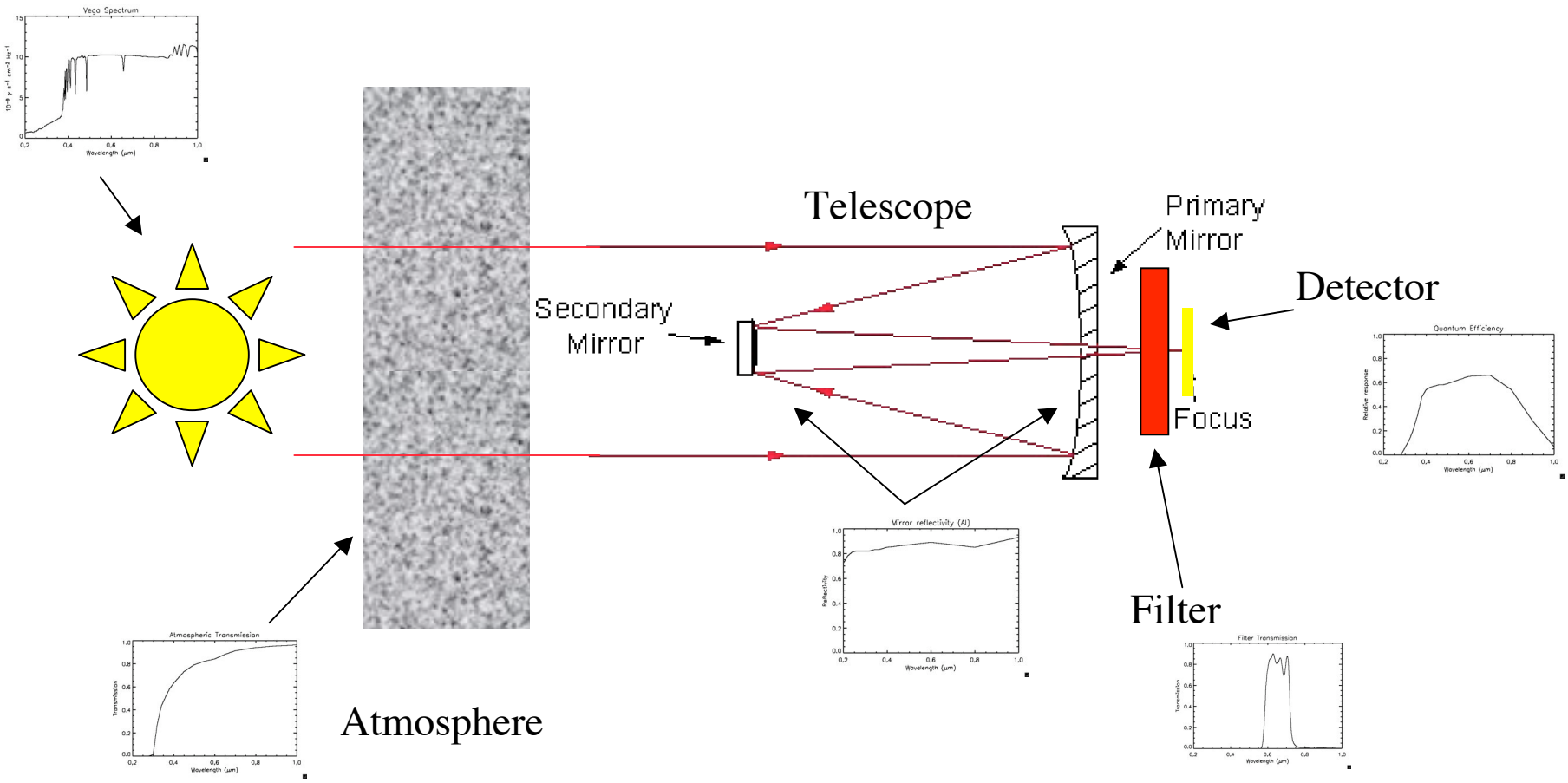
Steps to Photometry

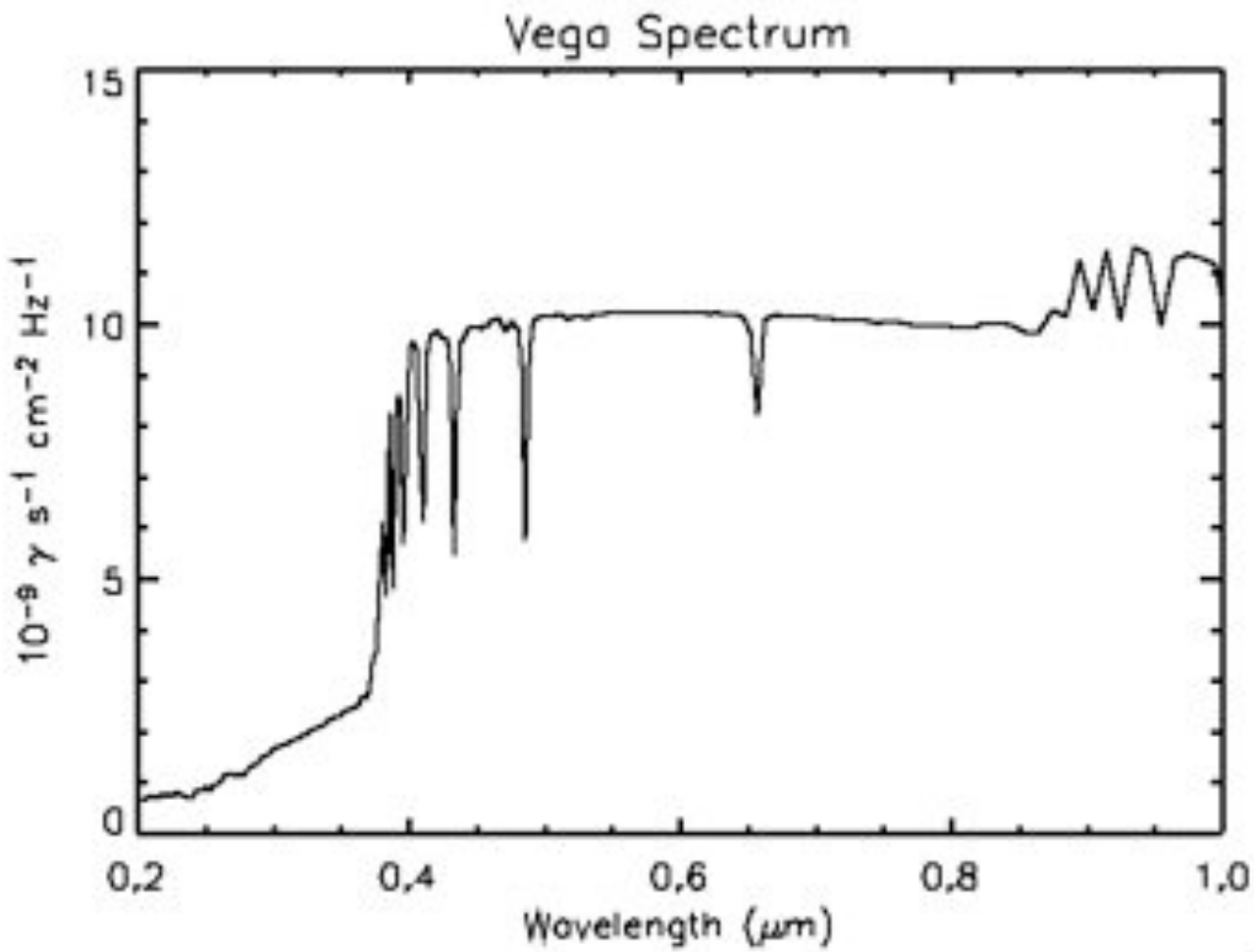
James R. Graham

10/10/2006

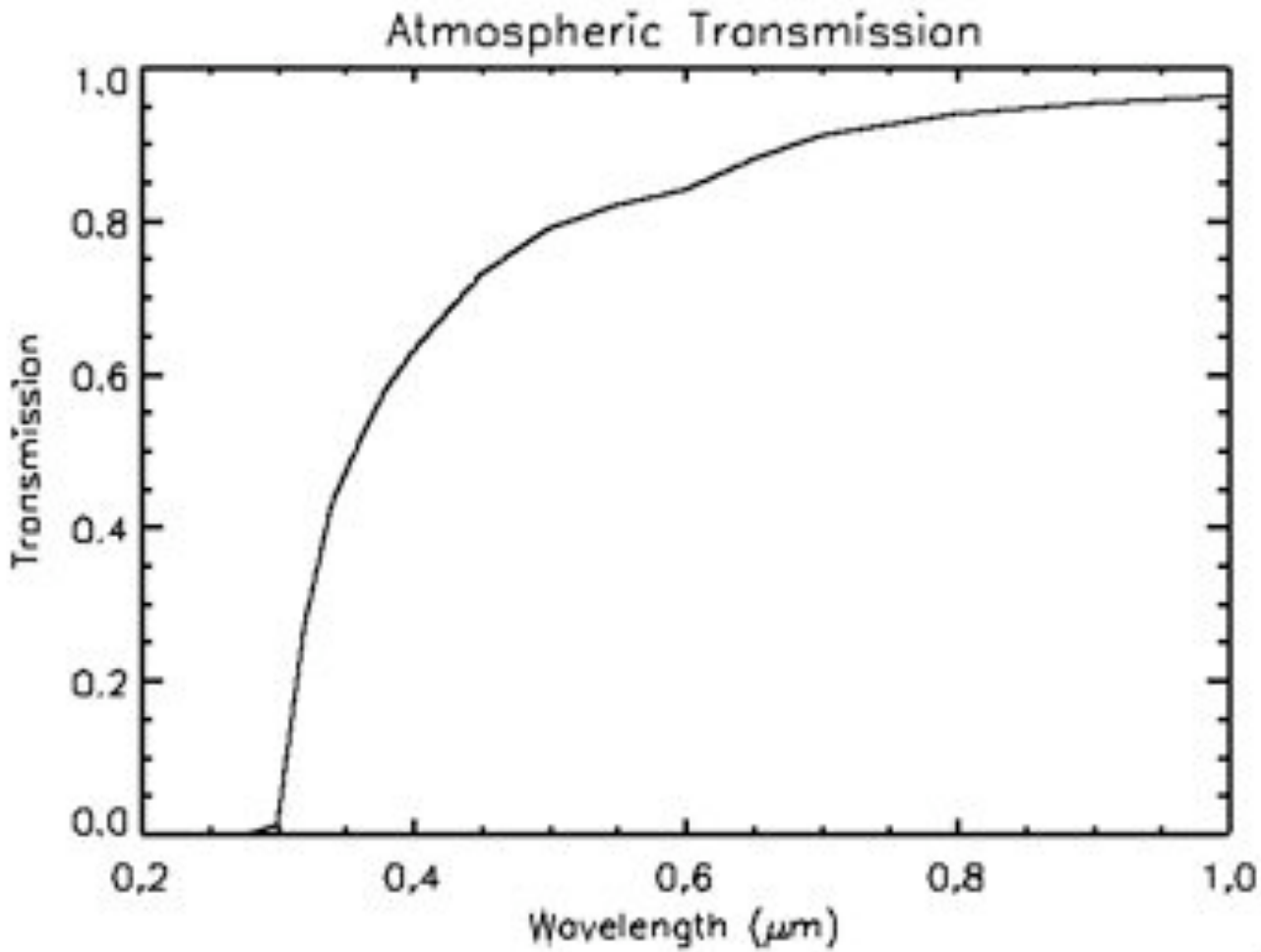
Step 1: The Photon Path



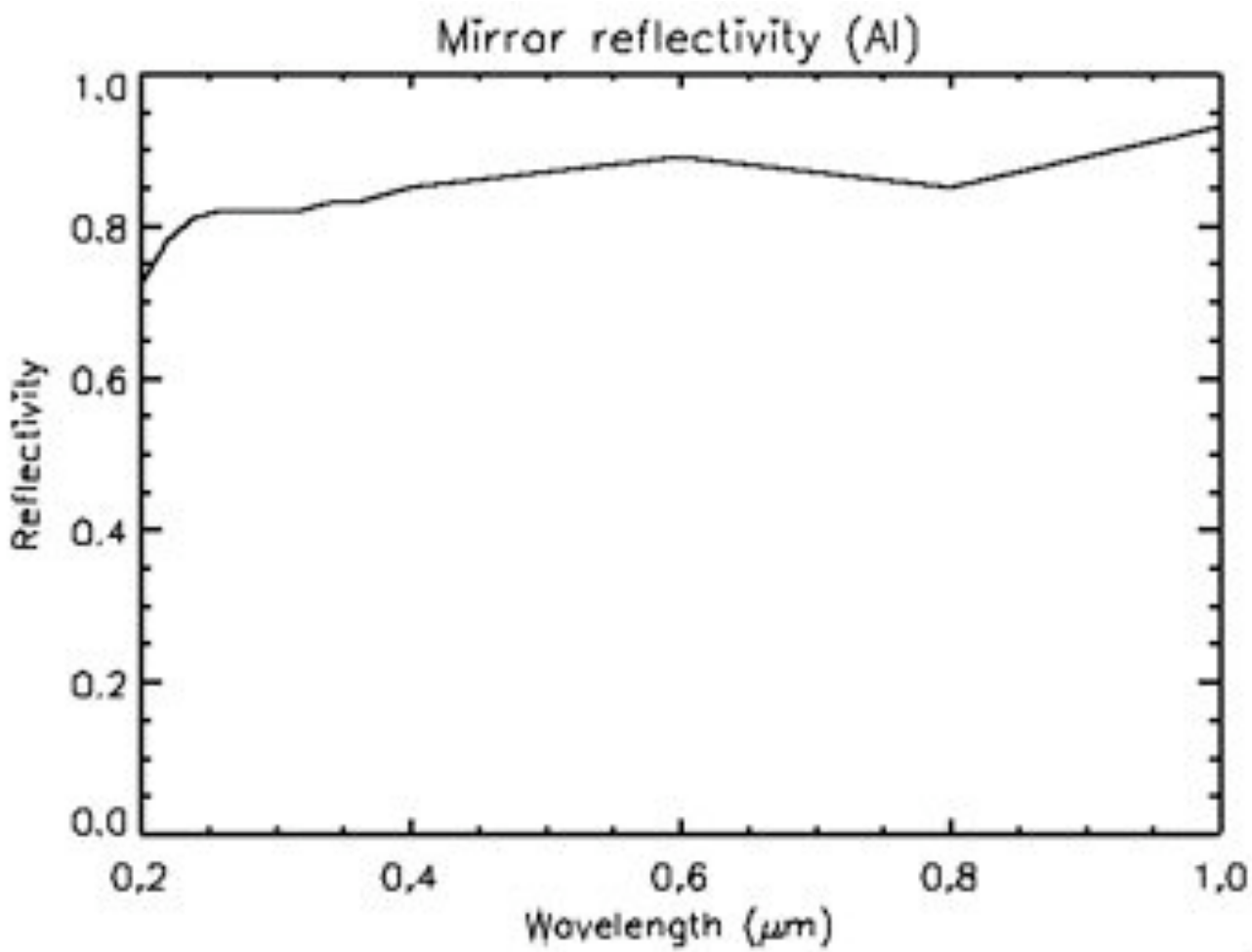
Spectrum of Vega



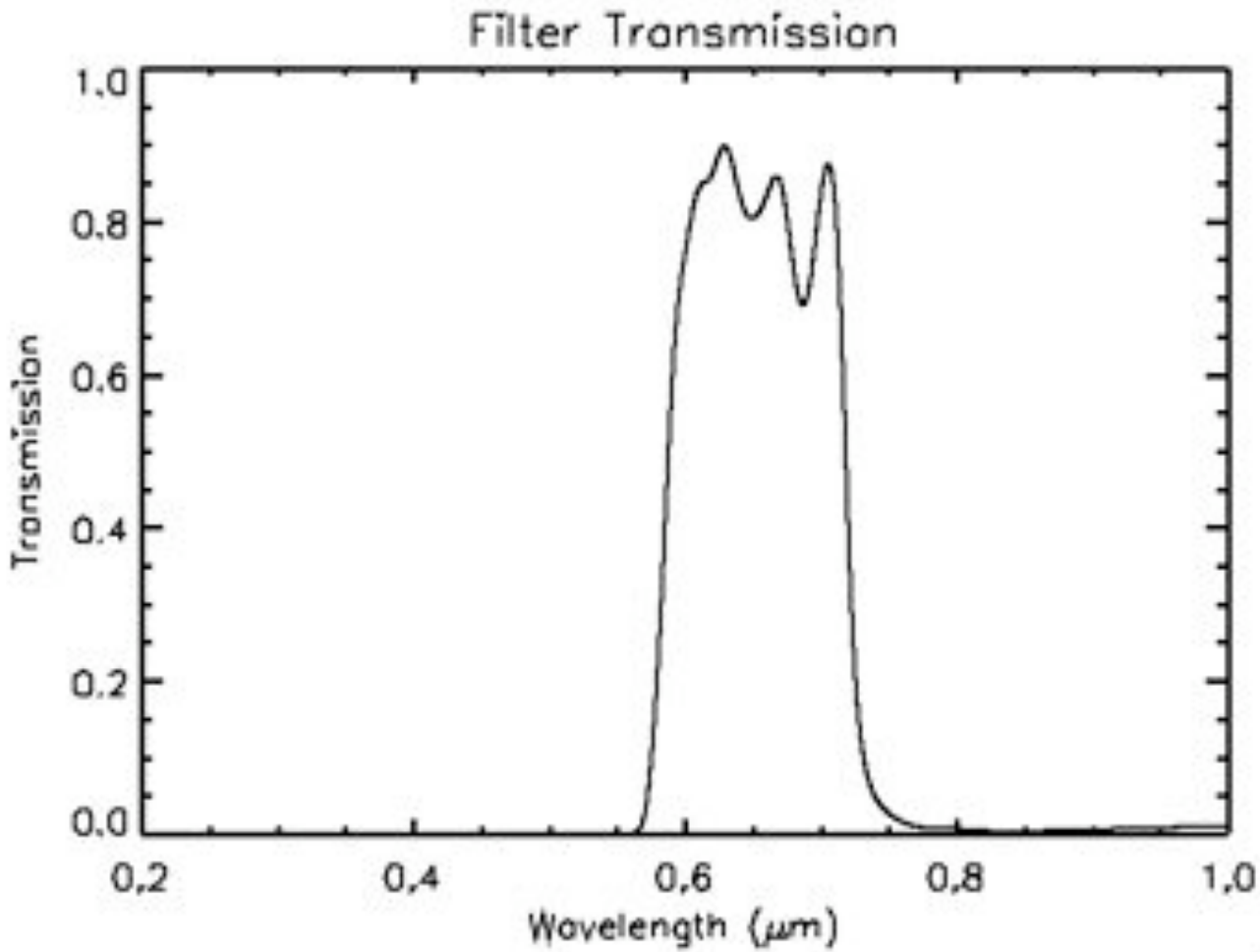
Scattering & Absorption by the Earth's Atmosphere



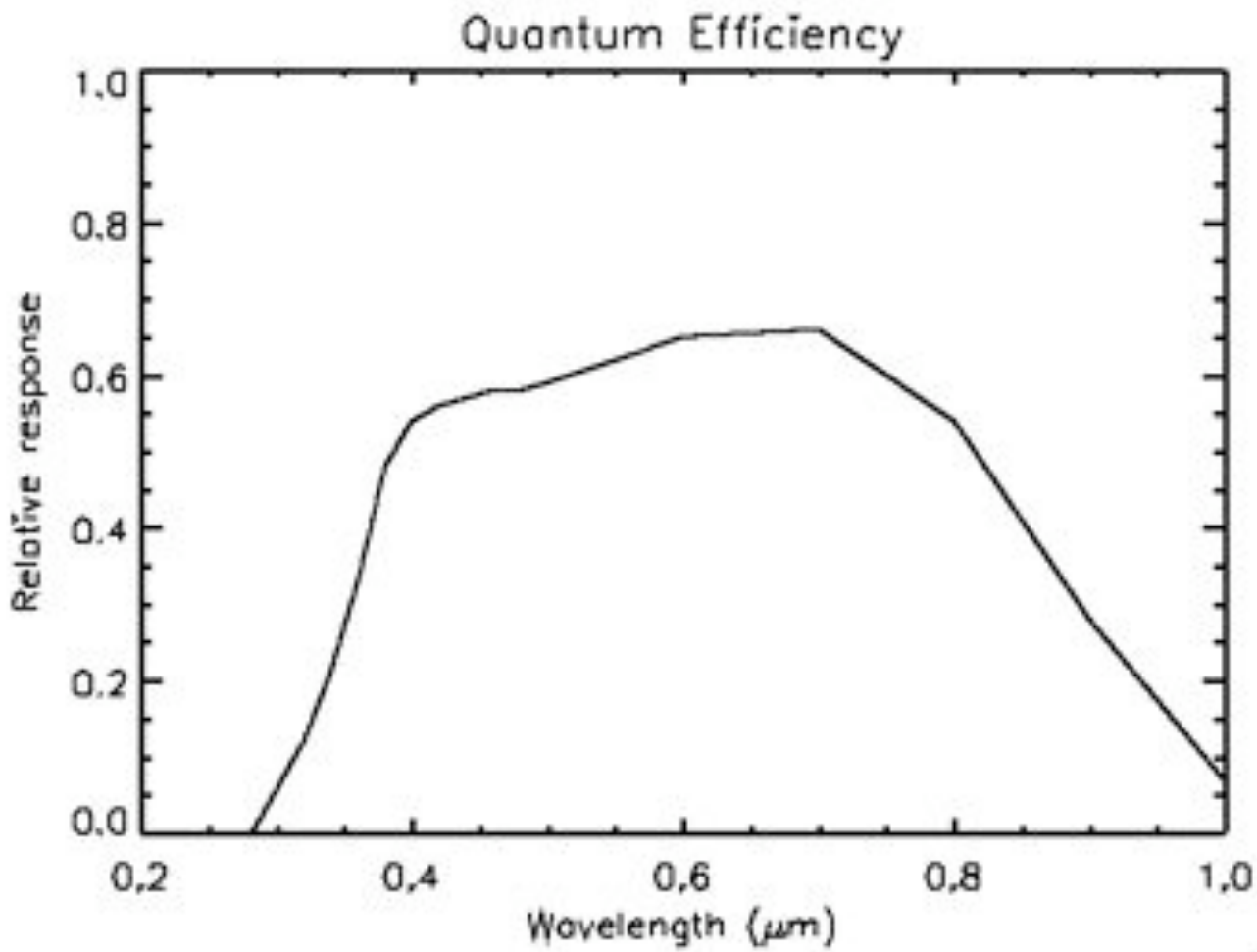
Mirror Reflectivity



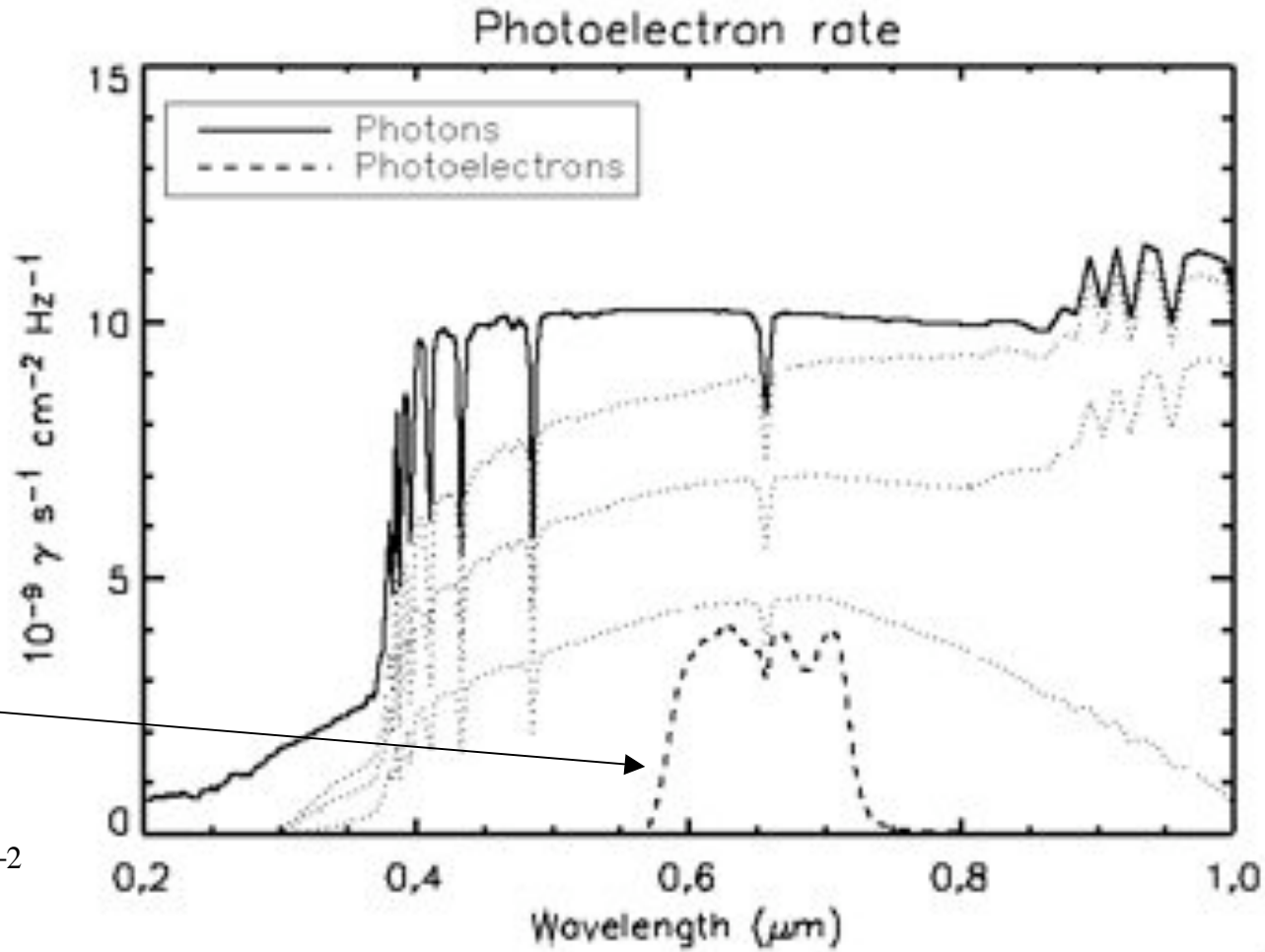
Filter Transmission



Detector Efficiency



System Throughput



$$\int_{\nu_1}^{\nu_2} \frac{\eta_\nu F_\nu}{h\nu} d\nu =$$

$$5.88 \times 10^{10}\ \gamma\ s^{-1}\ cm^{-2}$$

Step 2: Systematic Errors

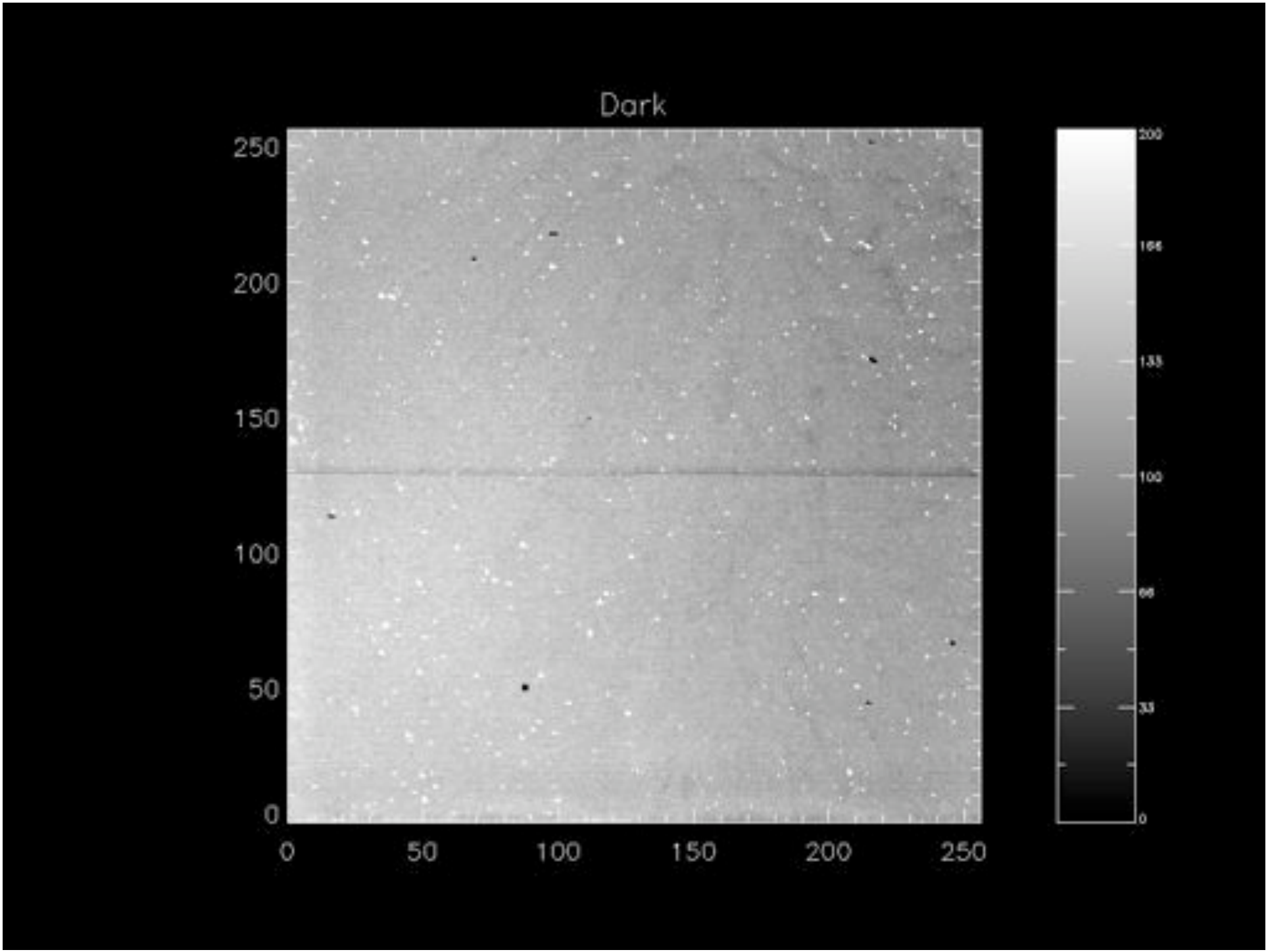
- Imaging detectors suffer from a number of errors that must be corrected before the data can be used for photometry
- Goal is to make the DNs from the `FITS` files proportional to the brightness of the astronomical source

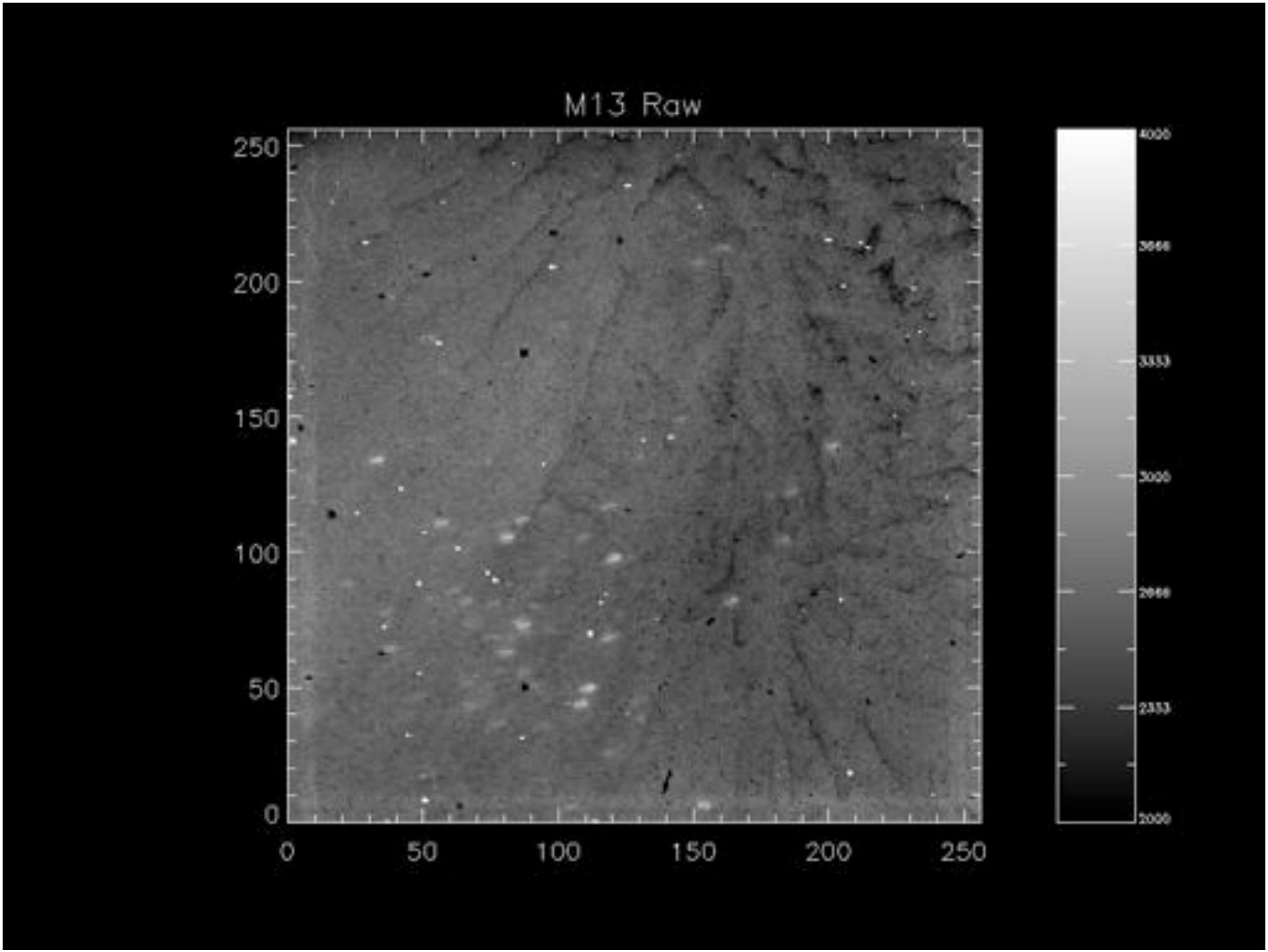
Bias & Dark Current

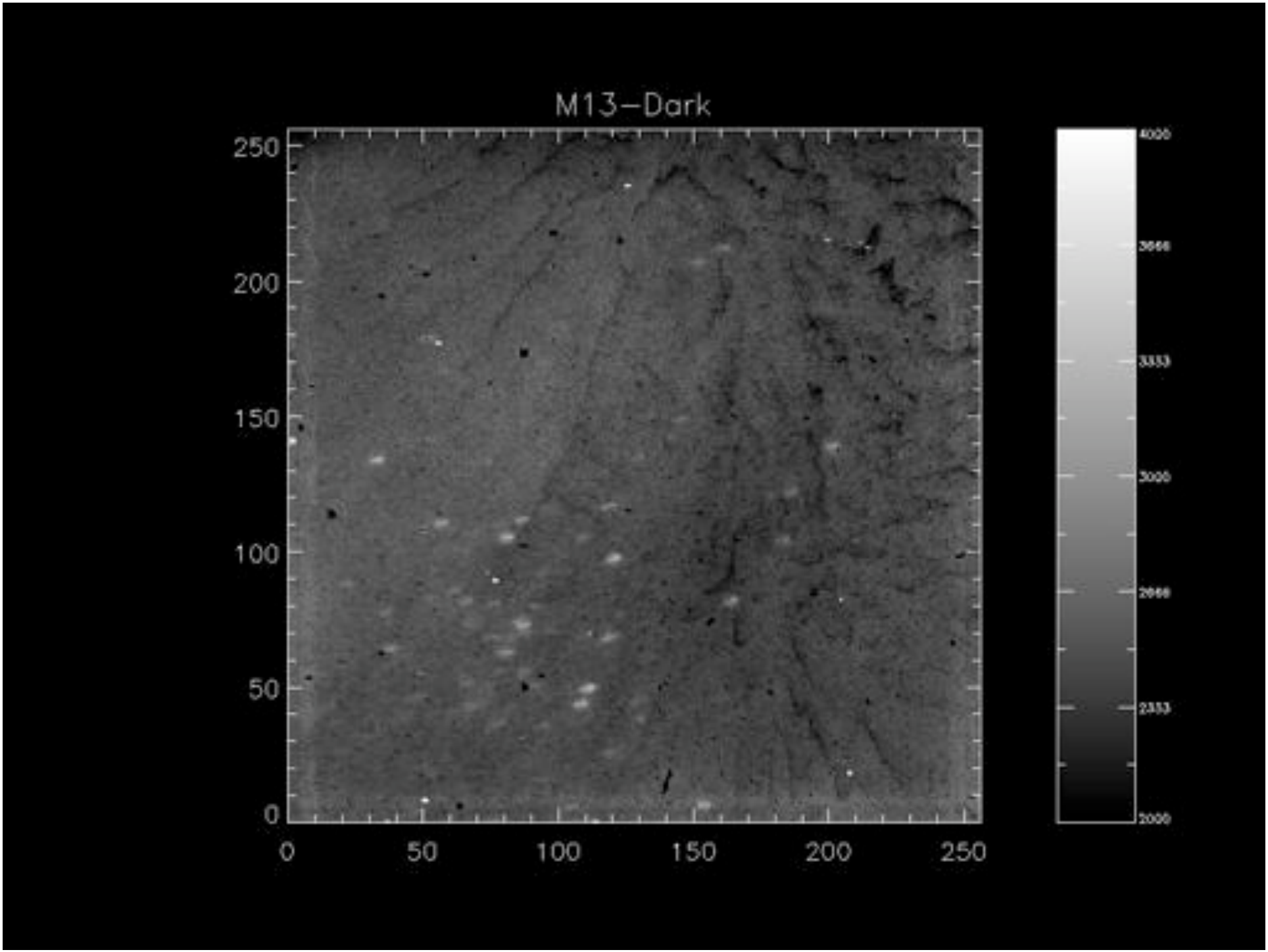
- Even a zero second exposure gives non-zero DN
  - Dark current masquerades as real signal
  - Bias & dark current can be subtracted either by
    1. Take a dark frame of the same exposure time as the science image—takes care of bias too, or
    2. Take an image of blank sky—takes care of bias, dark & can be used to subtract the sky brightness! (can be hard to find blank sky)

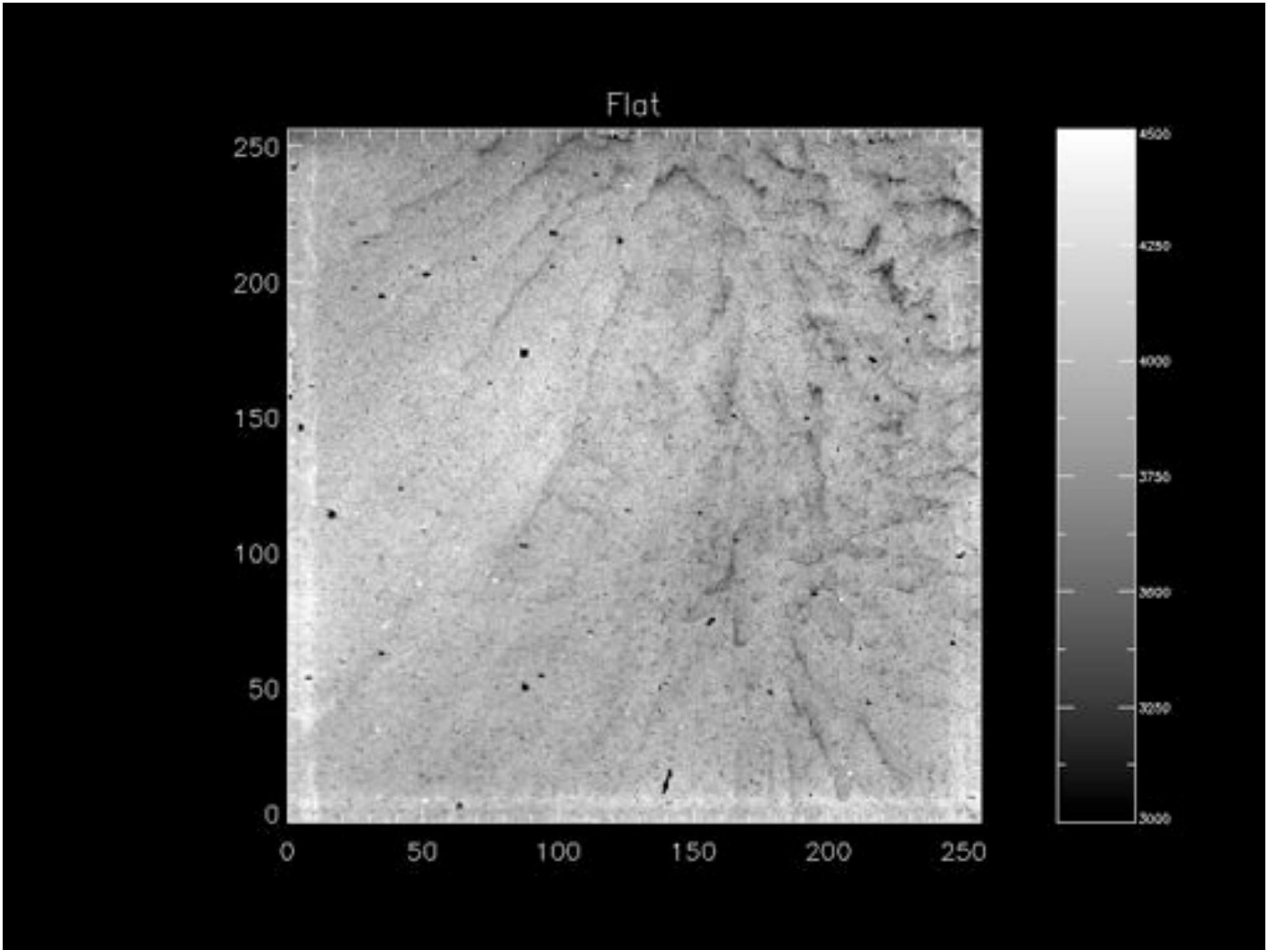
Flat Field

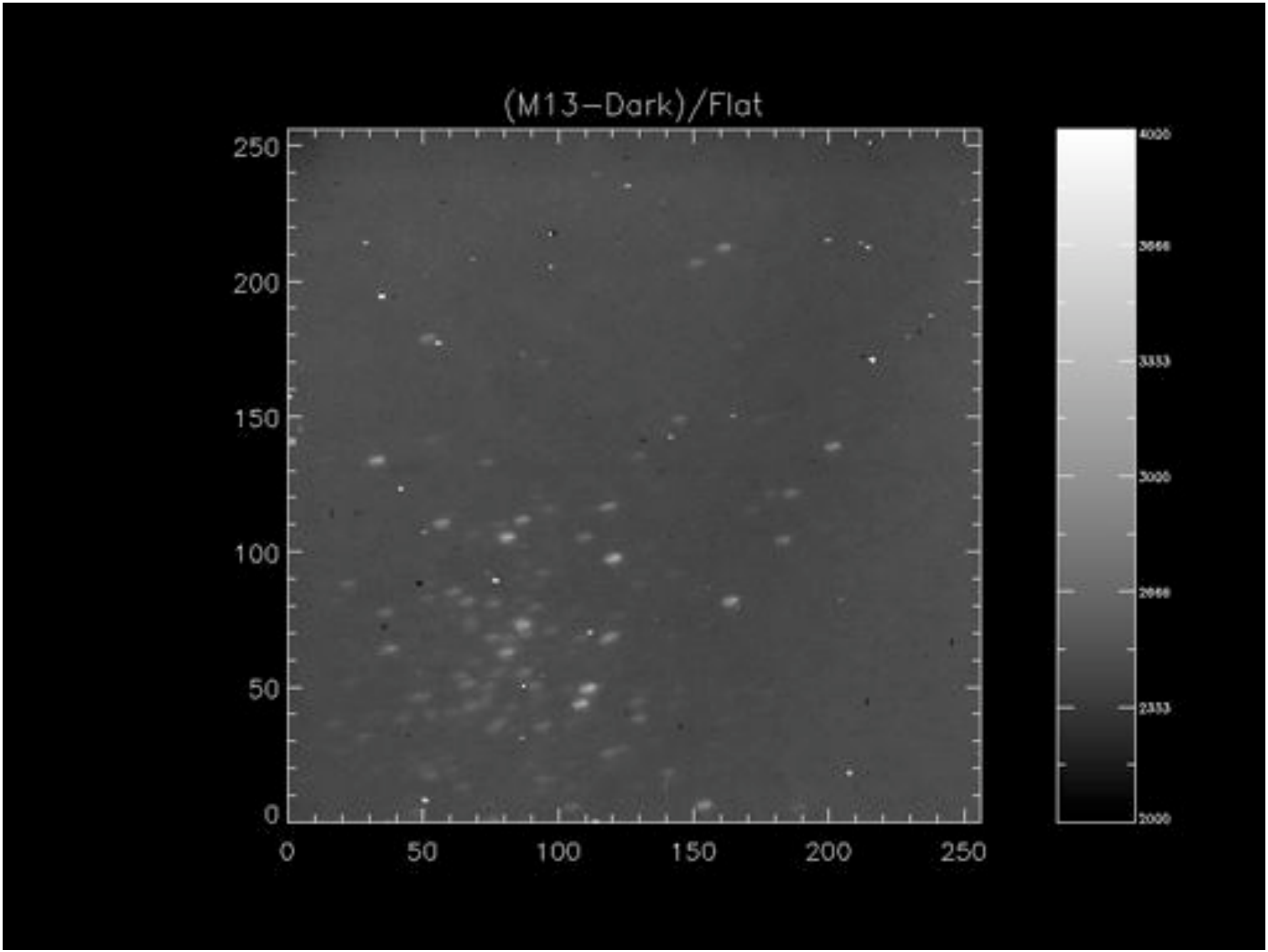
- Every pixel in the detector array has a slightly different response to light
  - Some pixels are more efficient than others
- Need to correct for pixel-to-pixel variations by constructing a flat field
  - Make a flat field by observing a uniform source, e.g., the twilight sky
  - ***Divide dark-subtracted images by the flat field***

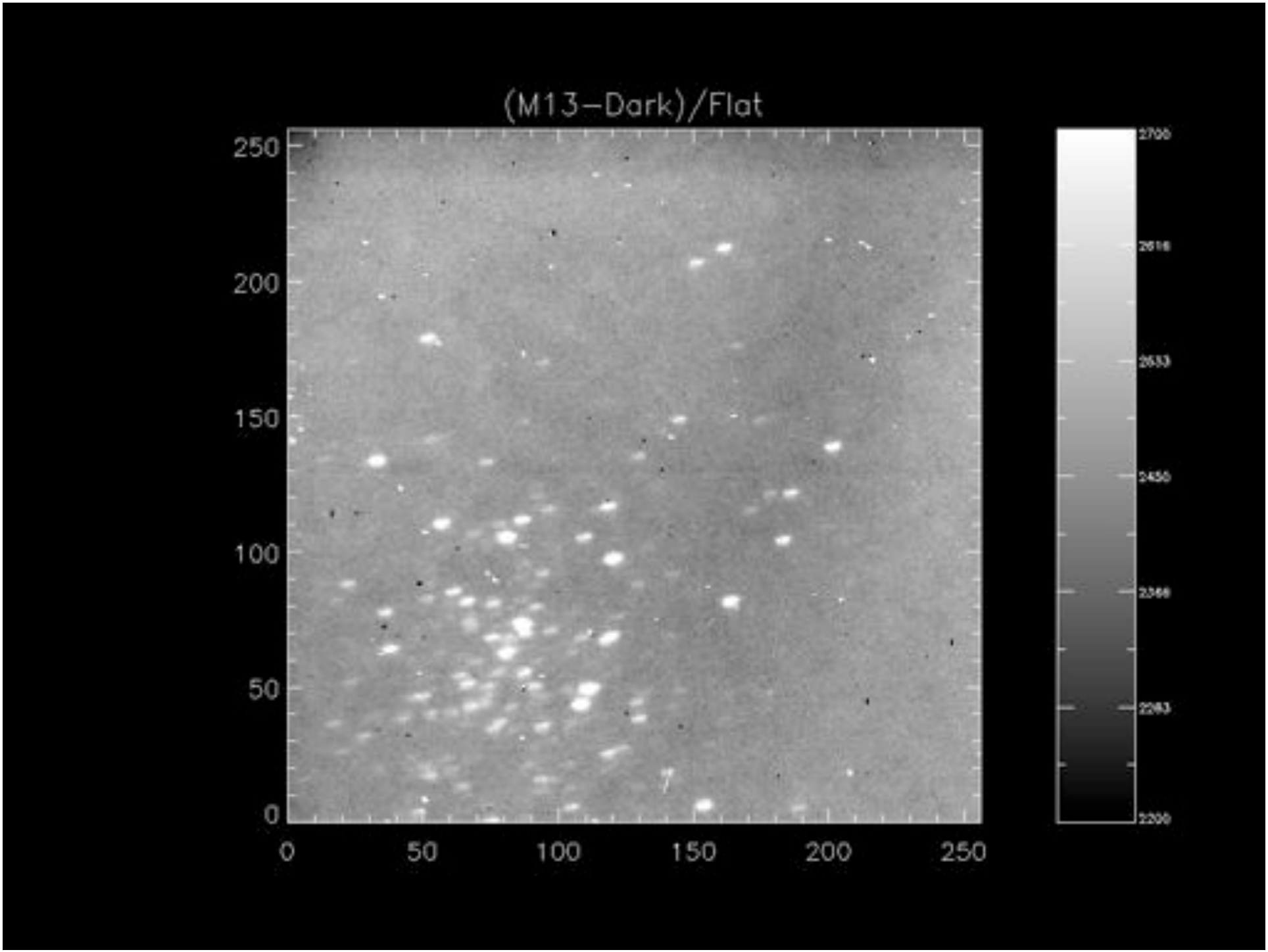

Dark
250
200
150
100
50
0
0
50
100
150
200
250
200
166
133
100
66
33
0


M13 Raw
250
200
150
100
50
0
0
50
100
150
200
250
4000
3666
3333
3000
2666
2333
2000


M13−Dark
250
200
150
100
50
0
0
50
100
150
200
250
4000
3666
3333
3000
2666
2333
2000

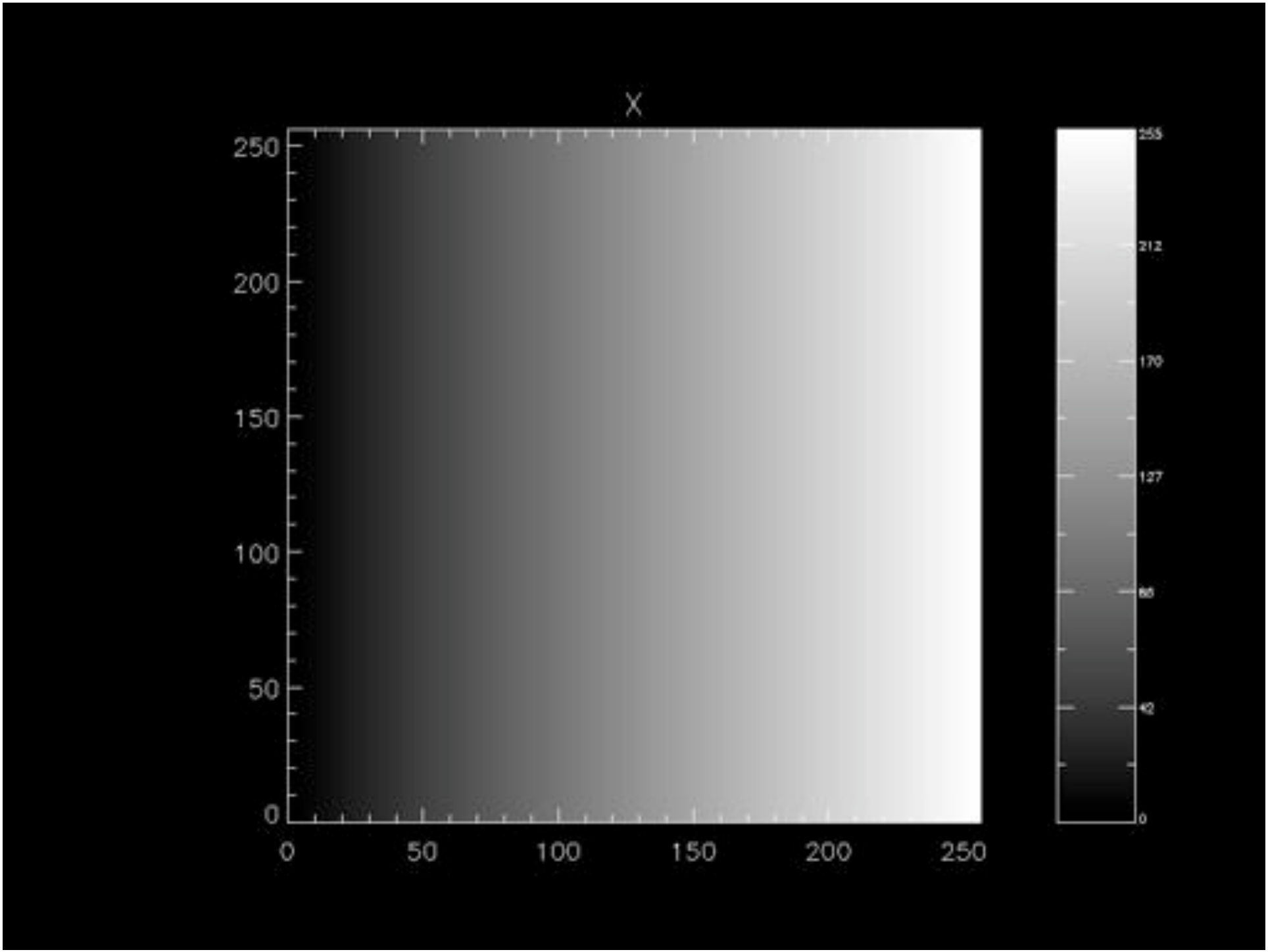

Flat
250
200
150
100
50
0
0
50
100
150
200
250
4500
4250
4000
3750
3500
3250
3000

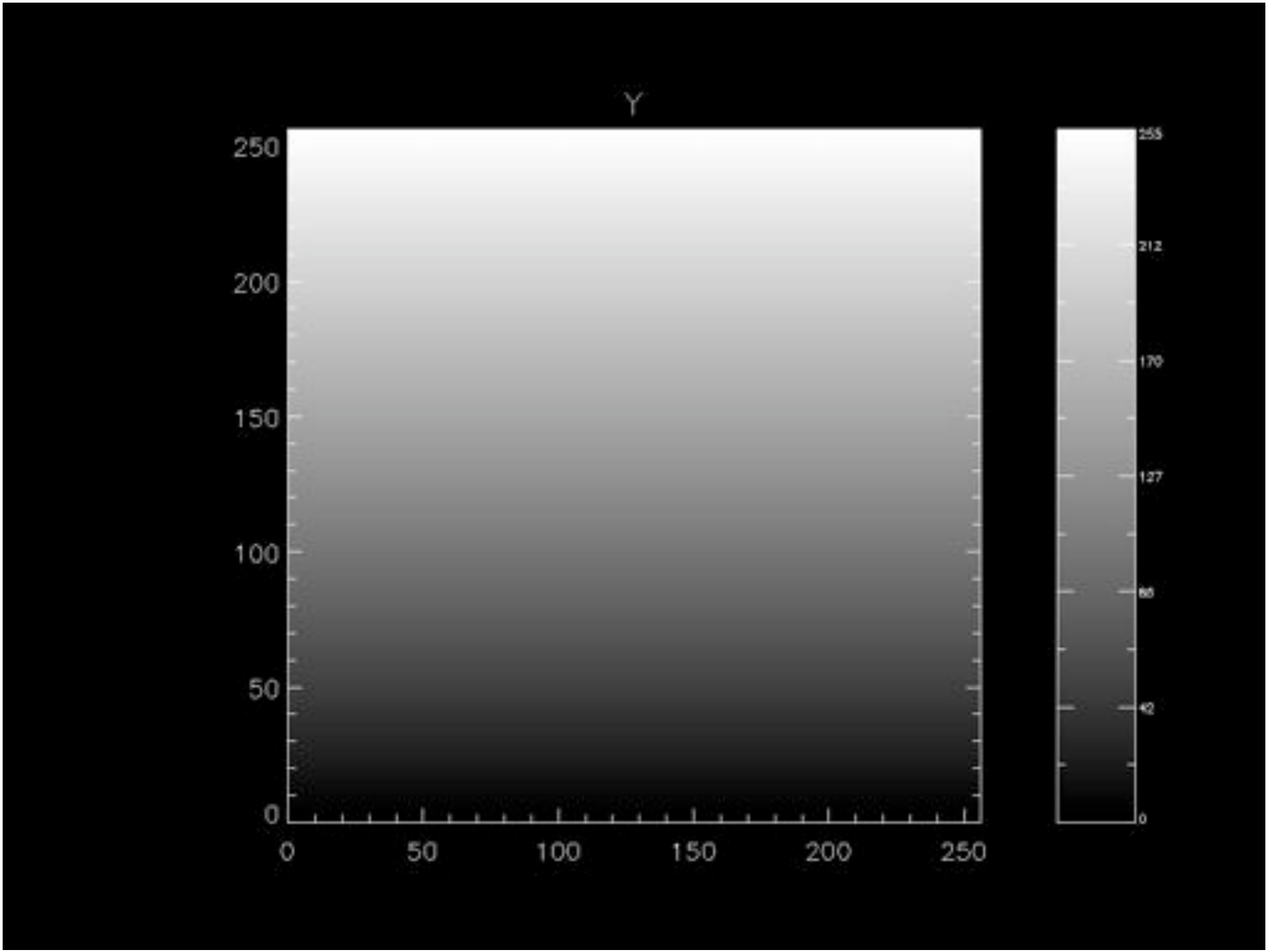

(M13−Dark)/Flat
250
200
150
100
50
0
0
50
100
150
200
250
4000
3666
3333
3000
2666
2333
2000

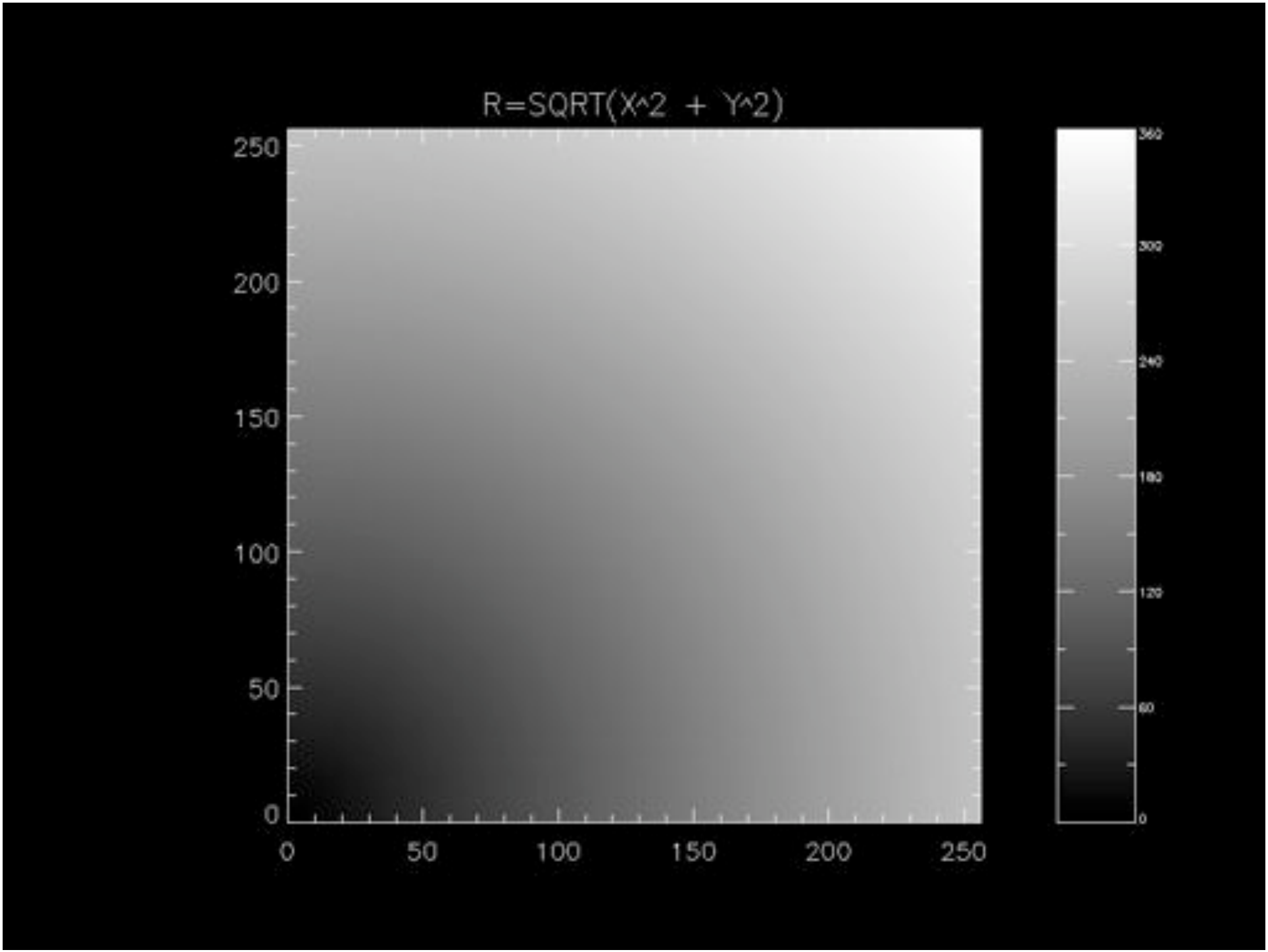

(M13−Dark)/Flat
250
200
150
100
50
0
0
50
100
150
200
250
2700
2616
2533
2450
2366
2283
2200

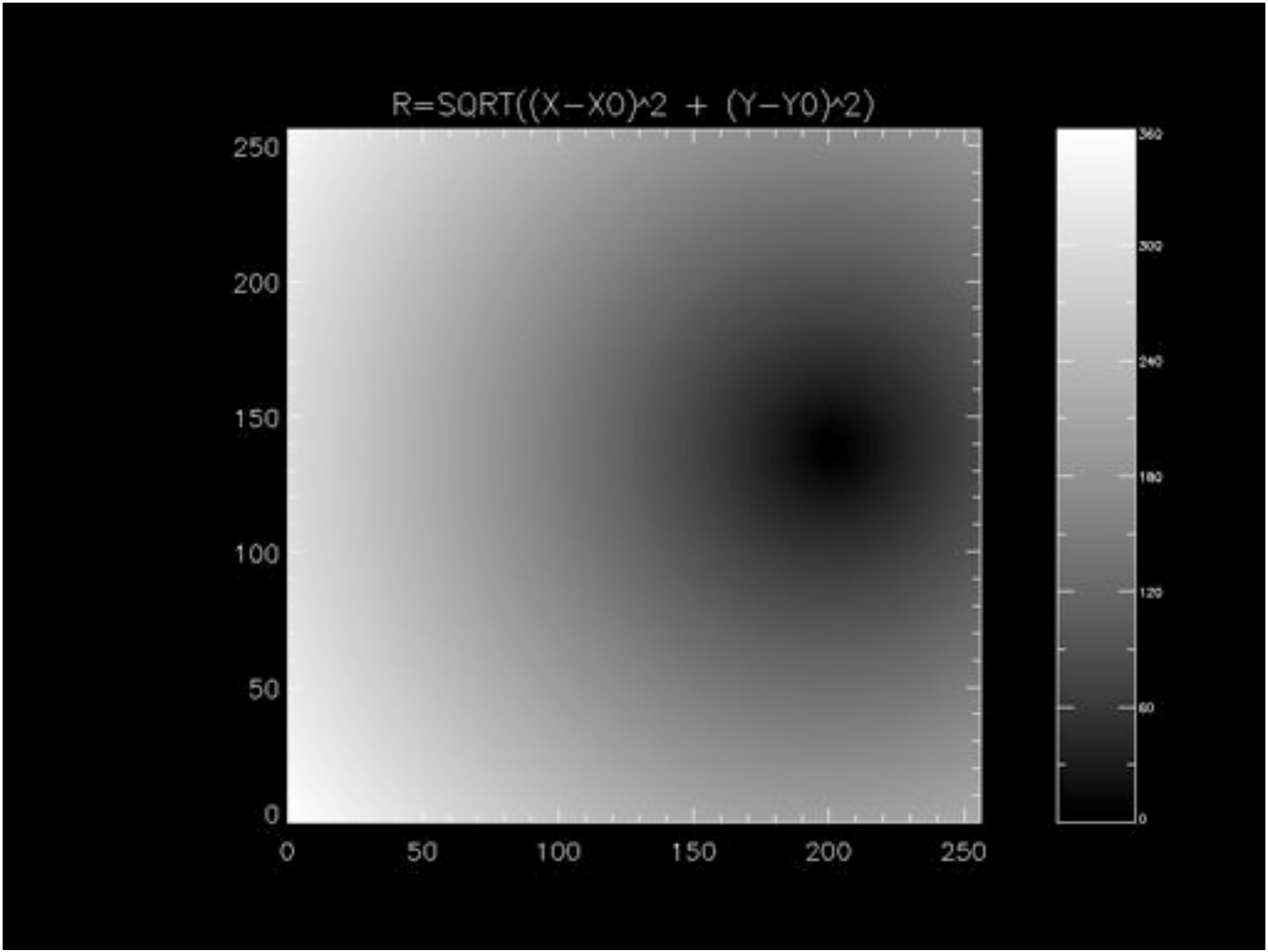
Photometry

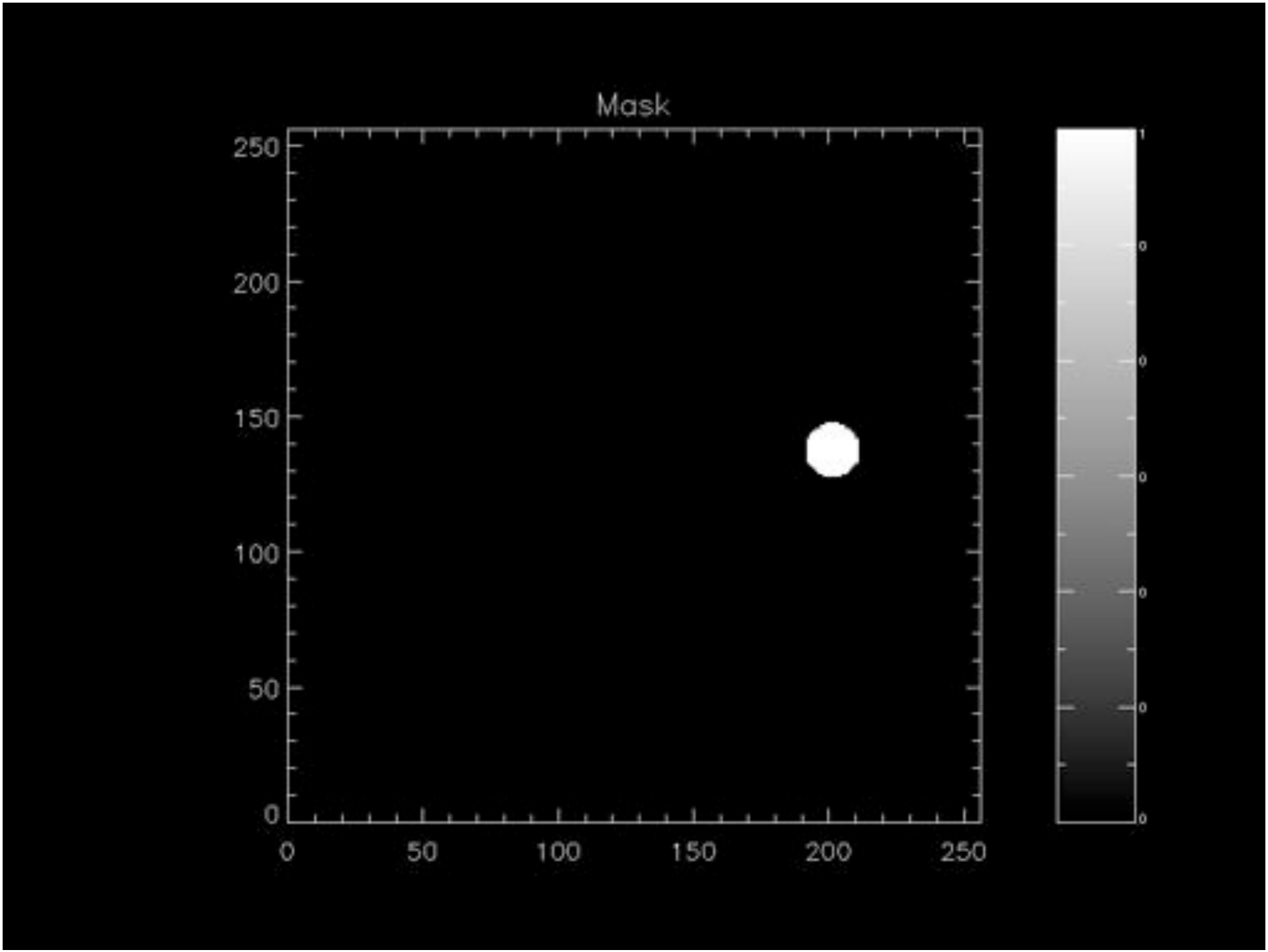
- The light from a star is spread over several pixels
- How do we sum the light to get a measure of the total signal from the star?
  1. Identify the location of the star (`RDPIX`)
  2. Select the associated pixels by making a mask
  3. Sum up the light (`TOTAL`)
     - Subtract the sky background if necessary

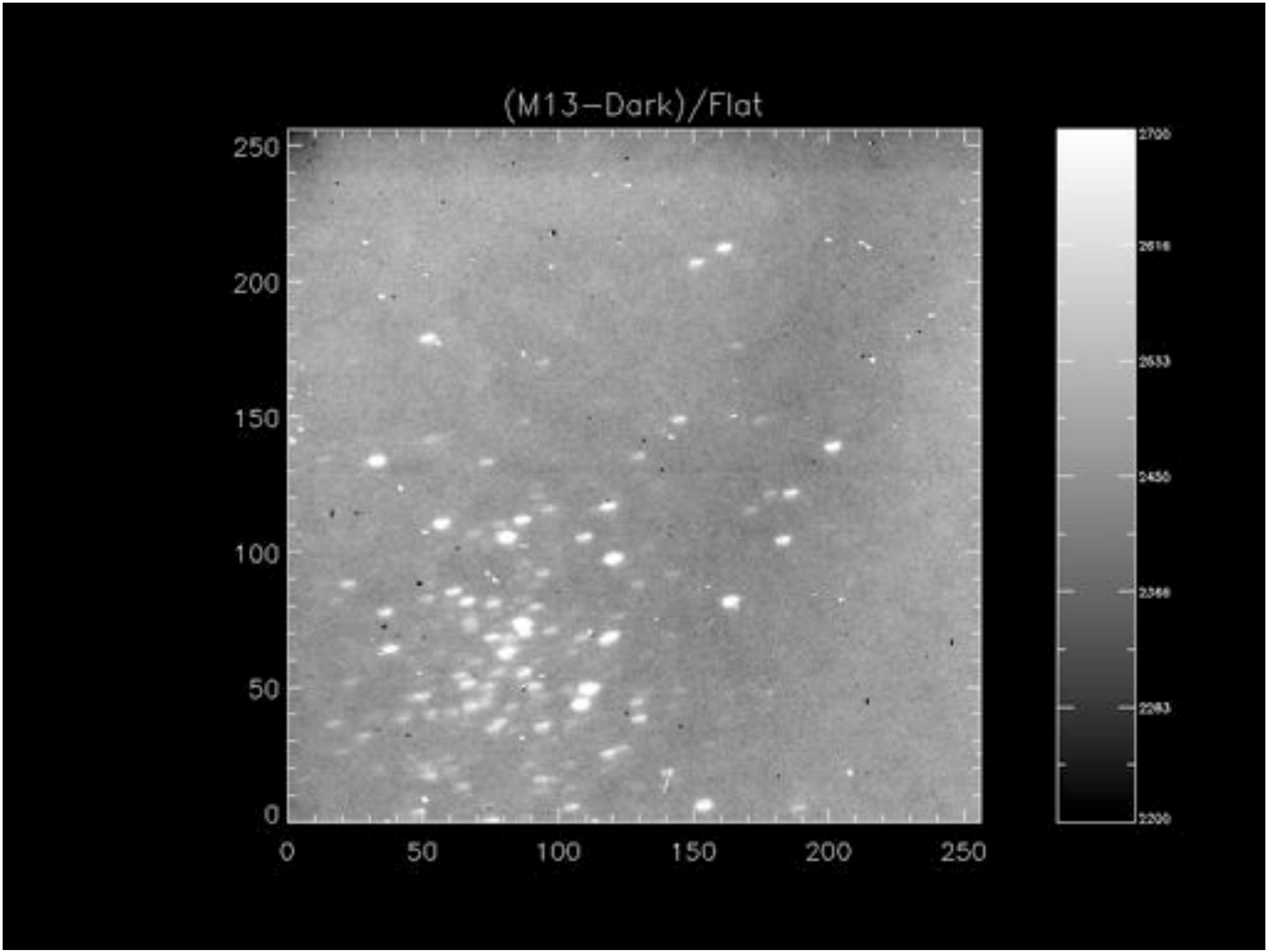

X
250
200
150
100
50
0
0
50
100
150
200
250
255
212
170
127
85
42
0

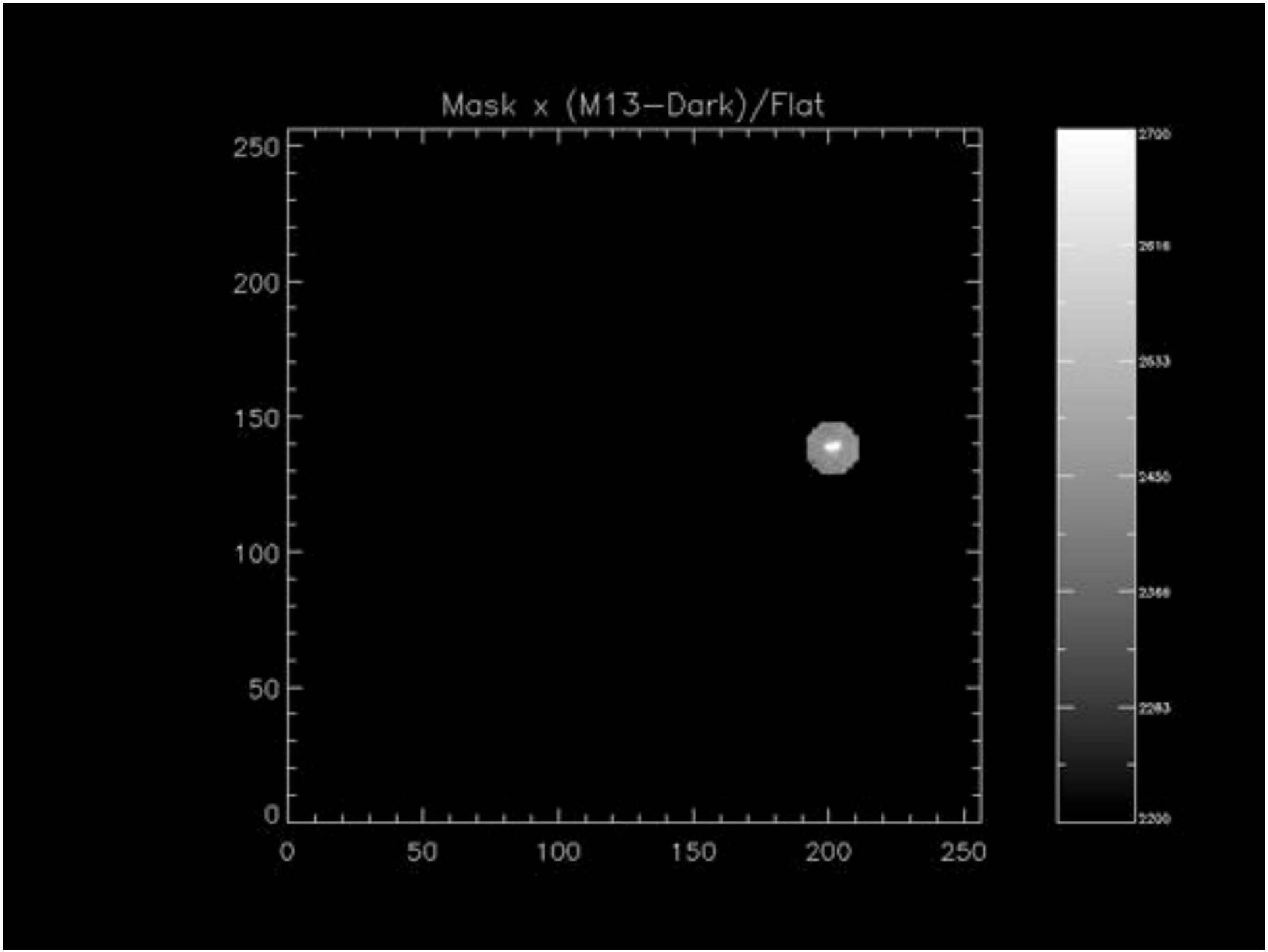

Y
250
200
150
100
50
0
0
50
100
150
200
250
255
212
170
127
85
42
0

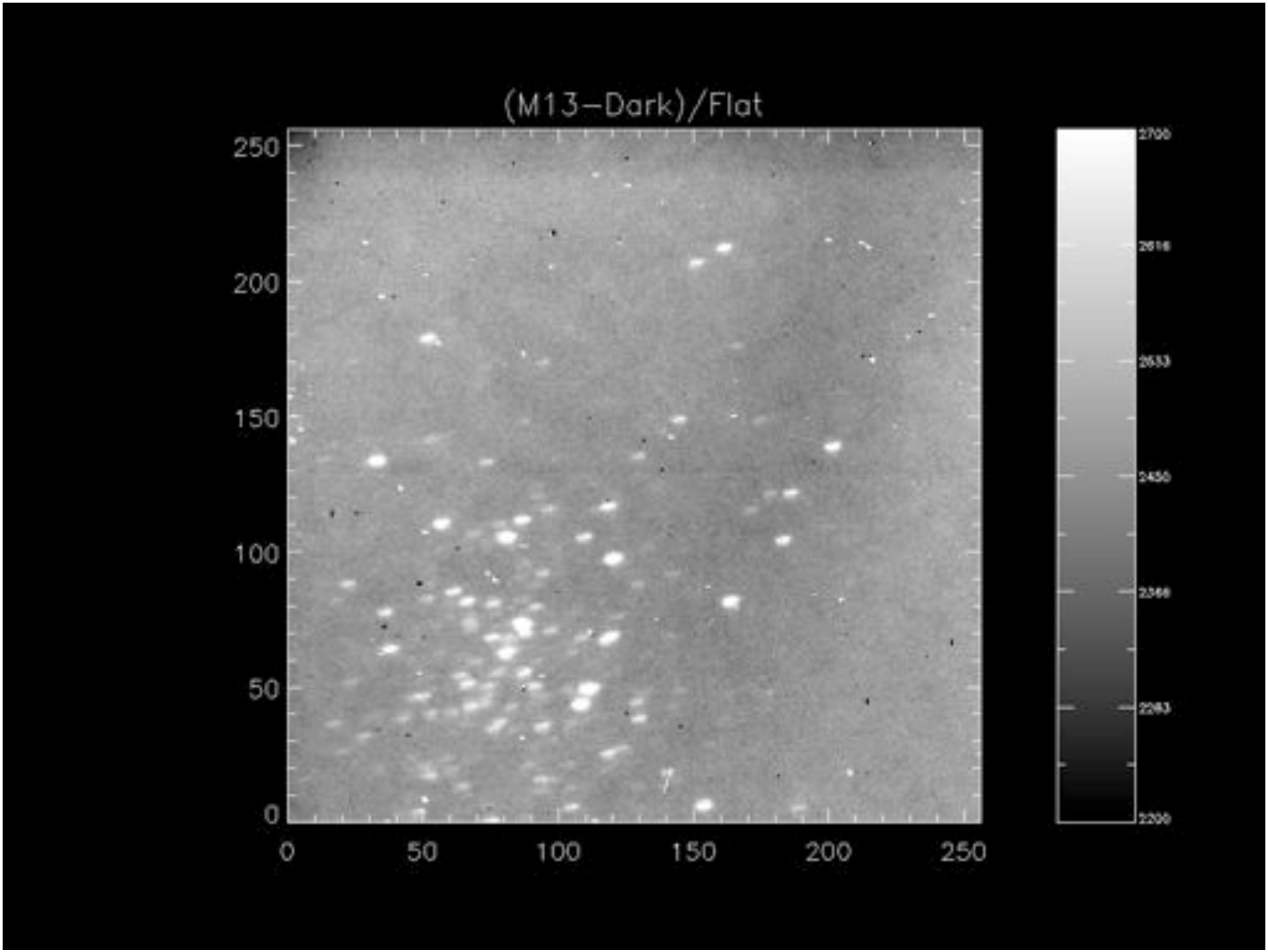

R=SQRT(X^2 + Y^2)
250
200
150
100
50
0
0
50
100
150
200
250
360
300
240
180
120
60
0

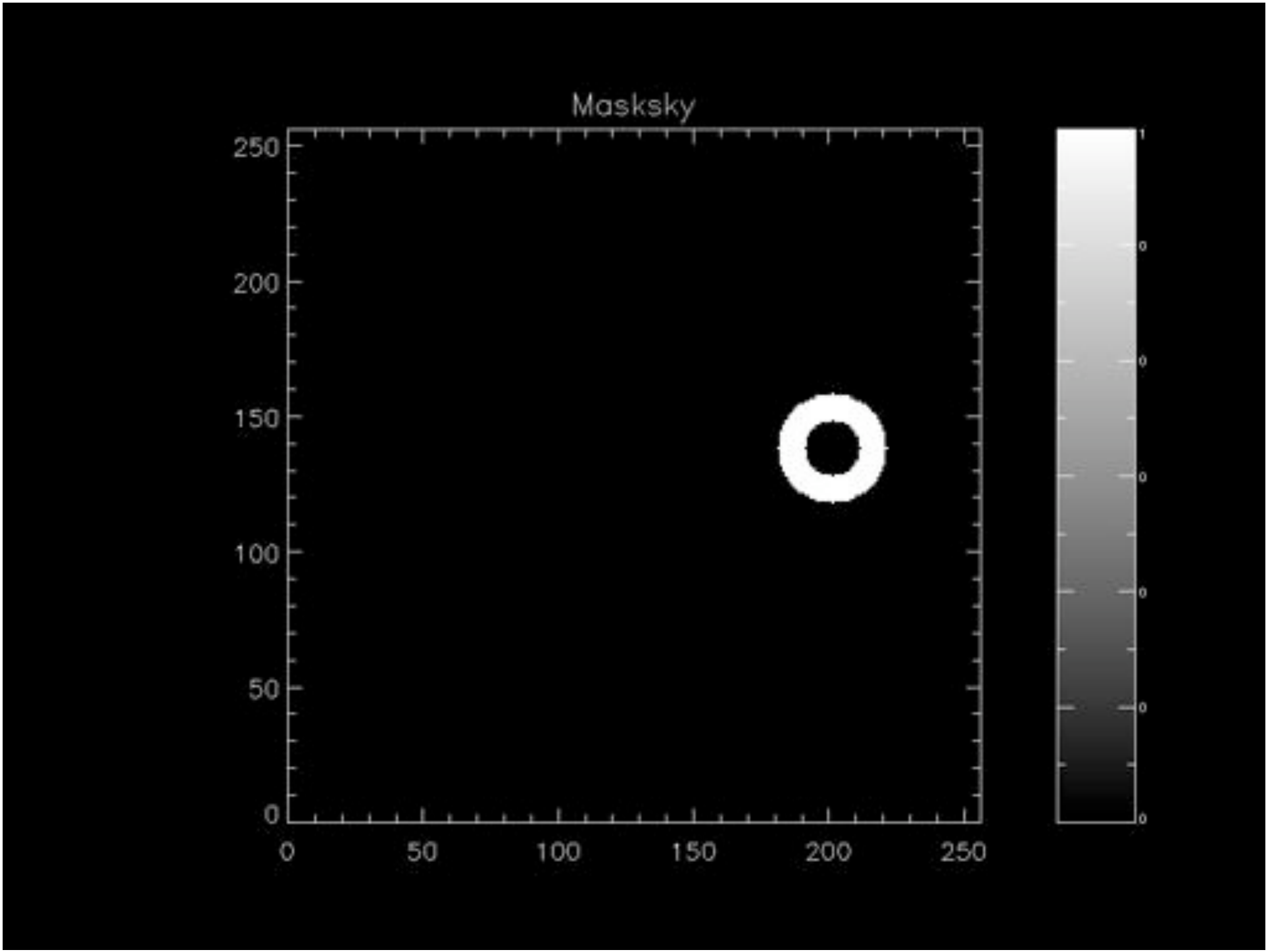

R=SQRT((X−X0)^2 + (Y−Y0)^2)
250
200
150
100
50
0
0
50
100
150
200
250
360
300
240
180
120
60
0

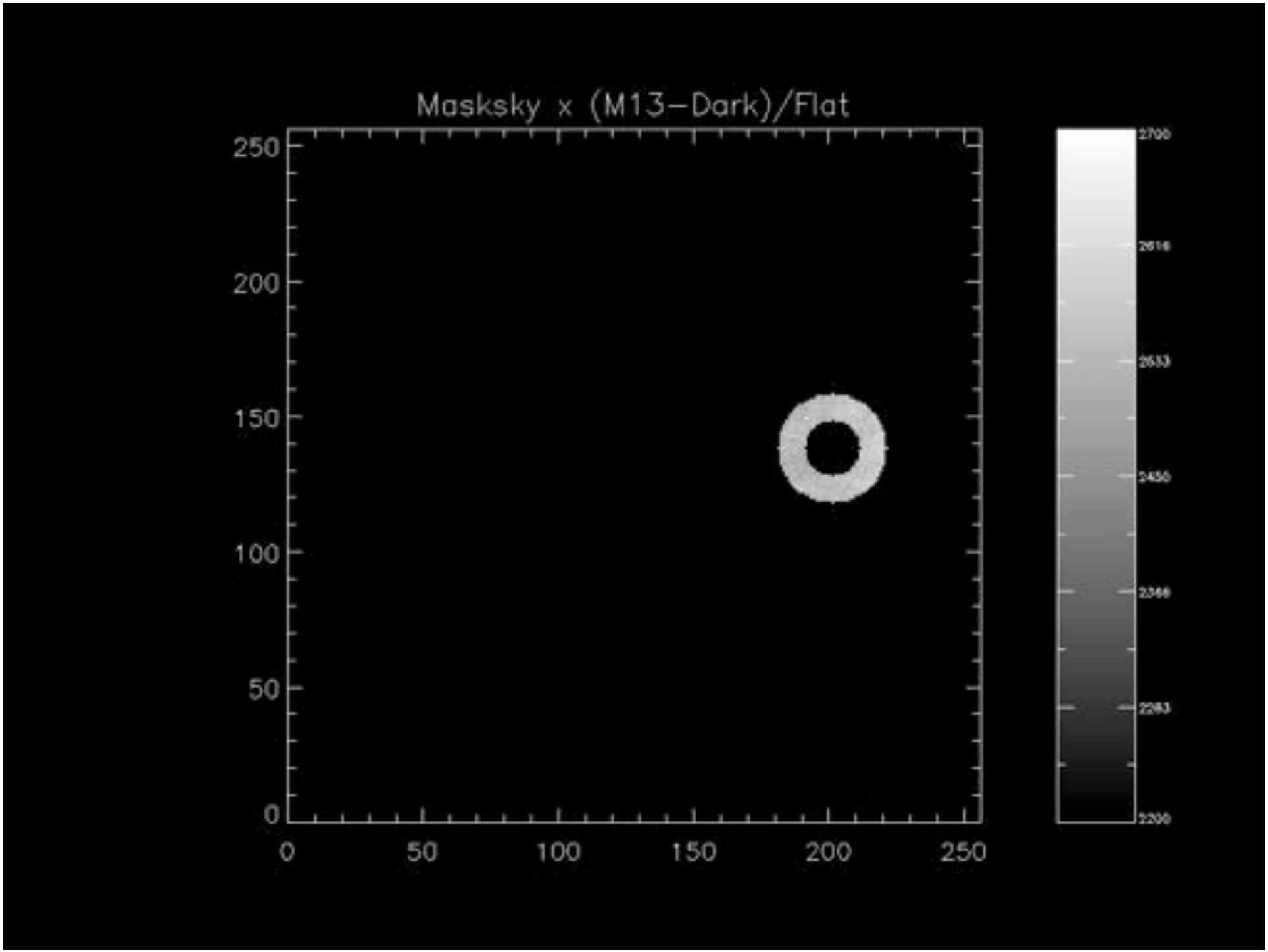

Mask
250
200
150
100
50
0
0
50
100
150
200
250


(M13−Dark)/Flat
250
200
150
100
50
0
0
50
100
150
200
250
2700
2616
2533
2450
2366
2283
2200


Mask x (M13−Dark)/Flat
250
200
150
100
50
0
0
50
100
150
200
250
2700
2616
2533
2450
2366
2283
2200


(M13−Dark)/Flat
250
200
150
100
50
0
0
50
100
150
200
250
2700
2616
2533
2450
2366
2283
2200


Masksky
250
200
150
100
50
0
0
50
100
150
200
250


Masksky x (M13−Dark)/Flat
250
200
150
100
50
0
0
50
100
150
200
250
2700
2616
2533
2450
2366
2283
2200

Step 3: Modeling the Noise

- What is the SNR of a given observation?
- How do I choose and optimize the photometric parameters
  - Exposure time required?
  - Aperture diameter?
  - Location and size of sky annuli?

How to Begin

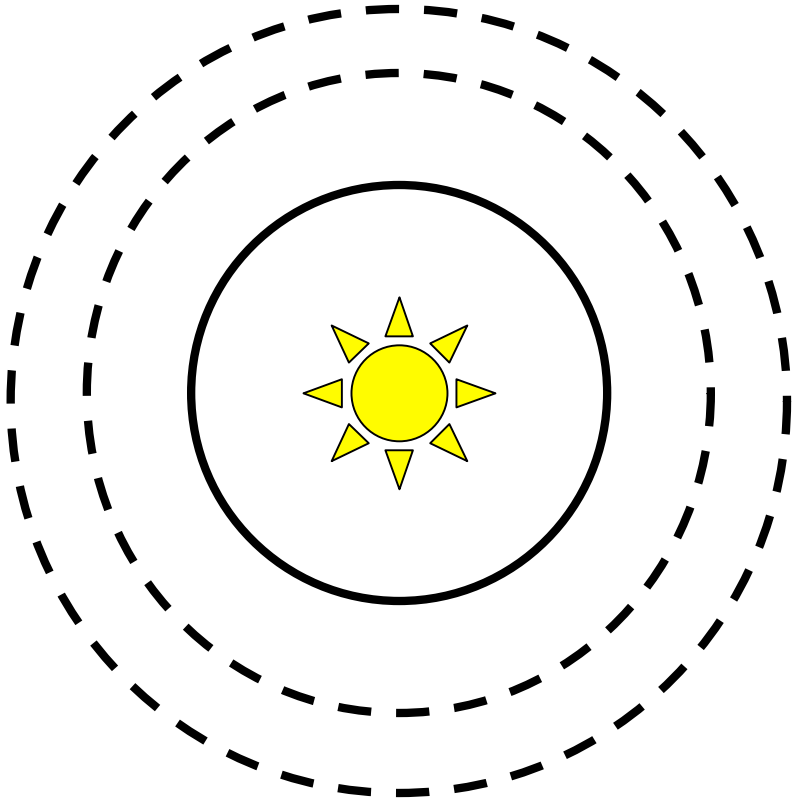
- Write down an expression for the signal and use error propagation to find the noise
  - Express results as signal-to-noise ratio vs. photometric parameters

The Model

- The purpose is to ***estimate*** the noise contributions
  - Often getting the answer to within a factor of two is fine
  - Make simplifying assumptions—so long as you can justify them

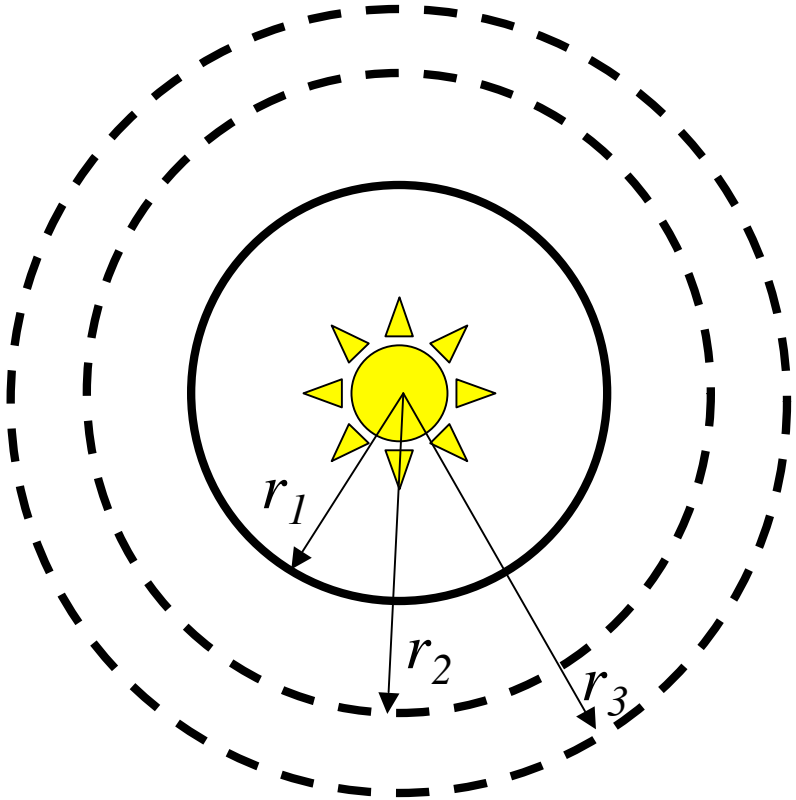
A Photometric Model

- What parameters describe the measurement?



A Photometric Model

- Star
  - Brightness
  - Center (x_0, y_0)
  - Width (σ)
- Sky background in annulus
  - B
- Detector
  - QE, readnoise, dark current
- Aperture sizes
  - r_1, r_2, r_3



Photometric Model

- Write down an expression for the signal, S_i , in units of photoelectrons
  - In an individual pixel

$$S_i = F_i + I_i + B_i + E_i$$

  - F_i is the stellar signal = $f_i t$ at pixel i [e^-]
    - Different for every pixel
  - I_i is the dark charge = $i_i t$ [e^-]
    - Varies from pixel to pixel, for SNR model assume constant
  - B_i is the sky background = $b_i t$ assumed uniform [e^-]
    - Varies from pixel to pixel, for SNR model assume constant
  - E_i is the readout electronic offset or bias [e^-]
    - Varies from pixel to pixel, for SNR model assume constant

The Stellar Signal

- The stellar signal is found by subtracting the background from S_i and summing over the N pixels that contain the star

$$F_i = S_i - \left(I_i + B_i + E_i\right)$$

$$F_N = \sum_{i=1}^{N_1} F_i = \sum_{i=1}^{N_1} S_i - \left(I_i + B_i + E_i\right)$$

$$N_1 = \pi r_1^2$$

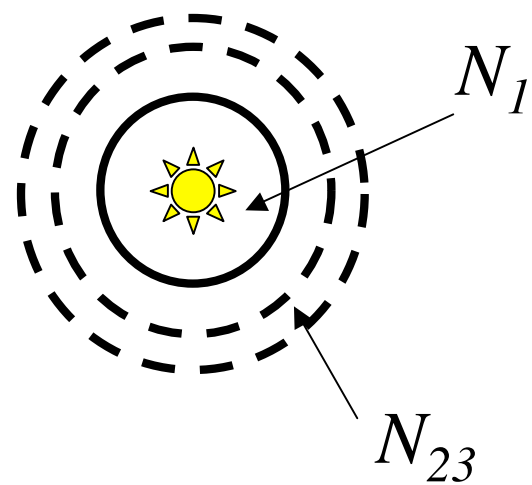
- Error in F_N is due to noise in in the signal itself, F_N
- Noise due to dark charge, I
- Noise from the background, B
- The read out noise σ_{RO}

Noise Sources

$$F_N = \sum_{i=1}^{N_1} F_i = \sum_{i=1}^{N_1} \left[S_i - \underbrace{\left(I_i + B_i + E_i\right)}_{Background} \right]$$

$$\sigma_F^2 = \underbrace{F_N}_{Signal\,Noise} + \underbrace{N_1\left(B_i + I_i + \sigma_{RO}^2\right)}_{Noise\,within\,r_1} + \underbrace{N_1\left(B_i + I_i + \sigma_{RO}^2\right)/N_{23}}_{Noise\,within\,r_2<r<r_3}$$

$$\underbrace{N_1 = \pi r_1^2}_{Star}, \quad \underbrace{N_{23} = \pi r_3^2 - \pi r_2^2}_{Sky}$$



- How do we choose r_1, r_2, r_3?
  - Signal increases with N_1
  - Noise increases with N_1 and decreases with N_{23}

Signal-to-Noise

$$SNR = \frac{\overbrace{F_N}^{Signal}}{\sqrt{\underbrace{F_N}_{Signal\,Noise} + \underbrace{N_1\left(B_i + I_i + \sigma_{RO}^2\right)}_{\substack{Sky\,Dark\,\&\,RON \\ in\,star\,aperture}} + \underbrace{N_1\left(B_i + I_i + \sigma_{RO}^2\right)/N_{23}}_{\substack{Sky\,Dark\,\&\,RON \\ in\,sky\,aperture}}}}$$

- How do we choose r_1, r_2, r_3?
  - Signal increases with N_1
  - Noise increases with N_1 and decreases with N_{23}

An Example

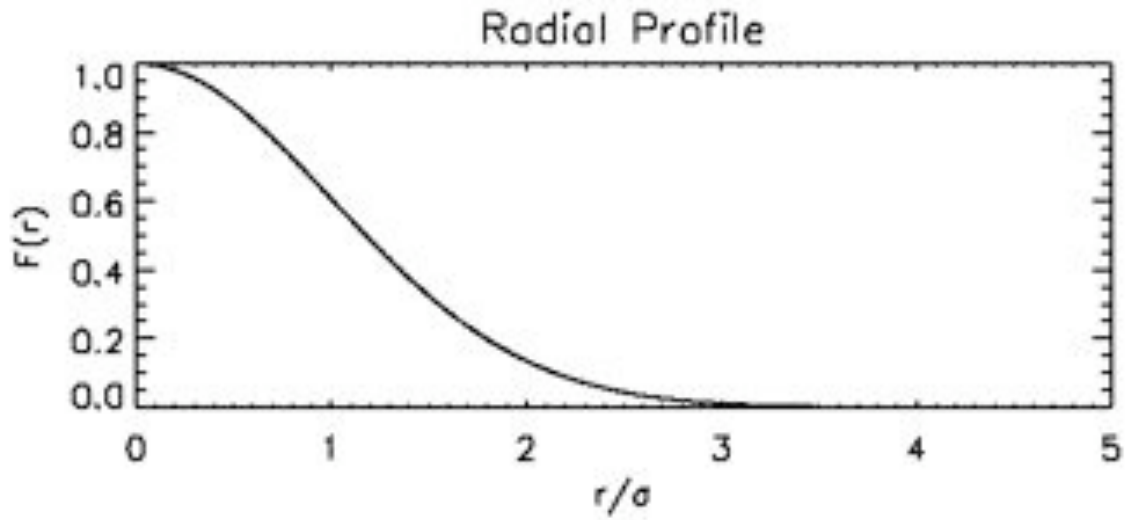
- Suppose the stellar signal has a 2-d Gaussian shape

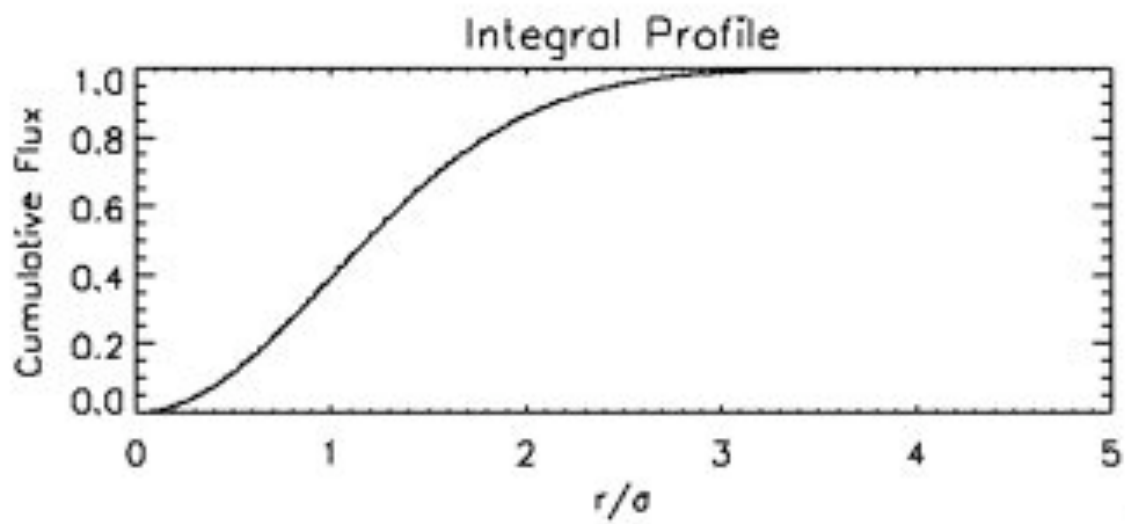
$$F_i = \frac{F_0}{2\pi\sigma^2}\exp\left[-\frac{1}{2}\left(\frac{r_i}{\sigma}\right)^2\right]_i, \quad r_i^2 = (x - x_0)^2 + (y - y_0)^2$$

$$F_N = \int_0^{r_1} 2\pi r F_i dr$$

  – This tells us how F_N changes with aperture radius

Star Profile





SNR vs. r_1

- $F_0 = 100$ e$^-$
- $B_i = 100$ e$^-$
- $I_i = 0$ e$^-$
- $\sigma_{RO} = 10$ e$^-$ *rms*
- $N_{23} >> N_1$