g(r)}$$



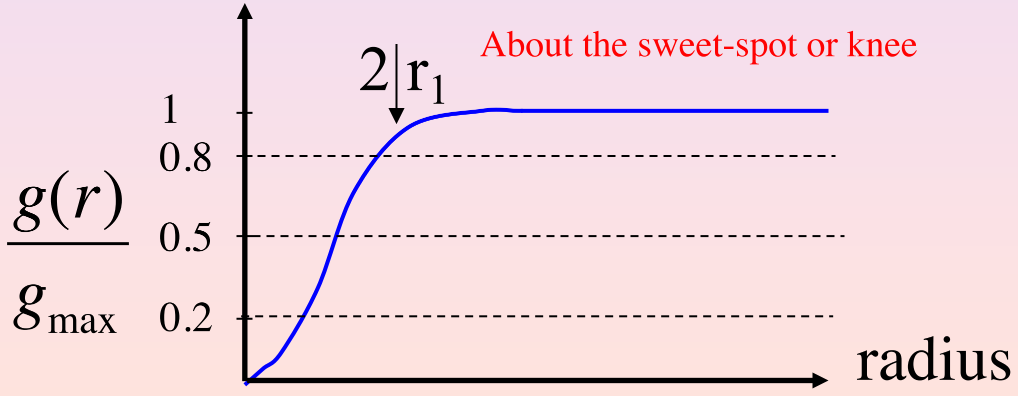
Kron 1980, ApJS, 43, 305
Bershady et al. 1994, AJ, 108, 870

Problems:
How to set limits of integration?
How *similar* is *similar*?

$2r_1$ as a total aperture

- *Source Extractor* calls r_1 the "Kron radius"
- Uses isophotal limit for r_{max}, as did Kron.
- OK?
- Large systematics (33%) in underestimating true r_1 for Sersic index n=4. Only 62% of light enclosed.
- Redefine $r_{max} = 3\ r_1$ as a *progressive* integral is accurate, but noisy (imprecise).

This is "how similar is similar"



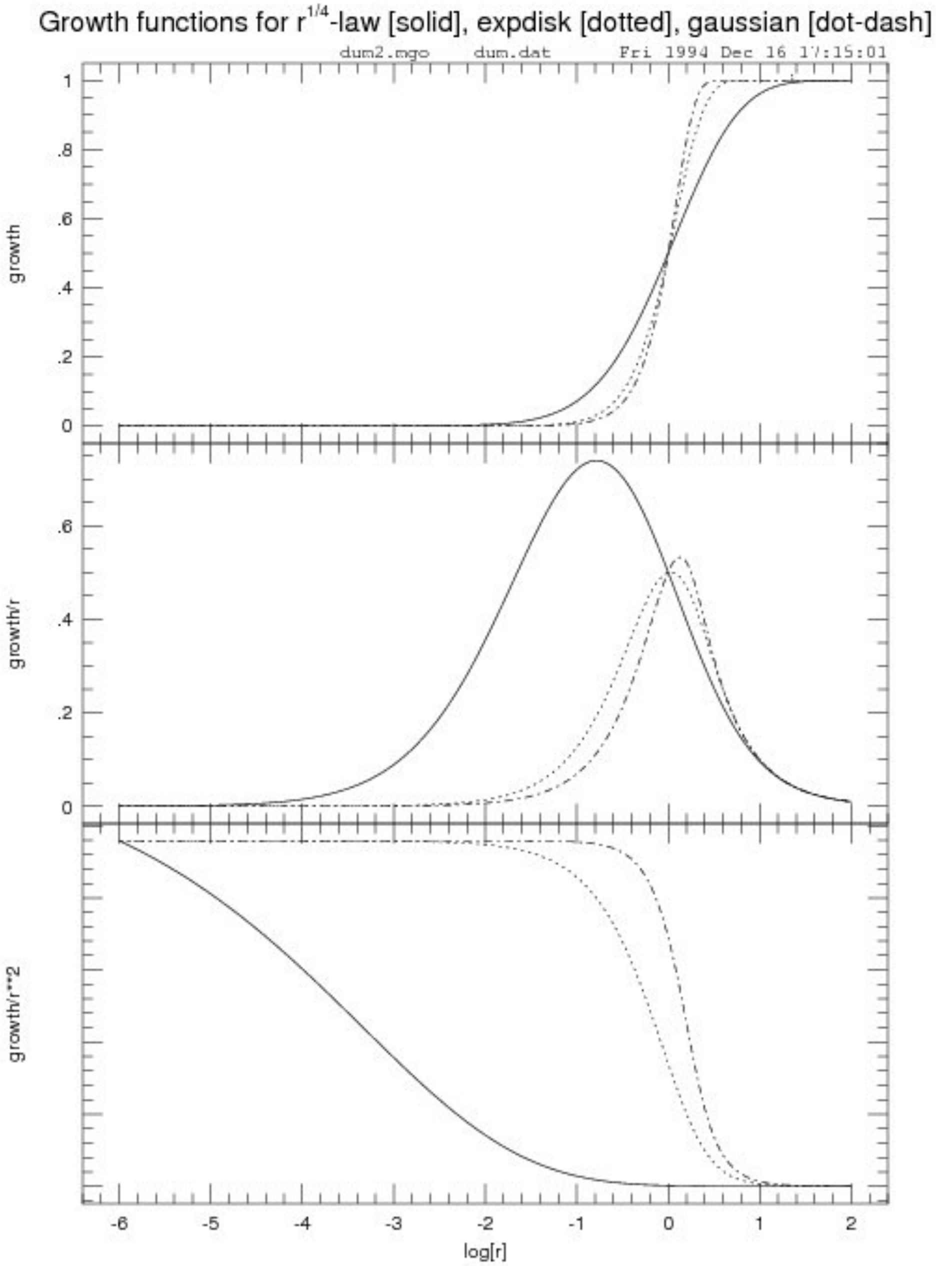
Would really like aperture that encloses nearly constant fraction of light, regardless of profile shape, near S/N peak.

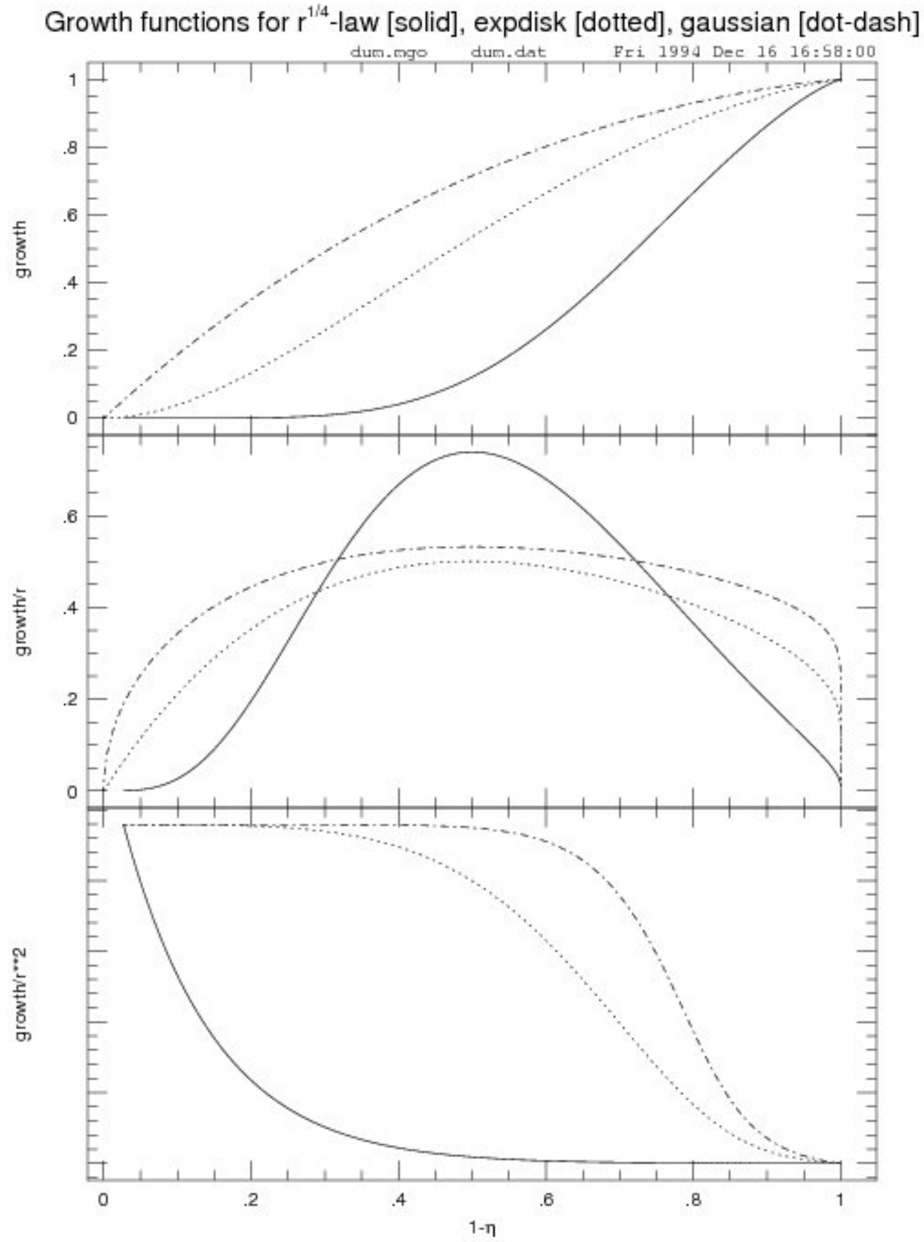
Petrosian η function

- $\eta = I(r) / <I>$, where $<I> = g(r)/\pi r^2$
  - $\eta(0) = 1$
  - $\eta(\infty) = 0$
- η is a monotonically decreasing function of radius for fairly restrictive limits on dI/dr.
  - However, η is not always monotonic, e.g., lumpy galaxies.
- *Theorem*: η = 0.5 is where S/N peaks in background limit.
- The beauty of η is that is a semi-integral quantity which requires no information about the light distribution.
- η can be used to define characteristic sizes and shapes as before: r(η□□□□□or $C_\eta = 5 \log(r_{\eta 1}/r_{\eta 2})$, $\eta 1 < \eta 2$

SDSS uses η=0.3,0.9

- η is not a panacea: a given value of η does not enclose the same fraction of light, but η=0.2 is pretty good.


Growth functions for r^1/4-law [solid], expdisk [dotted], gaussian [dot-dash]
dum2.mgo dum.dat Fri 1994 Dec 16 17:15:01
growth
growth/r
growth/r**2
log[r]


Growth functions for r^1/4-law [solid], expdisk [dotted], gaussian [dot-dash]
dum.mgo dum.dat Fri 1994 Dec 16 16:58:00
growth
growth/r
growth/r**2
1-η

The ideal total magnitude

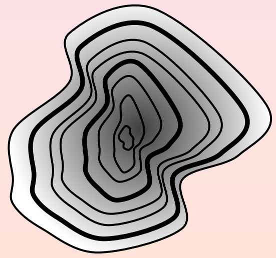
Desiderata:

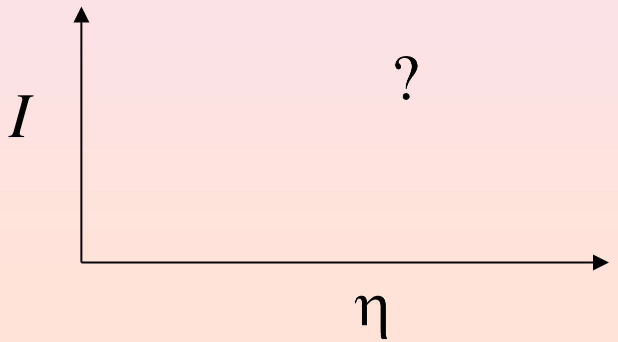
1. Balances random and systematic error
2. Accounts for differences in profile shape and size that is independent of isophotal limit

- This probably requires some η-based total aperture that is scaled in some way with a shape parameter, e.g.,

  $r_{tot} = f(C_\eta) r_\eta$, where f is some function of C_η.

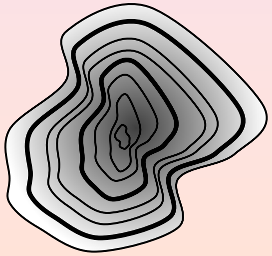
- Ideal extension would base aperture shape and size on isophotes, but choose isophote that satisfies above condition on η or $I[f(C_\eta) r_\eta]$





Photometric calibration (revisited)

- With stars, absolute calibration was easy because sources and calibrators all had the same light profile.
- That means that any aperture, as long as it was the same aperture, enclosed the same light on the same image, and …
- The same number of aperture widths (e.g., a Gaussian σ or FWHM) enclosed the same light even on images with different seeing.
- What do we do for galaxies?

When does this:  look like this: ?

Other shape indices

- A - rotation asymmetry (low-order odd azimuthal moments)
- S - amplitude of smooth to clumpy light distribution
- Gini coefficient - deviation from constant surface-brightness
- M_{20} - 2nd moment of light distribution for brightest pixels containing 20% of galaxy flux

See Lotz et al. 2004, AJ 128, 163
Conselice et al. 2000, 2003

- All correlate with "Hubble type"
- These are all poor-person's approach to Fourier analysis of 2D light distribution in polar coordinates (r,θ), well suited for faint, marginally resolved sources.

Gini Coefficient

Origins in social science measures of wealth distribution; in these terms an exponential profile is more equitable than $r^{1/4}$-law profile.

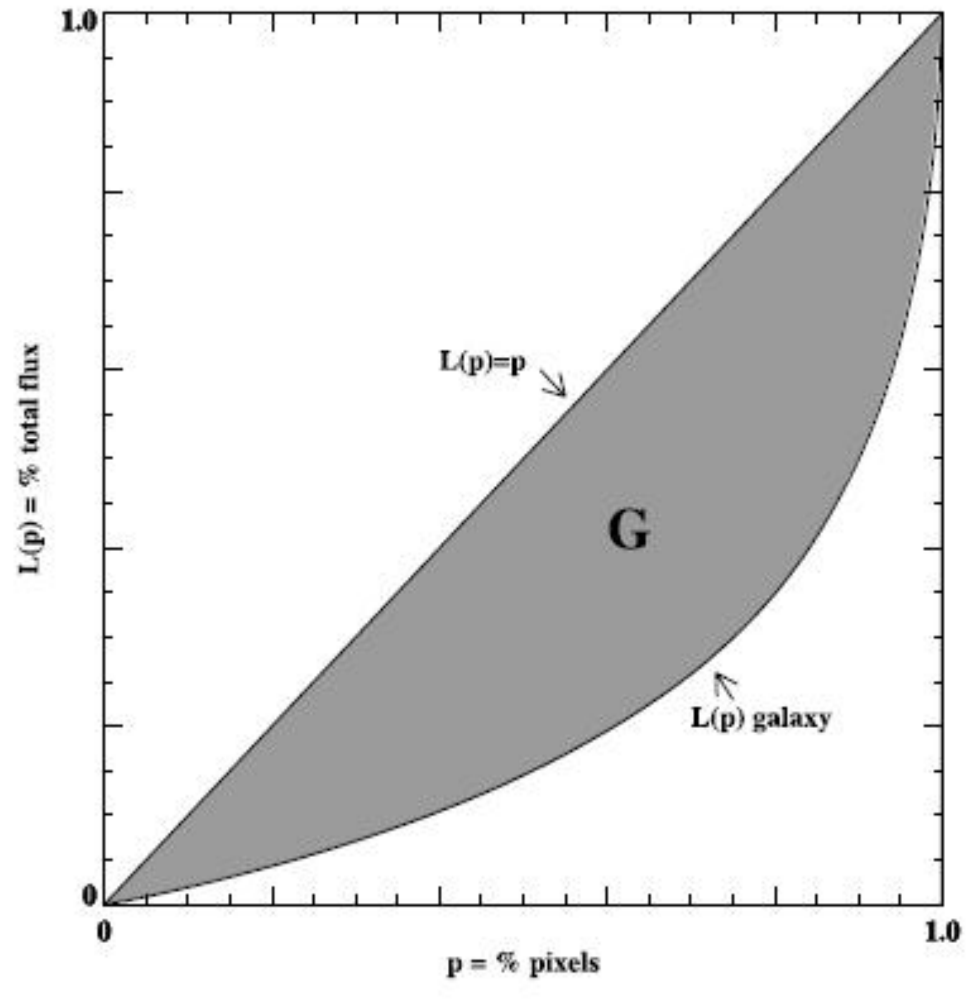


FIG. 1.—Lorenz curve: the Gini coefficient is the area between the Lorenz curve of the galaxy's pixels and that of equitable distribution (*shaded region*). The given curve is for S0 NGC 4526, $G = 0.59$.

Lotz et al. 2004, AJ 128, 163

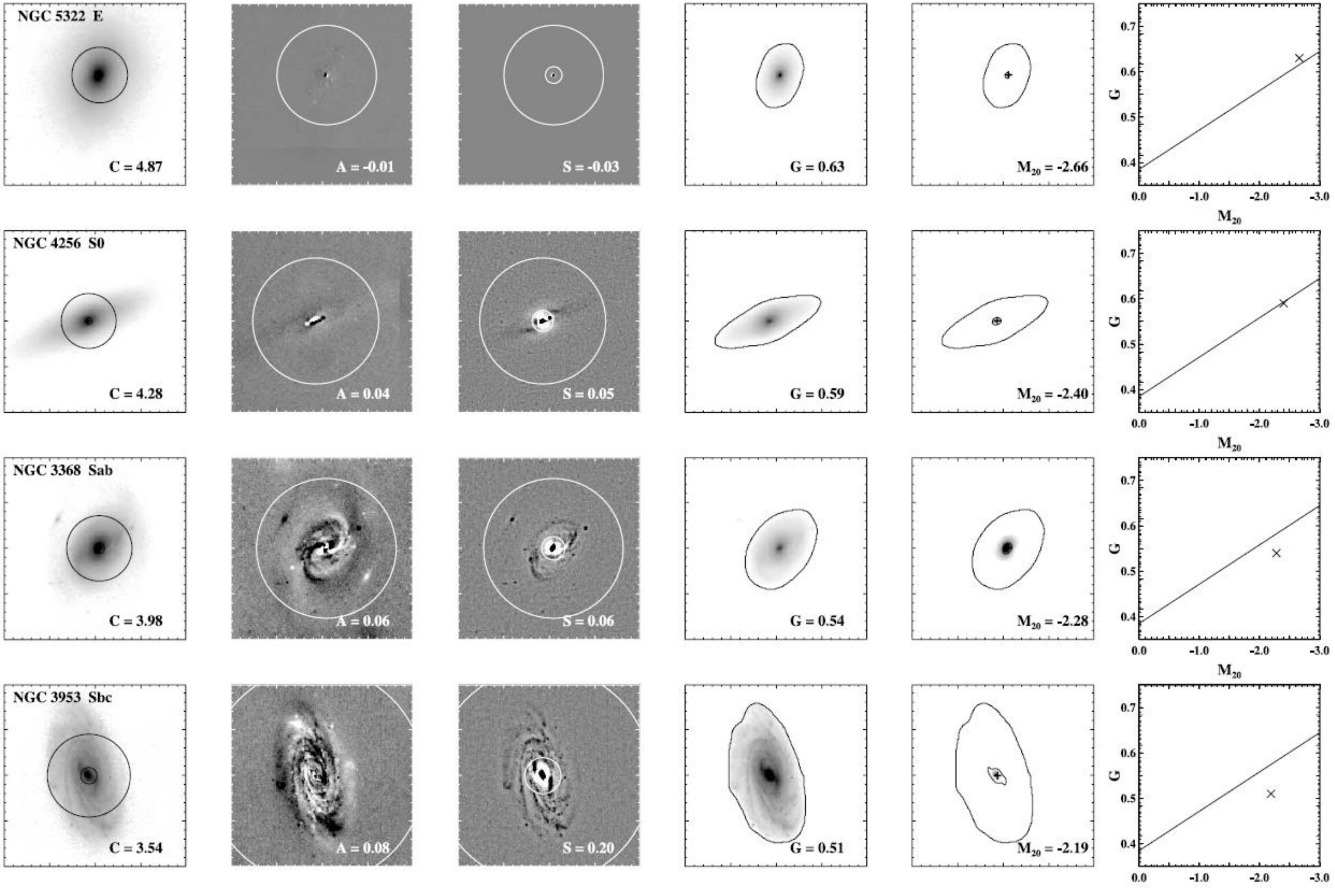
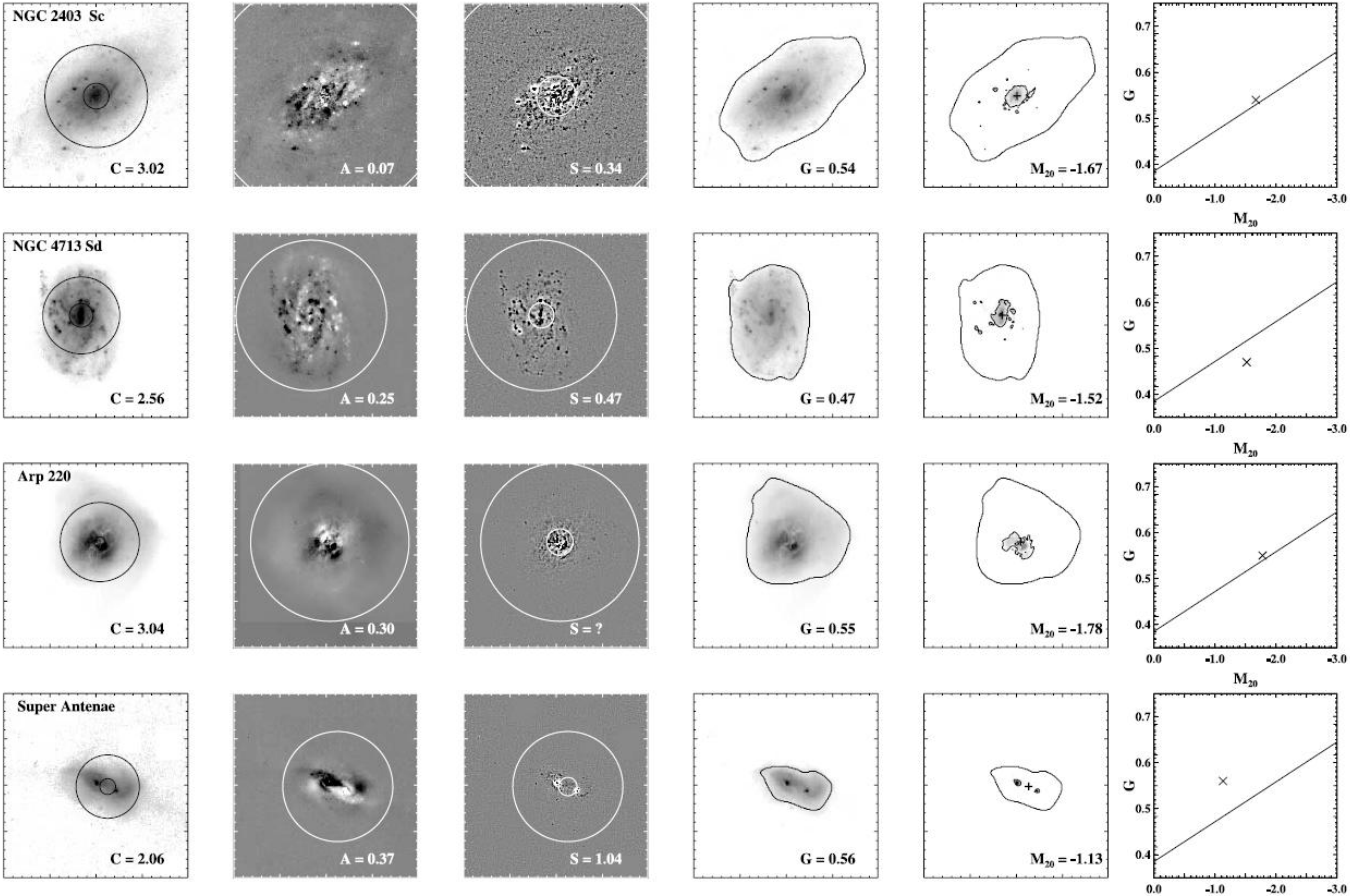


FIG. 3.—Test galaxy morphological measurements C, A, S, G, and M_{20} for rest-frame ~6500 Å images (Table 1). In the first panel inner and outer circles enclose 20% and 80% of the flux within 1.5 r_p. The second panel shows the residual $I - I_{180}$ image, with the circle at 1.5 r_p. The third panel shows the residual $I - I_S$ image, with the inner and outer circles at 0.25 and 1.5 r_p. The fourth panel images are the original galaxy images scaled such that the minimum surface brightness matches that used to create the galaxy segmentation maps. The outer edge of the segmentation map are the outer contour plotted in the fourth and fifth panels. The inner contours plotted in the fifth panel trace each galaxy's brightest 20% of it flux, while the crosses indicate each galaxy's center. The final panel plots each galaxy's G and M_{20}, where the solid line is for reference.

Lotz et al. 2004, AJ 128, 163



Lotz et al. 2004, AJ 128, 163