Basics of photometry

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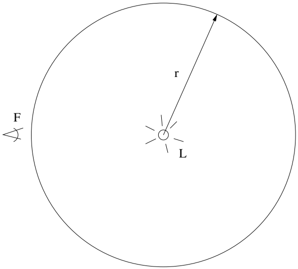
Luminosity and flux density

- An object has a total energy output = *Luminosity* L [erg s^{-1}].
- The observer at distance r sees only part of this energy as flux density (flux) F [erg s^{-1} cm^{-2}].
- For an *isotropic source*

$$F = \frac{L}{4\pi r^2}.$$



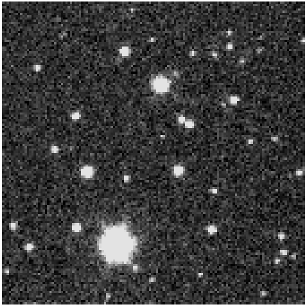
Spectral flux

- Flux is the observed quantity, luminosity calculated (with a set of assumptions).
- Typically in astronomy one talks about flux when meaning *spectral* flux.
- Spectral flux has a unit of
  erg s^{-1} cm^{-2} Å^{-1} (F_λ) or
  erg s^{-1} cm^{-2} Hz^{-1} (F_ν)
- Note that $F_\lambda(\lambda_0) \neq F_\nu(\nu_0)$ although $\lambda_0 = c/\nu_0$, because $d\lambda = -c/\nu^2 d\nu$.

The problem

CCD-cameras do not measure flux density F directly.
They record something proportional to *energy* stored to the detector over the exposure time.

Light $\rightarrow$ electrons $\rightarrow$ voltage $\rightarrow$ ADUs ("counts")



How to derive F from the pixel values on the CCD?

Three problems

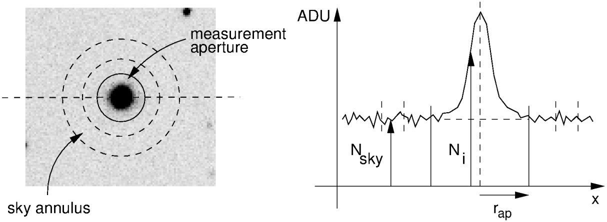
1) How to measure the counts from a target? Available techniques:
   - aperture photometry
   - PSF photometry
   - model fitting (e.g. galaxies).

2) How to correct the counts for
   - the atmosphere
   - instrumental response and artifacts.

3) Calibration: How to convert the measured counts to F?
   - "'Differential" vs. "absolute" calibration: In the former the calibration targets are on the same CCD frame as the target, in the latter they are on different CCD frames.

1. Counting the photons

1.1 Aperture photometry



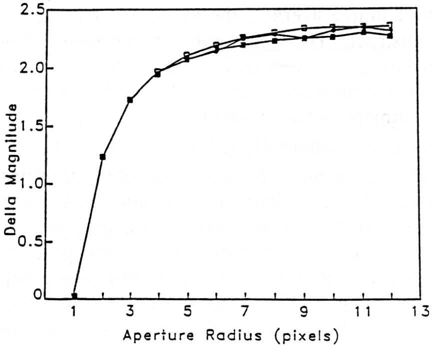
$$N = \sum_{i=1}^{n_{ap}} (N_i - N_{sky}) \; , \qquad (1)$$

where N_i = counts in the ith pixel inside the aperture
n_{ap} = number of pixels in the aperture ($\sim \pi r_{ap}^2$)
N_{sky} = average sky brightness inside the aperture.

How to choose aperture radius r_{ap}?

Guided by two facts:

1) *Growth curve*: N increases with increasing r_{ap}.



This means that one should use a very large aperture to include all target light, *but*

2) Maximum signal to noise is often achieved with a relatively small aperture, especially when the target is faint..

Signal to noise in aperture photometry:

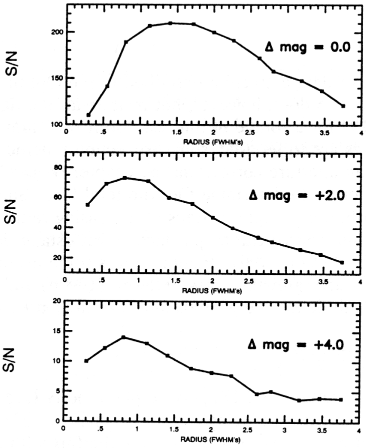
$$\mathrm{S/N} = \frac{N}{\sqrt{N + n_{ap}\sigma_{sky}^2 (1 + \frac{n_{ap}}{n_{sky}})}} \qquad (2)$$

N = target counts [e^-]

σ_{sky} = rms sky noise [e^-]

n_{ap} = number of pixels in the aperture

n_{sky} = number of pixels in the sky annulus.



Howell (1989) PASP 101, 616

IRAF phot output (bright target)

```
c_e_20110206_16_1_1_1.f451.800   301.800   1     nullfile             0       \
   451.193    304.201    -0.607  2.401   0.006   0.006          0    NoError   \
   69.56563        6.318079       2.231493       4689   36        0    NoError   \
   1.              INDEF          INDEF                  INDEF                  \
   5.00     442399.4      78.80149   436917.6      10.899 0.001 0    NoError   *\
   7.50     496859.1      176.9911   484546.6      10.787 0.001 0    NoError   *\
   10.00    525029.1      314.4589   503153.6      10.746 0.001 0    NoError   *\
   12.50    547029.8      491.2861   512853.2      10.725 0.001 0    NoError   *\
   15.00    568272.6      707.141    519079.9      10.712 0.001 0    NoError   *\
   17.50    590793.5      962.5003   523836.5      10.702 0.001 0    NoError   *\
   20.00    615294.3      1256.851   527860.7      10.694 0.001 0    NoError   *\
   22.50    641928.2      1590.738   531267.5      10.687 0.001 0    NoError   *\
   25.00    671305.       1963.718   534697.8      10.680 0.001 0    NoError   *\
   27.50    703837.6      2376.03    538547.6      10.672 0.001 0    NoError   *\
   30.00    738392.7      2827.51    541695.2      10.666 0.001 0    NoError   *\
   35.00    813511.4      3848.458   545791.       10.657 0.001 0    NoError   *\
   40.00    899088.       5026.669   549404.6      10.650 0.002 0    NoError   *\
   45.00    994715.1      6362.06    552134.4      10.645 0.002 0    NoError   *\
   60.00    1345367.      11309.81   558592.4      10.632 0.003 0    NoError   *\
   70.00    1634051.      15393.9    563164.4      10.623 0.003 0    NoError   *
```

r_{ap} N mag mag err

For bright targets aperture correction is not needed, the S/N is always good!

IRAF phot output (faint target)

```
c_e_20110206_16_1_1_1.f196.200   484.200   2     nullfile            0       \
   195.618    483.560    -0.582  -0.640  0.070   0.068          0    NoError   \
   68.95222        6.23297        2.632393       4703   20        0    NoError   \
   1.               INDEF          INDEF                  INDEF                  \
   5.00      9369.124      78.84562   3932.542      16.013 0.019 0    NoError   *\
   7.50      16638.16      176.9813   4434.906      15.883 0.023 0    NoError   *\
   10.00     26254.11      314.3169   4581.261      15.848 0.029 0    NoError   *\
   12.50     38558.43      491.3904   4675.975      15.825 0.035 0    NoError   *\
   15.00     53700.28      706.8641   4960.433      15.761 0.040 0    NoError   *\
   17.50     71445.58      962.7172   5064.095      15.739 0.047 0    NoError   *\
   20.00     91834.17      1256.521   5194.255      15.711 0.053 0    NoError   *\
   22.50     114996.9      1591.084   5288.081      15.692 0.060 0    NoError   *\
   25.00     140757.4      1963.296   5383.831      15.672 0.067 0    NoError   *\
   27.50     169155.7      2376.665   5279.284      15.694 0.077 0    NoError   *\
   30.00     200351.3      2827.048   5420.033      15.665 0.085 0    NoError   *\
   35.00     270491.6      3848.048   5160.146      15.718 0.110 0    NoError   *\
   40.00     351731.4      5026.392   5150.483      15.720 0.134 0    NoError   *\
   45.00     444207.3      6362.046   5530.06       15.643 0.150 0    NoError   *\
   60.00     785383.       11310.65   5488.602      15.651 0.242 0    NoError   *\
   70.00     1067326.      15394.69   5828.265      15.586 0.298 0    NoError   *
```

r_{ap} N mag   mag err

For faint targets the S/N quickly deteriorates at large radii.

Choosing the aperture

Facts 1) and 2) give contradicting guidance:

- on one hand a large aperture should be used to obtain total N
- on the other hand, best S/N is achieved with a small aperture, which does not yield total N.

Solution : Use *aperture correction*:

- Measure the target counts N inside the “best S/N” radius ${r_{ap}}^{(1)}$ (rule of thumb: use ${r_{ap}}^{(1)} = 1.5 \times$ FWHM).
- Select a *bright* star in the field and measure the counts N_{ap1} inside ${r_{ap}}^{(1)}$ and the counts N_{ap2} inside a “big” aperture ${r_{ap}}^{(2)}$.
- Aperture correction $c(\mathrm{ap}) = N_{\mathrm{ap2}}/N_{\mathrm{ap1}}$.
- Corrected counts $N_{\mathrm{apcorr}} = c(\mathrm{ap}) \times N$
- Works for point sources only!

1.2 PSF photometry (point sources only)

PSF = "Point Spread Function" i.e. how a point source looks through the optical system.

Stars are practically point sources $\rightarrow$ PSF = image of a star.

PSF photometry :

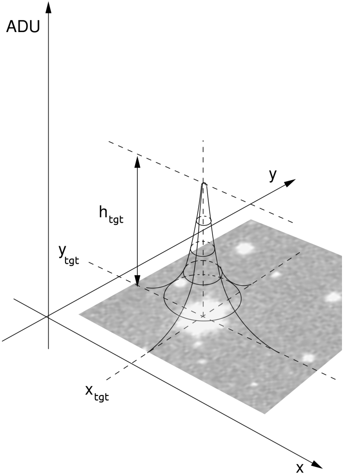
1) Create the PSF model = 2-dim image of a point source
   - Can use a theoretical model, an analytic function or an image of a sufficiently bright star in the CCD frame (the last option usually gives the best results).
   - Common analytical functions:

Gauss : $I(r) = I_0 \exp(-r^2/2\sigma^2)$

Moffat : $I(r) = I_0 \left[1 + K \left(\frac{r}{R}\right)^2\right]^{-\beta}$, $R = \mathrm{FWHM}/2,\ K = 2^{1/\beta} - 1$

PSF photometry

2) Obtain aperture photometry of your PSF $\rightarrow$ relationship between total counts and height : $N_{PSF} = k * h_{PSF}$
3) Fit the PSF model to the target. Free parameters of the fit : x_{tgt}, y_{tgt}, h_{tgt}.
4) $N_{tgt} = k * h_{tgt}$



1.3 Sky estimation

- Select the sky annulus as close to the target you can without introducing target light into the annulus.
- Check that there are no bright targets in the annulus.
  - IRAF can cope to some extent with stars in the sky annulus by using sigma clipping and by using mode of the sky pixel distribution as N_{sky}. In practice IRAF computes the mode from

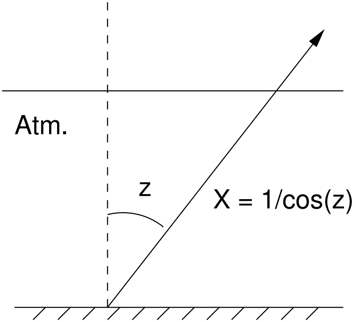
$$mode = 3 \times median - 2 \times mean$$

- Sky estimation is important for faint targets, where it can easily be the largest source of error.

2. Correcting the counts

2.1 Atmosphere

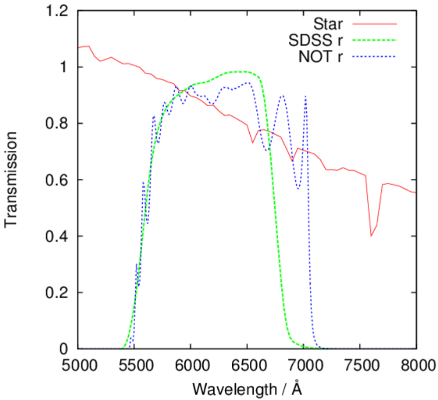
- Absorbs light in an altitude-dependent way.



- Parameterized through *airmass* X.
  $z = 0$ deg $\rightarrow X = 1$
  $z = 60$ deg $\rightarrow X = 2$

2.2 Instrumental effects

- Bias, dark, "cosmic rays" create artificial signal.
- Pixels have different gains.
  $\rightarrow$ Corrected by image processing.



- Filter mismatch: e.g. "r-band flux" is a *monochromatic* quantity [erg s^{-1} cm^{-2} $Å^{-1}$] defined at some wavelength.

  However, it is measured with a broad filter $\rightarrow$ the result depends on the transmission curve of the filter.

3. Calibration

3.1 Magnitudes

Traditionally, the calibration is done using magnitudes. The relationship between fluxes F and magnitudes m is

$$F = F_0\, 10^{-m/2.5}, \tag{3}$$

where F_0 is the flux corresponding to magnitude 0. By taking the logarithm and multiplying by -2.5 we get

$$m = 2.5 \log_{10} F_0 - 2.5 \log_{10} F = m_0 - 2.5 \log_{10} F\ . \tag{4}$$

If we observe N_s counts/s from a target, we can write

$$F = c\, N_s\ , \tag{5}$$

where c is a constant. Thus

$$m = \underbrace{m_0 - 2.5 \log_{10} c}_{zp} - 2.5 \log_{10} N_s\ . \tag{6}$$

3.2 Calibration equation

$$m_c = zp - 2.5 \log N - k \times X - C \times Color + 2.5 \log T_{exp} \,, \quad (7)$$

where

N	= observed counts
X	= airmass
$Color$	= difference of target magnitude in two filters, e.g. (B-V)
T_{exp}	= exposure time
zp	= system zero point (drifts slowly with time)
k	= extinction coefficient (varies from night to night)
C	= color term of the filter (does no change).

Calibration = determine zp, k and C.

Absolute calibration

- You have obtained CCD-images of several calibration targets (“standard stars”) with known m and $color$. The goal is to determine zp, k and C from these observations.
- This method works only of the night is *photometric*, i.e. extinction k stays constant.
- It is important to cover a wide range of airmasses (from 1 to 2) and colors.

Absolute calibration : *zp*, *k* and *C*.

- Measure N for each standard star.

- Compute *instrumental magnitudes* m_i from

$$m_i = m_0 - 2.5 \log_{10} N + 2.5 \log_{10} T_{exp} \,, \qquad (8)$$

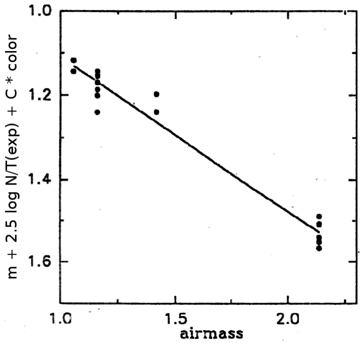
  where m_0 is an arbitrary zero point (IRAF default 25.0).

- Plot each observation in a 3-d space with X, *color* and $m - m_i$ as axes, where m is the catalog magnitude of the star. The points should fall on a plane (Eq. 7).

- Fitting a plane to this 3-d data will give you *zp*, *k* and *C*.

Absolute calibration : *zp*, *k*

- Usually C is know for the system and it doesn't vary. It is then sufficient to determine only zp and k from a 2-d fit.
- For each standard star observation, plot X in the x-axis and $m - m_i + C \times color$ in the y-axis. A linear fit will then yield zp and k.



Differential calibration

- Assume that we have on the CCD image the target and a another target with known magnitude m_{ref}.
- If we mark with m the magnitude of our target of interest, we get from Eq. (7)

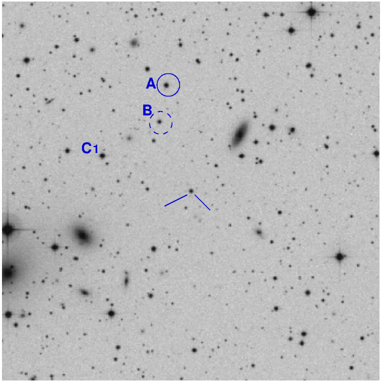
$$m = m_{ref} + 2.5 \log \frac{N_{ref}}{N} - C \times (Color - Color_{ref}) \qquad (9)$$

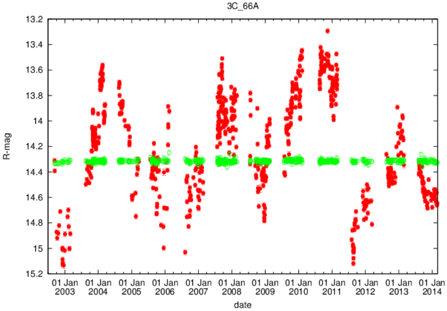
$\rightarrow$ m can be easily computed if C is known.

Advantages of differential calibration

- The zero point and atmospheric effects are almost completely eliminated. In practice small residual effects persist at $\sim$ 0.01-0.02 mag level and below.
- Works well even through clouds.
- No need for calibration observations if good quality survey data exist for the observed field and filters (e.g. SDSS).
- No need for aperture correction.

Tuorla blazar monitoring





From magnitudes to fluxes

$$F = F_0 * 10^{-0.4 * m_c} \;, \tag{10}$$

where F_0 is a filter-dependent zero point, for instance:

Filter	F_0 [Jy]
U	1790
B	4263
V	3636
R	3064
I	2416
SDSS u,g,r,i,z	3631