# Astrometry and Photometry with CCDs

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**Michelson Summer Workshop**

**25-29 July 2005**

# References

- References

S. Howell, “Handbook of CCD Astronomy”, Cambridge Univ. Press (2000)

A good up-to-date book on the CCD as a detector.

G. Walker, “Observational Astronomy”, Cambridge Univ. Press (1987), Ch. 7.

A good general introduction to all aspects of observational astronomy.

M. Newberry 1991, PASP, 102, 122

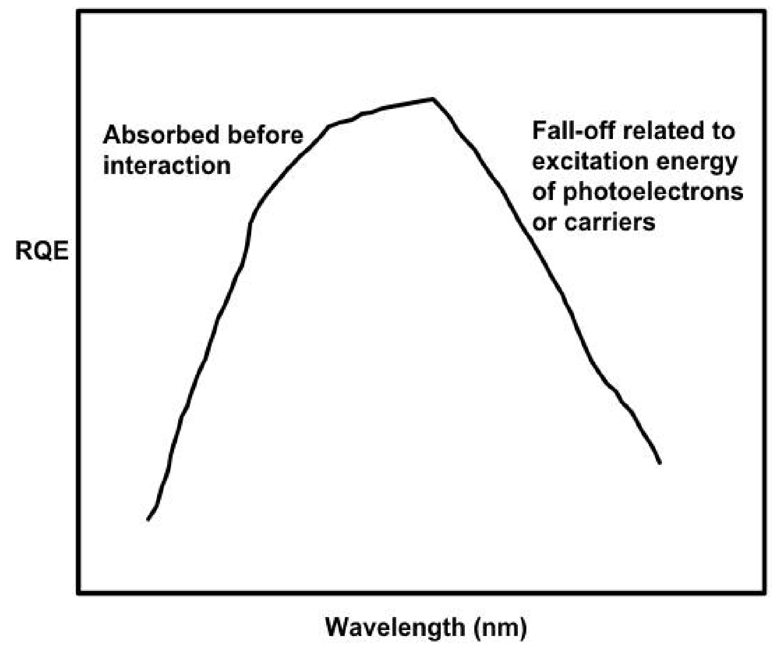
A detailed discussion of signal-to-noise

# CCD Quantum Efficiency

- Advantages of CCDs
  - High quantum efficiency.
    - Responsive QE
      - RQE = N(detected)/N(incident)

        25% > RQE > 95%
    - Detective QE
      - DQE = (S/N)out/(S/N)in
  - Spatially stable silicon substrate.
  - Reasonable resolution

    Typically 10-20 microns
  - Modest format size (4k x 4k)
- Disadvantage
  - Need to enhance blue response with down-converting phosphors.



# Front-side versus Back-side Illumination

- Front-side illumination
  - The electrical connections interfere with the access of the photons to the sensitive area
    - Potential for systematic “pixel-phase” position errors
    - Reduced sensitive area > lower QE
    - QE(max) ~ 25%
- Back-side illumination
  - Thick semiconductor
    - Photons are absorbed and charge carriers created too far from the depletion layer
    - Thinning the backside to ~10 microns can yield QE ~ 95%!

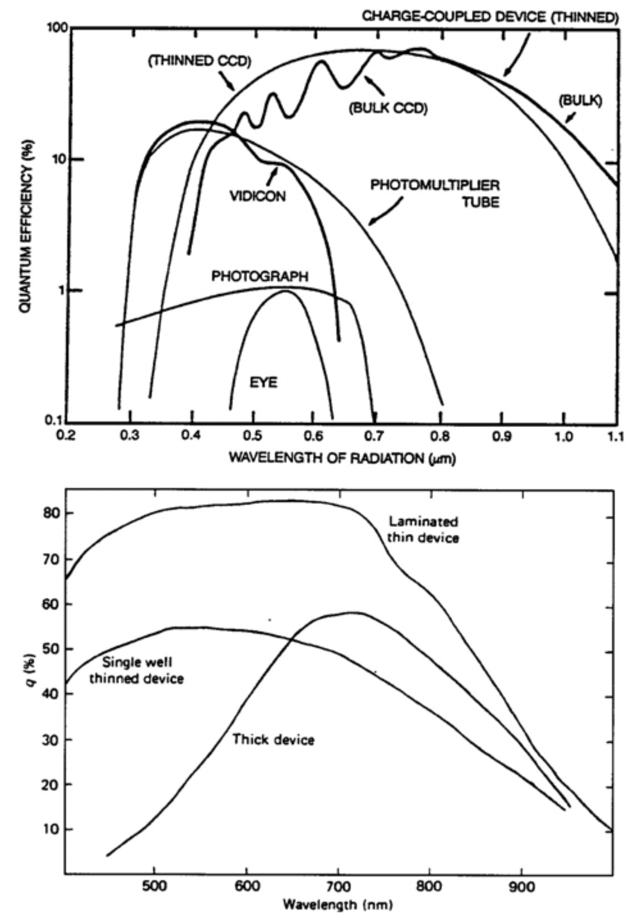



Fig. 3.2. The top panel shows QE curves for various devices indicating why CCDs are a quantum leap above all previous imaging devices. The failure of CCDs at wavelengths shorter than about 3,500 Å has been completely eliminated via thinning or coating of the devices. The bottom plot show representative QE curves for both thick and thinned devices. Laminated and single-well devices are two processes used to produce mechanically stable thinned CCDs.

# Charge-Transfer Efficiency

- Reiss (STScI-ACS 2003-009)
  - If the transfer of charge is not 100% from pixel to pixel during the read out, then CTE loss occurs.
  - CTE loss occurs from radiation damage, temperature of CCD and scene characteristics (# counts, extent of image, local and global background)

| CTE | 1k chip | 2k | 4k |
|---|---|---|---|
| 0.999975 | 3% | 5% | 10% |
| 0.9999975 | 0.3% | 0.5% | 1% |

  - Minimization of CTE loss:
    - "pre-flashing" chip
    - "charge injection" in front of image readout direction

# CTE versus Pixel Flux

- Charge-transfer efficiency effects on Astrometry and Photometry

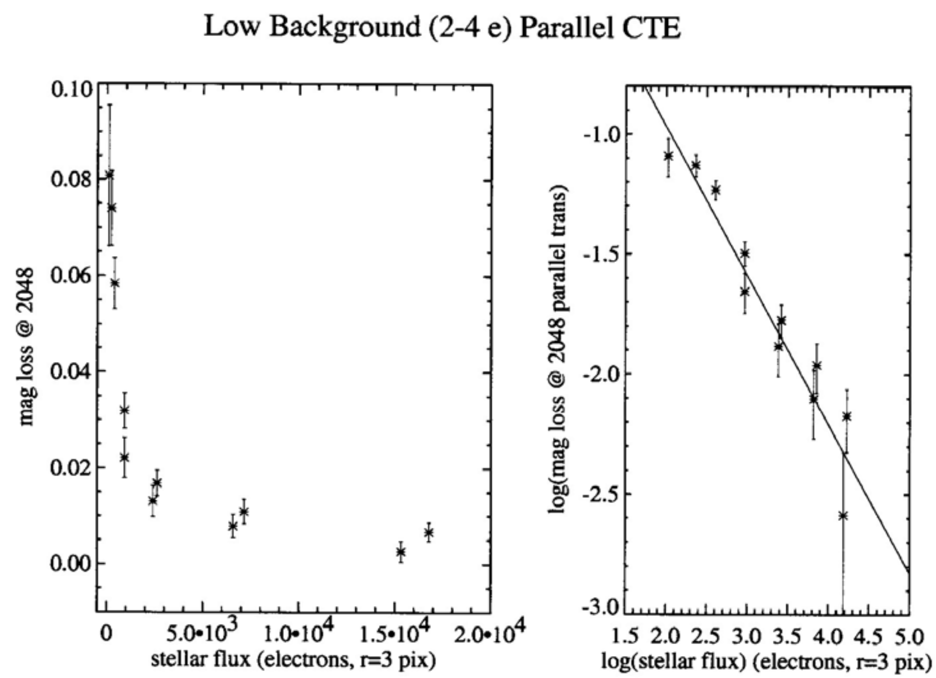



**Figure 4:** The dependence of parallel transfer CTE loss versus stellar flux contained within an r=3 pixel aperture (all images at low sky level). As shown the relation is strong and suggests a power-law relation which was utilized in the correction formulae. The panel on the right shows the same in log-log space.

# Saturation Effects

- CCD Full- Well/Saturation level
  - Full well is proportional to the volume of a pixel, i.e. the area times the thickness of the depletion region.
    - Typical: Manufacturer says full well = 250,000 $e^{-1}$; using a 16-bit A/D converter ($2^{16}$ - 1 = 65535 bits)
      - Gain = 250,000/65535 = 3.81 $e^{-1}$ / ADU (analog-to-digital units)

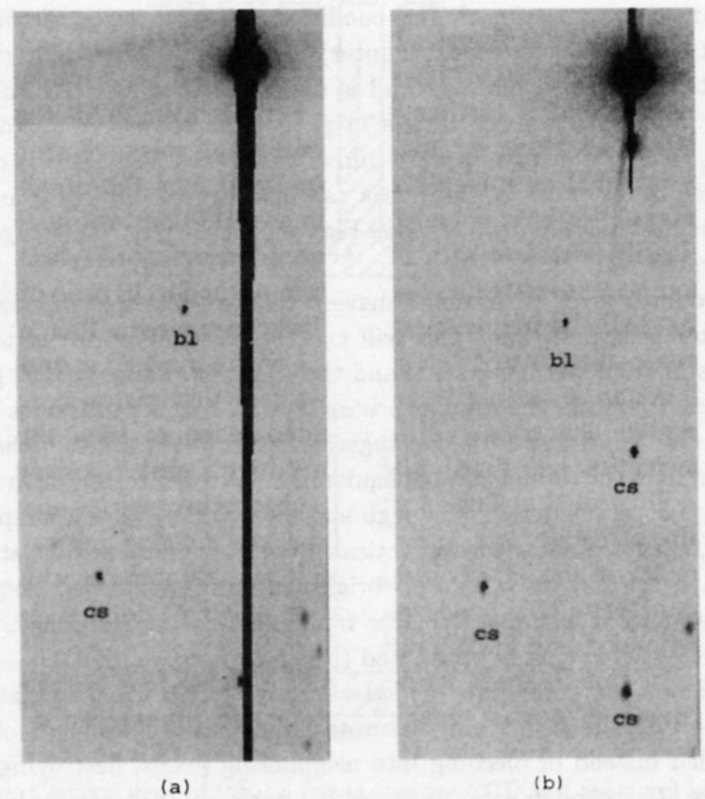
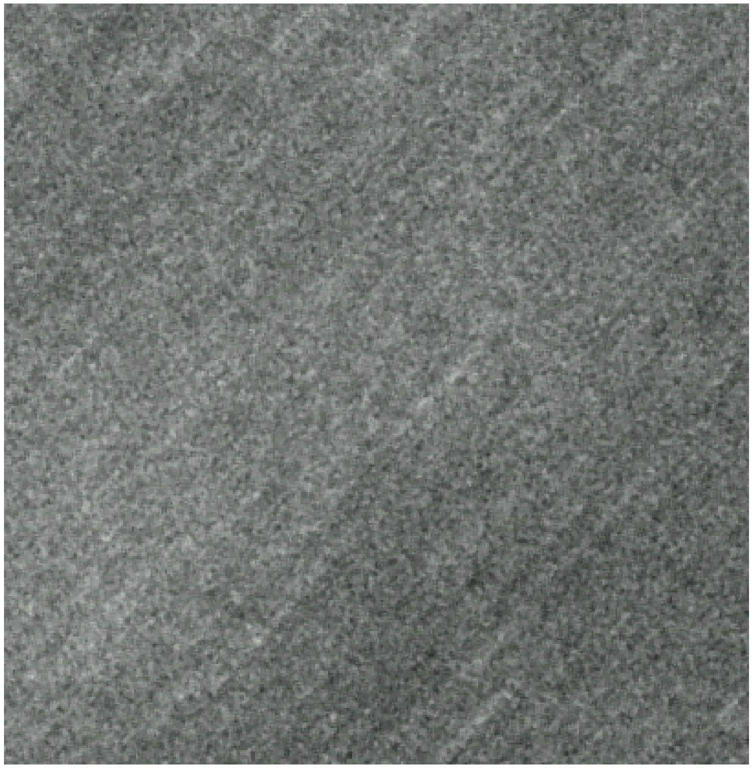



Fig. 2.5. Two equal-length CCD exposures of a bright star (SAO 110456). The normal CCD exposure (a) shows typical bleeding caused by saturation within the CCD. The CCD exposure on the right (b) was made with an antiblooming CCD and clearly shows the much reduced bleeding from the bright star. From Neely & Janesick (1993).

# How the Flat-Field Effects Astrometry

- Types of Flat fields
  - Median Flat-Field (MFF) from several exposures in each filter.
    - Median gets rid of cosmic ray hits and bad data.
  - Super-sky flat - median average all exposures during a night.
    - Random star locations in field-of-view average out in median.
    - Generally low S/N due to low sky background.
  - Dome-diffuser flat - plexiglass diffuser in front of objective or corrector in a Schmidt.
    - Good for wide fov.
    - High S/N since it is a dome flat and bright lights.
    - Zhou, Burstein, et al. 2004, AJ 127, 3642.



S-S flat taken with wire objective grating (45$^{o}$) in place. Diagonal streaks are due to partial overlapping of the stars in the deep and dense exposures. Fluctuations in the S-S flat are ~8%.

# Micro- and Macro-Noise

- Micro-noise and Macro-noise - useful concepts
  - Macro: $\sigma^2 = (1/N)\Sigma^N_{\iota=1}(\langle S\rangle - S_i)^2$
  - Micro: $\sigma^2 = [1/2*(N-1)]\Sigma^{N-1}_{\iota=1}(S_{i+1} - S_i)^2$
- Macro-noise includes the large-scale non-uniformities (or errors) while Micro-noise includes only the point-to-point fluctuations
  - Astrometry is limited primarily by Micro-noise
    - Noise in defining the image center
  - Photometry is limited primarily by Macro-noise
    - Zero-point variations in the scale over the field

# Signal-to-Noise

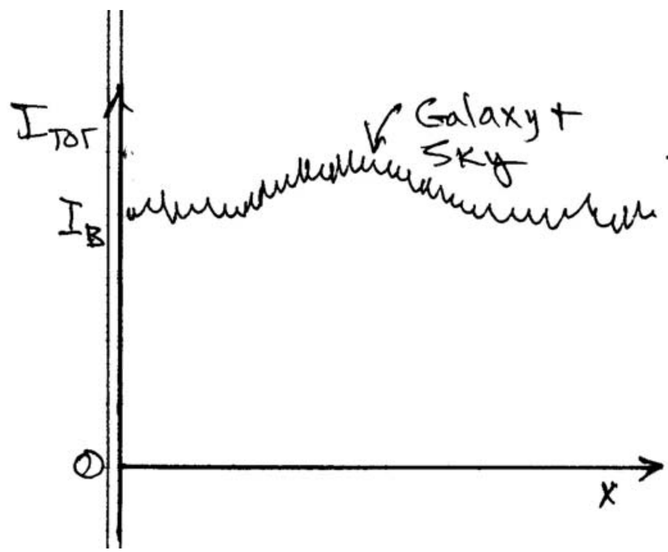
- References
  - Newberry 1991, PASP 103, 122.
  - Newberry 1994, CCD Astronomy
  - Howell, “Handbook of CCD Astronomy”, p. 53
- S/N sets the fundamental limit on our ability to measure the signal from the target.
- Bias, Dark and Flat-field corrections all contribute to degrading the S/N in the measured signal.

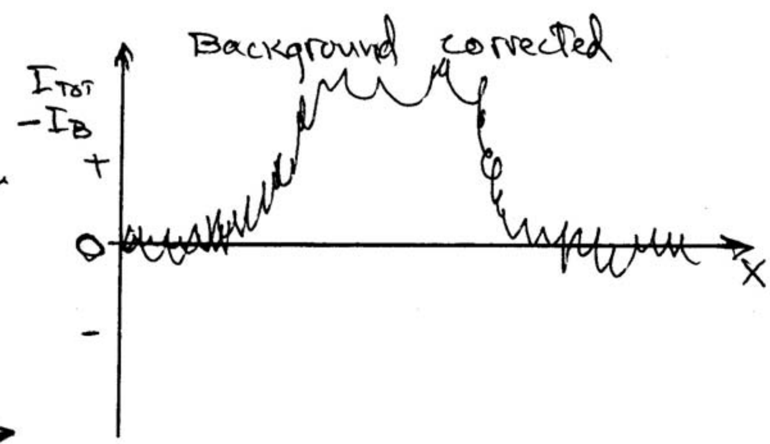
# CCD Photometry

- References
  - "Astronomical CCD Observing and Reduction Techniques", S. B. Howell, ed., 1992, *ASP Conf. Series* 23.
  - Stetson, P. 1990, *PASP* 102, 932.
  - DaCosta, G., 1992, *ASP Conf. Series* 23, 90.

# Surface Photometry

- Surface Photometry
  - Generally trying to determine the surface brightness of a galaxy that is very faint in the presence of a “bright” sky.
  - Goal is to trace the galaxy out to, say, $\leq$ 1% of sky level.
    - I(x,y) = Galaxy(x,y) + Sky(x,y
    - Need Sky(x,y) to better than 1% accuracy, or $\sigma_s(x,y) \leq 0.01 * S(x,y)$
    - Macro noise is critical here, due to possible poor flat-field.



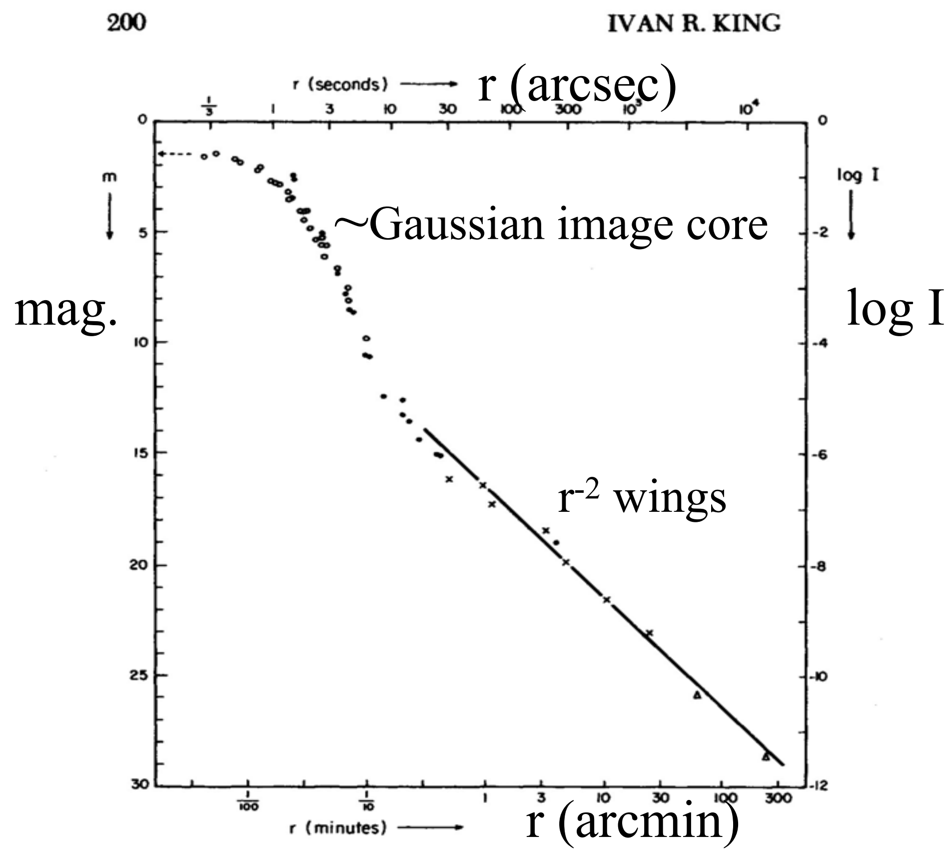
# Sky Background

- Sky background and its error
  - $<S>$ = corrected mean sky
  - $\sigma_m$ = macro-noise in the sky
    - $\sigma_m$ = Poisson + Read Noise + Large scale background fluctuations.
    - $\sigma_m = [ S + N_r^2 + ??]^{0.5}$
  - $\sigma(<S>)$ = error of mean sky
  - X = % error desired in $<S>$
    - $X = \sigma(<S>) / <S>$, e.g. 1%
      - $\sigma(<S>) = \sigma_m / N^{0.5}$ , or $X = \sigma_m / [N^{0.5} * <S>]$
      - **$N = \{\sigma_m / [X * <S>]^2$**
        - » $<S>$ = 100 counts, $N_r$ = 5 counts, X = 1%, then N=121 pixels
        - » $<S>$ = 100 counts, $N_r$ = 5 counts, X = 0.1%, then N=12,100 pixels

# Stellar Profile

- King, PASP 83, 199, 1971
  - Stellar profile observed through atmosphere.
    - Sky background near star is affected by presence of stellar wings

**Fig. 1** — Surface brightness, in magnitude per square second, in the image of a star of magnitude zero. Open circles are derived from 60-inch Cassegrain images, closed circles from diameters of NPS stars on the Palomar Observatory Sky Survey (POSS), and crosses from other stars on POSS. Straight line is inverse-square law found by de Vaucouleurs. Triangles are from sky brightness near the sun.



# Aperture Photometry

- Aperture photometry
  - DaCosta, G. ASP Conf. Series **23**, 90, 1992.
    - Select an aperture of radius **r** that contains the image and sum all of the pixels that fall within the aperture
      - $I_{sum} = I_* + \langle S \rangle$
      - What radius should be used to include all of the stellar flux?
        - » Remember that the King stellar profile extends many arcsec.
      - What about the sky within the aperture?

# Aperture Corrections

- Stetson, P. PASP **102**, 932, 1990
- Large r to include all star light, but:
  - Includes other stars
  - Adds sky noise
- All stars have the same psf, so all psfs scale with the # photons
  - psf is constant, except for
    - optical aberrations
    - seeing variations over field (short exposures)
  - CCD is linear, except for
    - saturation and CTE
  - $dm = -2.5 \log_{10} I_2/I_1$
    - $dm = -2.5 \log X$
      - Constant aperture correction, **dm**.

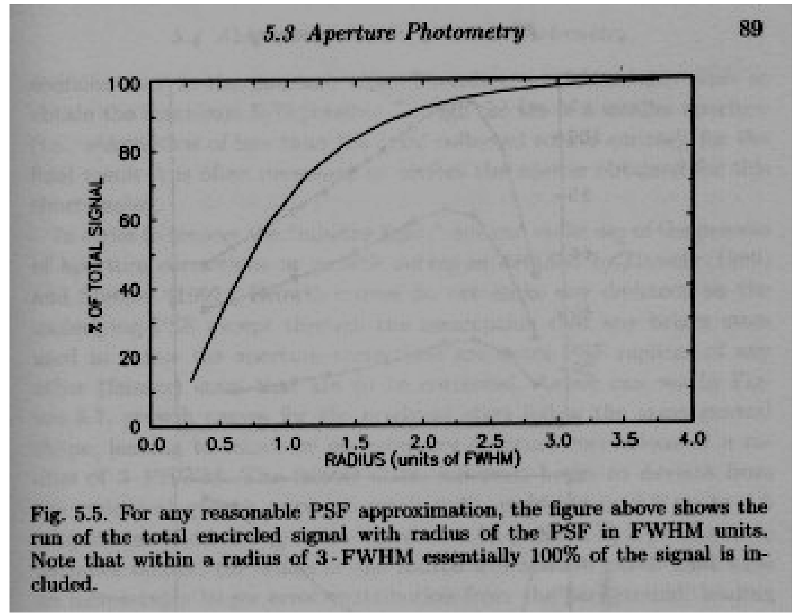


**Fig. 5.5.** For any reasonable PSF approximation, the figure above shows the run of the total encircled signal with radius of the PSF in FWHM units. Note that within a radius of 3 · FWHM essentially 100% of the signal is included.

“Optimal” aperture = 1.35 FWHM
Ap. corr. = 0.2 mag for a Gaussian

Star image must be accurately centered in aperture for this to work.

# Photometric Errors

- Sky background
  - Select many star-free spots and average the results
  - Probability plot analysis of background and scale to aperture
- Error in photometry
  - $S_o$ = total stellar signal, but noise and read-out noise are per pixel
    - $\sigma^2 = S_o + n(S_s + N_r^2)$
      - $mag = m_o - 2.5 \log_{10} S_o$
      - $\sigma_m = \sigma_{mo} - 2.5 (\log_{10} e) \sigma(S_o)/S_o$
      - $\sigma_m = \sigma_{mo} - 1.086 (1/S_o) \sigma(S_o)$
      - $\sigma_m = \sigma_{mo} - 1.086 (1/S_o) \{S_o + n(S_s + N_r^2)\}^{0.5}$
        - » = Zero pt. Error + Poisson + Sky + Read-out noise
        - » $\mathbf{S_o}$ is fixed, so the larger **n**, the greater the contribution of the **sky** and **read-out** noise is to the error.

# Sky Noise

- Sky noise
  - Ideally the histogram of pixel values is unimodal and we determine the mode.
  - Mode is usually difficult to determine and poorly defined.
  - Kendal & Stuart, p.40, 1977
    - mean-mode = 3(mean-median)

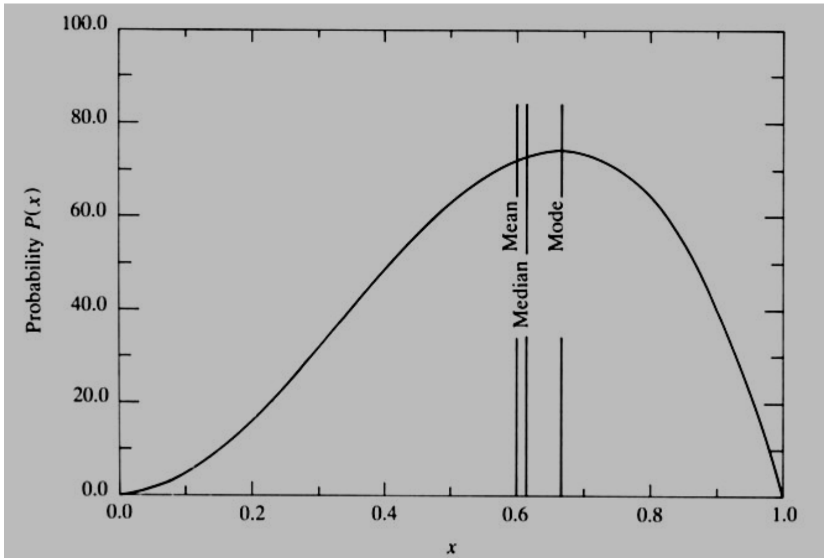



**FIGURE 1.3**
Asymmetric distribution illustrating the positions of the mean, median, and most probable value of the variable.

# Fitting PSFs

- King found the stellar profile to be approximately Gaussian in the core:
  - $G(x) = (\sigma_x\sqrt{2\pi})^{-1}$ exp-$\{0.5[(x - x_c)/\sigma_x]^2\}$
    - $\int_x G(x) = 1.0$
    - $G(x = x_c) = 0.3989$
    - $G(x = x_c \pm \sigma_x) = 0.2420$: 0.607 height at $x = x_c$
    - $G(x = x_c \pm$ fwhm$/2) = 0.1995$: one-half the height at $x = x_c$
  - Gaussian doesn't fit in wings, so other functions are added
    - Modified Lorentzian: $L(x) = C^*\{1 + (x^2/\sigma^2)^{\beta}\}^{-1}$
    - Moffat function: $M(x) = C^*\{1 + (x^2/\sigma^2)\}^{-\beta}$
      - C = constant
  - Not even those are perfect so a table of corrections (H(x,y) is added to give the final model PSF:
    - $PSF(x,y) = [a^*G(x,y) + b^*L(x,y) + c^*M(x,y)] * [1 + H(x,y)]$
    - DAOPHOT and IRAF: See Stetson, P. in PASP **102**, 932, 1990.

# Photometric Passbands

- Passbands and filters
  - UBVRI: Bessell PASP 102, 1181, 1990
  - JHKLM: Bessell & Brett PASP 100, 1134, 1988
  - IR: Astrophys. Quant. IV (AQ4), A. N. Cox, ed. Ch. 7.1-7.7
  - Visual: AQ4 Ch 15.3
  - Asiago Database on photometric systems (ADPS)
    - http://www.pd.astro.it/Astro/ADPS/

# Photometric Surveys

| Band | Sloan (NG cap) | DENIS (South) | 2MASS (All sky) | UCAC (All sky) | NPM (N) SPM (S) |
|---|---|---|---|---|---|
| u | 22.0 | | | | |
| g | 22.2 | | | | |
| r | 22.2 | | | | |
| i | 21.3 | 18.5 | | | |
| z | 20.5 | | | | |
| B | | | | | 18.5 |
| V | | | | | 17.5 |
| R | | | | 16.5 | |
| J | | 16.5 | 15.8 | | |
| H | | | 15.1 | | |
| $K_s$ | | 14.0 | 14.3 | | |

# Image Centering

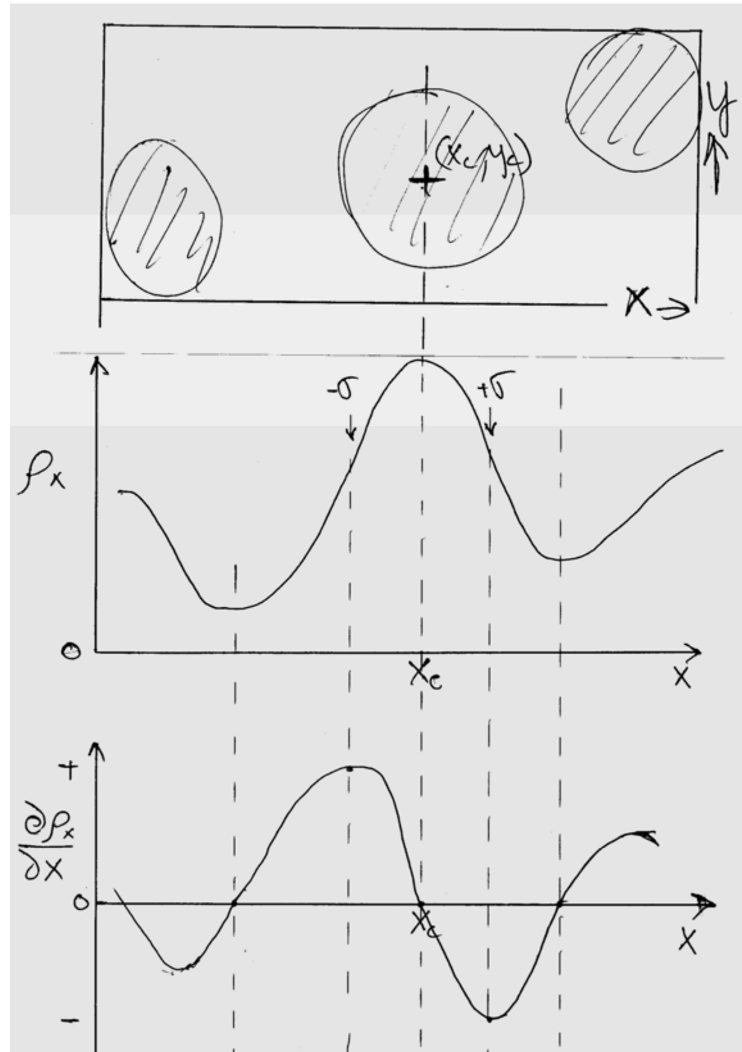
- References
  - van Altena and Auer: in “Image Processing Techniques in Astronomy”, p. 41, 1975
  - Auer and van Altena: AJ 83, 531, 1978
  - Lee and van Altena: AJ 88, 1683, 1983

# Centroids versus Image Centers

- Given an intensity distribution, S(x,y)
  - The **Centroid, center of mass** or **1st moment** of the distribution.
    - See: van Altena and Auer: in "Image Processing Techniques in Astronomy", p. 41, 1975
    - $<x> = \sum_{x,y}\{x_i*[S(x,y) - B]\} / \sum_{x,y}[S(x,y) - B]$,
    - $<y> = \sum_{x,y}\{y_i*[S(x,y) - B]\} / \sum_{x,y}[S(x,y) - B]$
      - where B is the assumed sky background around the image.
      - The centroid is very sensitive to the adopted sky background, but it is also works well for very faint images.
  - The **Image Center**
    - See: Auer and van Altena: AJ 83, 531, 1978
    - and Stetson in DAOPHOT manuals.
    - The Marginal distributions are defined by:
      - $\rho_x(x) = N_y^{-1}\sum_y S_o(x,y)$
      - $\rho_y(y) = N_x^{-1}\sum_x S_o(x,y)$

# Marginals and Image Centers

- Derivative-search centers
  - Take the x-marginal, $\rho_x(x)$, in the middle panel.
    - Image crowding noted where $\rho_x(x)$ increases at edges of the diagrams.
  - The derivative of the x-marginal, $\rho'_x(x)$, is in lower panel.
    - Peaks at ± gaussian radius, $R_x$ = FWHM / 2.36
    - Zeros at image center and inflection points in $\rho_x(x)$ that indicate image crowding.



# Univariate Gaussian

$$\rho_x(x) = a_x + b_x(x-x_c) + [1 + c_x(1.5t - t^3)]h_x\exp(-0.5t^2)$$

- Univariate Gaussian
  - $t = (x-x_c) / R_x$
  - $h_x = N_x / [R_x\sqrt{2\pi}]$
  - $R_x$ = Gaussian radius
  - $b_x$ = sloping background
  - $c_x$ = skewness of image
  - Generally take $b_x = c_x = 0.0$, since there is usually a high degree of correlation between the *odd* terms and this degrades the image center precision, i.e. use a symmetric Gaussian for the fit.

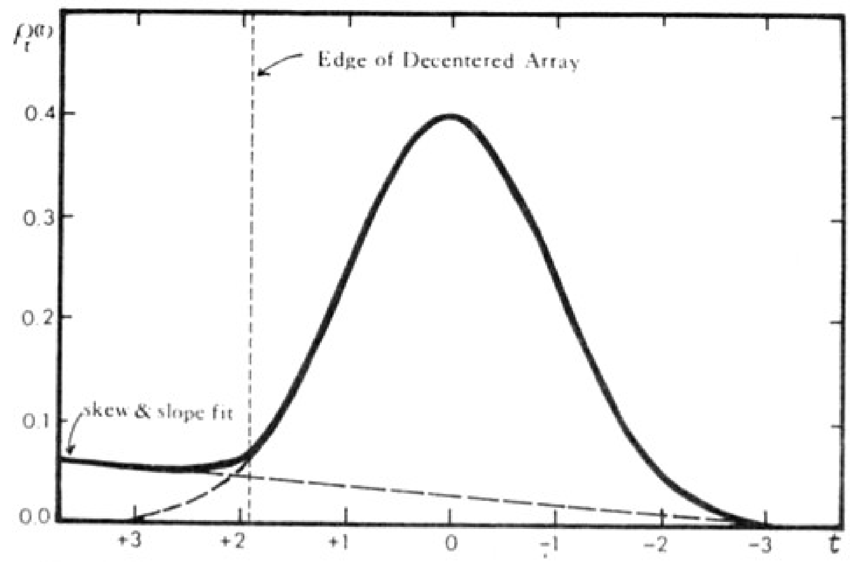
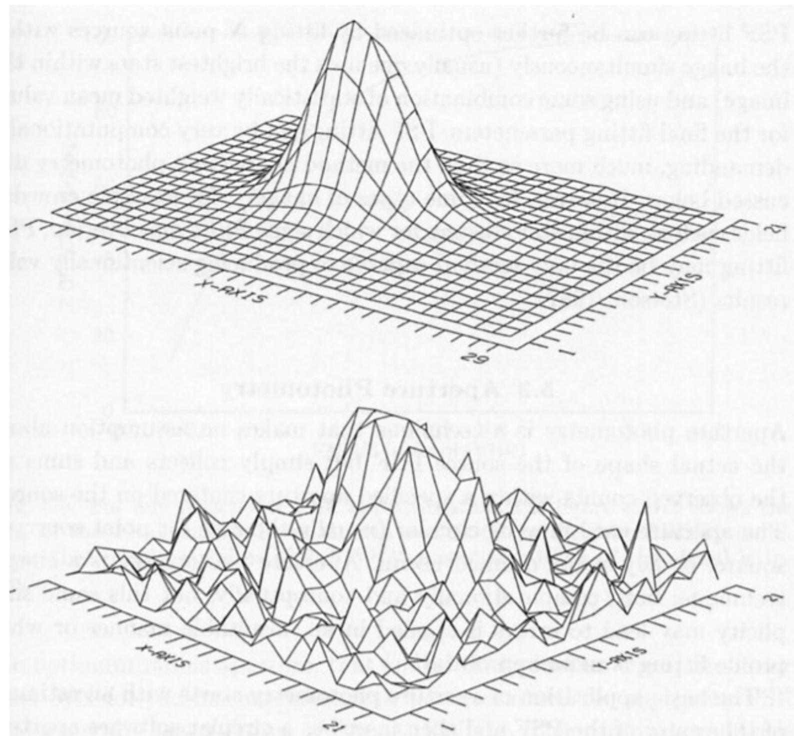



FIG. 2. Illustration of how a poorly centered array can yield a spurious, but apparently good fit with a skewed Gaussian and a slooping background when the true image is symmetric and the background flat.

# Bivariate Gaussian

$$F(x,y) = D_o \exp(-0.5 r^2 / R^2) + B$$

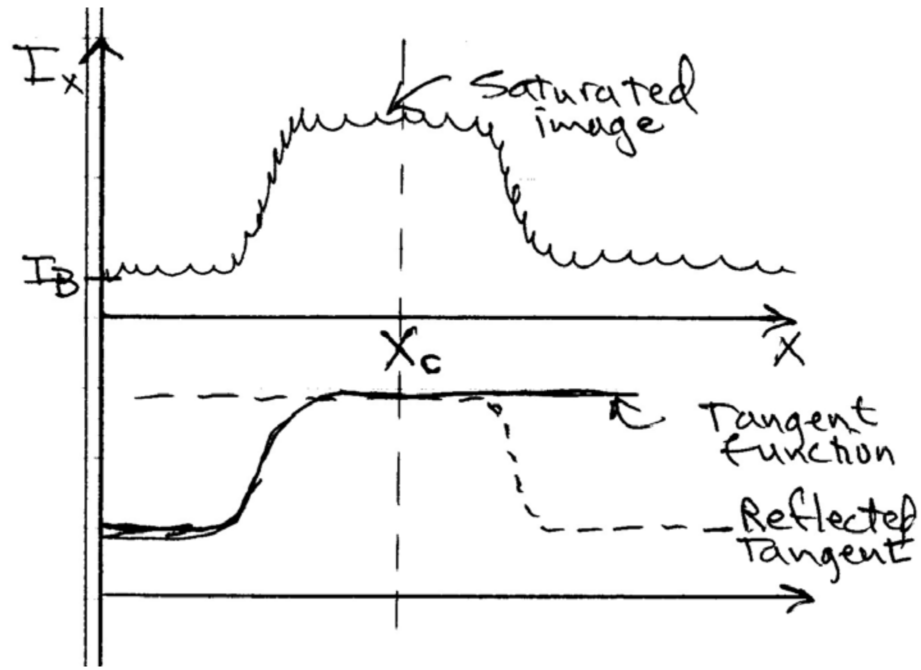
- Bivariate Gaussian
  - Lee and van Altena: AJ 88, 1683, 1983
  - $D_o$ = image height at center
  - $r^2 = (x-x_c)^2 + (y-y_c)^2$
  - R = Gaussian radius
  - B = background
- Precision
  - #1 Bivariate
  - #2 Univariate
  - #3 Centroid
- Convergence
  - Inverse order of precision, i.e. the centroid is most stable, especially for faint images.



# Dealing with Saturated Images

$$F(x) = a[2\tan^{-1}bc]^{-1}\{\tan^{-1}[b(x-x_o+c)] - \tan^{-1}[b(x-x_o-c)]\} + d_o$$

- Saturated photographic image usually has a flat top and Gaussian fits poorly
- Two arctangent functions fit very nicely
- Stock, J. ~1997
  - a = image height above background
  - $d_o$ = background
  - c is proportional to image width
  - b = scale factor for image slope and gradient
- Winter (Ph.D. thesis 1995) - a generalized Lorentz profile also works well.



# Image Center Precision Estimators

- Precision of the image center
  - $h = N_x / [R_x\sqrt{(2\pi)}]$ = central height of the Gaussian
  - $R = FWHM / 2.36$ = Gaussian radius
  - $N$ = integral under the univariate function
  - $\sigma_1$ = standard error of fit to the univariate function, i.e. the dispersion of the intensities around the best fit to the marginal distribution.
  - $\sigma_h$ = standard error of the central height of the Gaussian
  - $\varepsilon = (2/\pi^{1/2})\,(\sigma_1/h)\,R^{1/2}$
  - $\varepsilon = (2\pi^{1/4})\,(\sigma_1/N)\,R^{3/2}$
  - $\varepsilon = \sqrt{2}\,(\sigma_h/h)\,R$ based on photometric precision
  - $\varepsilon = \sqrt{2}\,R\,(S/N)^{-1}$ based on photometric precision

# Summary of Astrometry & Photometry (1/2)

- Maximum Photometric precision
  - Emphasis here is on the total number of counts
  - Fitting function is not too important, since a look-up table must be used to correct to psf.
  - Stetson: PASP 102, 932, 1990
  - DAOPHOT and IRAF manuals
  - DaCosta ASP Conf. Series 23, 90, 1992
- Under-sampled images, e.g. HST
  - Anderson & King: PASP 112, 1360, 2000
  - Anderson & King: PASP 115, 113, 2003
  - Druckier, et al. AJ 125, 2559, 2003

# Summary of Astrometry & Photometry (2/2)

- Maximum Astrometric precision
  - Emphasis must be placed on the image-profile gradients
  - Use functional fits to the image with weighting by the derivatives of the function
    - Auer and van Altena: AJ 83, 531, 1978
    - Lee and van Altena: AJ 88, 1683, 1983
  - For saturated images
    - Stock (1977) arctangent functions allow for saturation in photographic images
- Quick and Dirty Astrometry
  - Centroids
    - van Altena and Auer: in "Image Processing Techniques in Astronomy", p. 41, 1975