ASTR 2401

CCD Basics

Observational Astronomy

Agenda

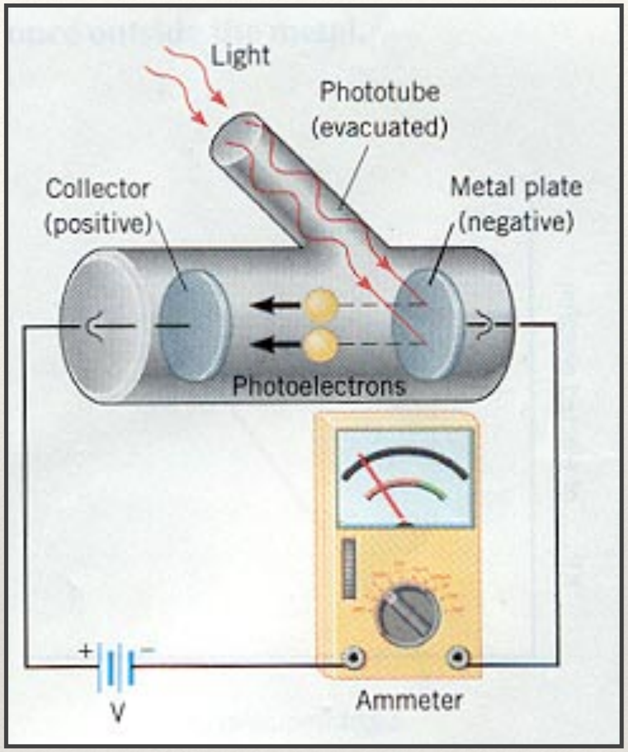
- Weather for Tonight
- CCDs and CCD Calibration

Electronic Detector Basics: Photoelectric Effect

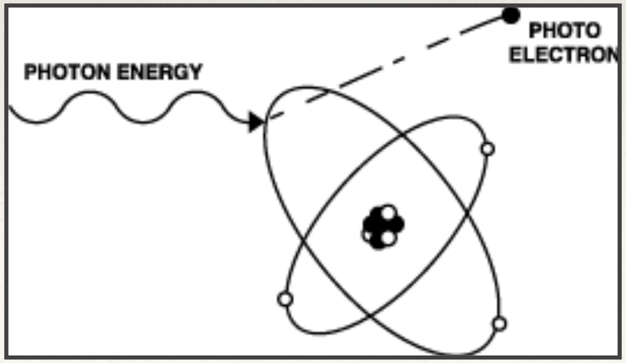
- Physical basis for most detectors in astronomy
- Photons of sufficient energy hitting surface of metal releases electrons (photoelectrons)
- Energy of released electrons depends NOT on intensity of light (if we think of light as a wave), but rather on the frequency of light (particle nature of light).
- There is a minimum frequency of light before any photo-electrons can be emitted from a particular metal:

$$KE_e = E_{photon} - W = h\nu - W = h(\nu-\nu_{min})$$

where KE_e is the KE of photoelectron, E_{photon} is photon energy, W is the work function of the metal, h is Planck's constant, ν is the photon frequency, ν_{min} is the minimum photon frequency of the metal.



sol.sci.uop.edu/~jfalward/particlesandwaves/



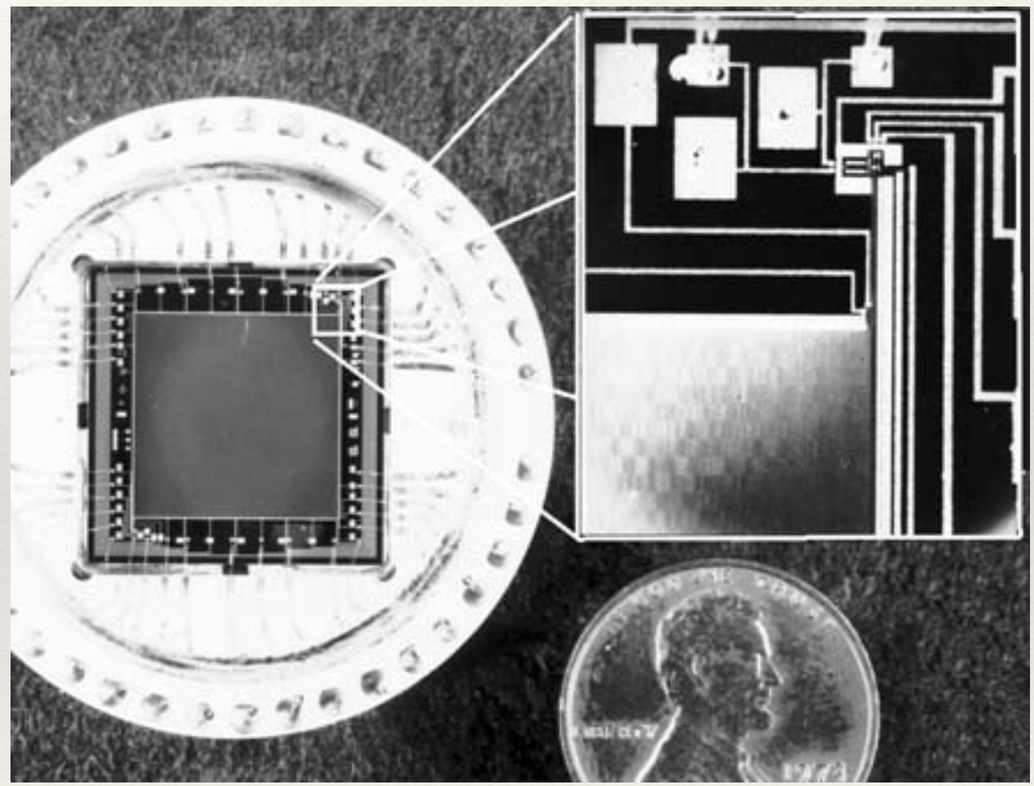
Charge Coupled Device (CCD)

Silicon-based integrated circuits consisting of a matrix of photodiodes which convert light energy in the form of photons into an electronic charge

Invented in 1960's

Standard detector for UV and optical

Photoelectrons are released by semiconductors, but freed photoelectrons stay inside device



The above illustration is of an 800x800 pixel CCD made by Texas Instruments (TI) for the Hubble Space Telescope WFPC. The inset shows the output amplifier.

Charge Coupled Device (CCD)

A CCD is a two-dimensional quantum detector that outputs a digital image. (We'll talk about the details shortly).

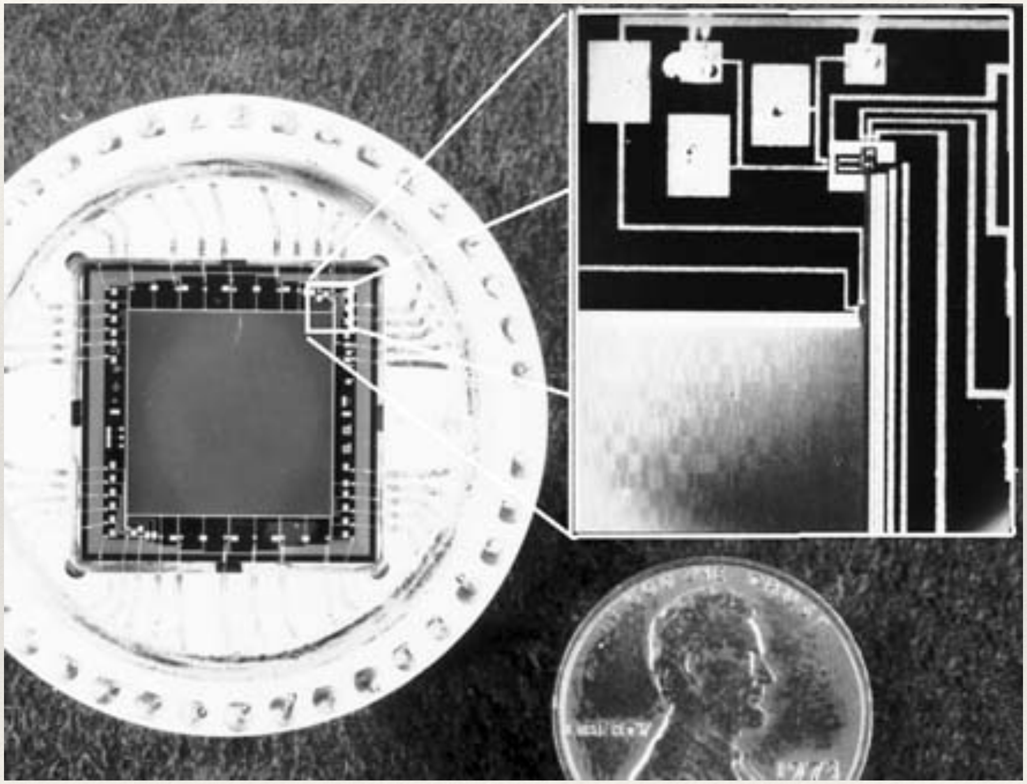
Photoelectric effect; photons captured as charge.

Detector consists of an array of "pixels" (picture elements) laid out in rows and columns

Charge filled pixels are manipulated to move the charge to the output and into a control computer.

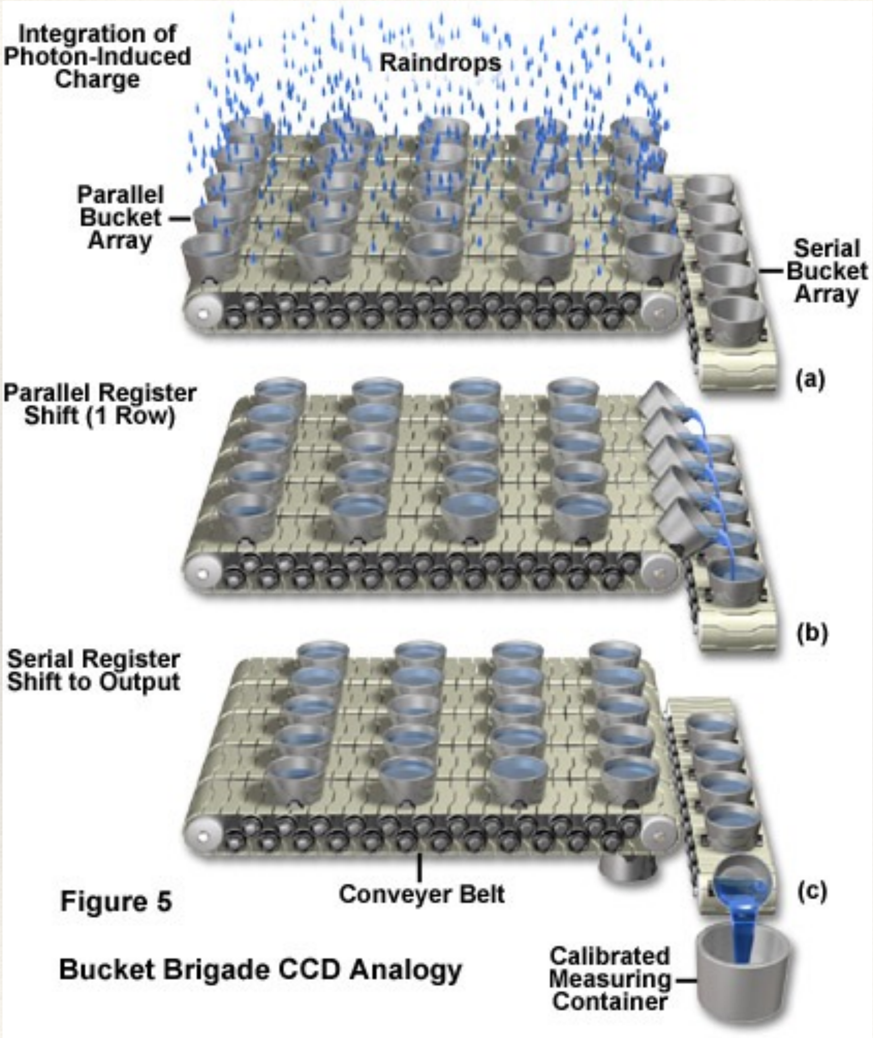
QE can be >90%, and response is reasonably linear.

Limited number of pixels, so must often make a tradeoff between resolution and FOV.



The above illustration is of an 800x800 pixel CCD made by Texas Instruments (TI) for the Hubble Space Telescope WFPC. The inset shows the output amplifier.

CCD “Bucket Brigade"



Exposure Times: S/N

Signal-to-Noise Ratio (S/N or SNR) is defined in astronomy, not surprisingly, as the ratio of the signal from the object that you are observing to the noise of the observation.

Let's start with a simple example:

Assume that you get 100 counts on your detector from a star, and that the only source of noise is **Poisson** uncertainty in the number of photons from your source.

In this case,

the *signal* is 100 counts
the *noise* is sqrt(100) = 10 counts
S/N = 100/10 = 10

What does this mean in practice?

S/N=10 means that you have a 10% uncertainty in your measurement of the objects flux.
S/N=3 means that you have a 33% uncertainty in your measurement.

Often the sky background is the main source of noise. In this case, S/N<3 means that you may just be looking at noise in the sky (68% likely for S/N=1).

Exposure Times

To determine what exposure time is required to observe an object, you must

1. Decide what S/N you need
   - S/N =5 if you want a solid detection
   - S/N>>5 if you want a nice picture
2. Calculate the signal you expect
3. Calculate the noise you expect

We'll start with calculating the signal.

To do so, we need to first digress into magnitude systems.

Magnitudes

The magnitude is the standard unit for measuring the apparent brightness of astronomical objects

If m_1 and m_2 = magnitudes of stars with fluxes f_1 and f_2, then,

$$m_1 - m_2 = -2.5 \log(f_1/f_2)$$

Alternatively,

$$f_1/f_2 = 10^{-0.4(m_1 - m_2)}$$

Note that 1 mag corresponds to a flux ratio of 2.5

Note that 5 mag corresponds to a flux ratio of 100

The lower the value of the magnitude, the brighter the object

Magnitude Systems

Vega

Traditionally, magnitudes are defined such that

$$m = -2.5 * \log_{10} [\text{(object flux)/(flux of reference source)}] = -2.5 \log_{10} (f/f_0)$$

Vega Magnitude System

Vega is the reference, so the magnitude of Vega is zero in all filters.

AB Magnitude System

Somewhat of a variation. Defined such that an object with a flat energy distribution (constant flux at all frequencies) has the same magnitude in all filters.

$$m = -2.5 * \log_{10} [\text{(object flux)/ (frequency width of filter)}] -48.6$$

Need to know that both exist, but Vega are by far the more relevant for this class.

Magnitude Systems

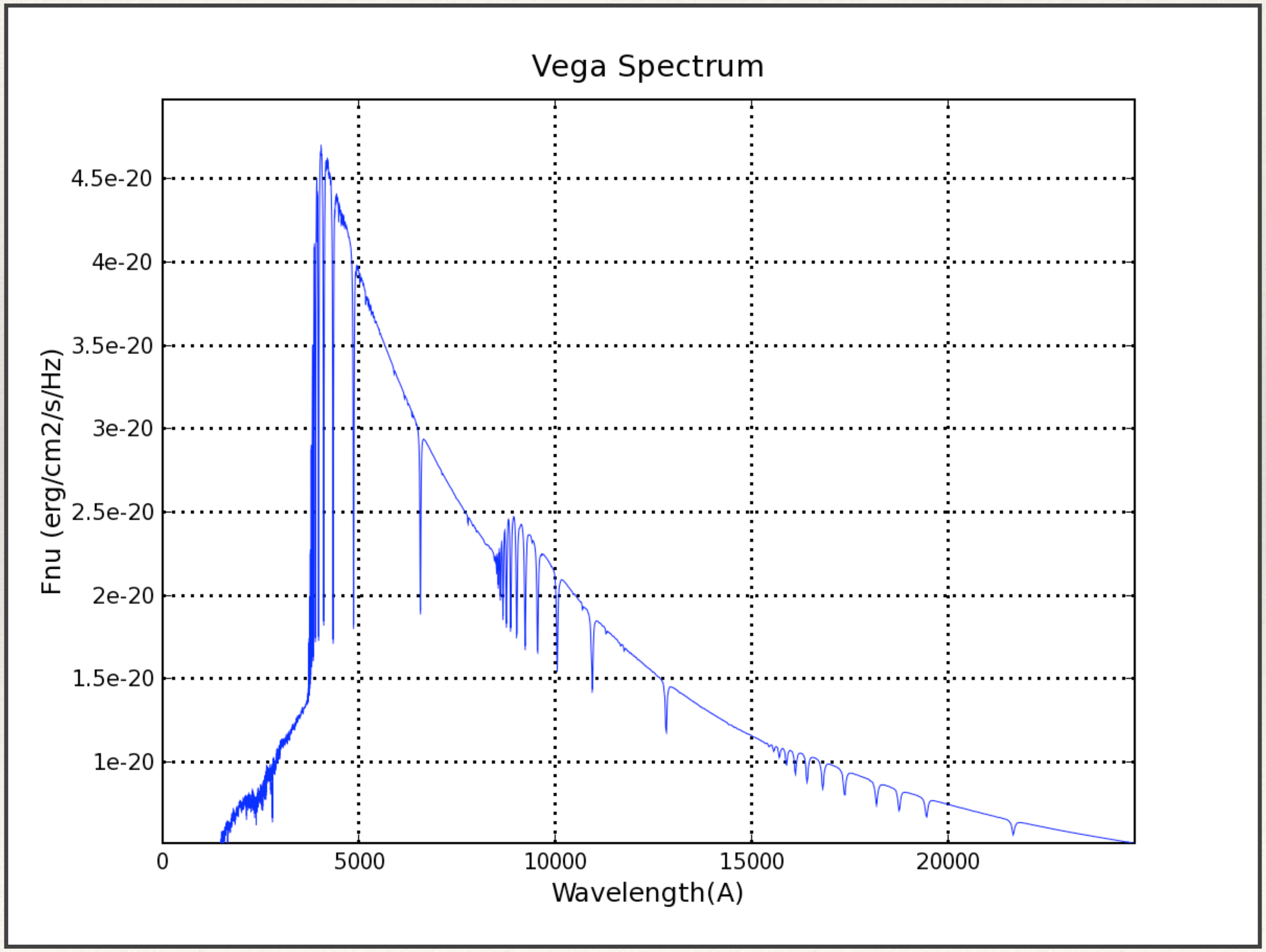
Magnitude of Vega on AB System in Different Bands

B=-0.163

V=-0.044

R= 0.055

I= 0.309



Magnitude Systems

How does this help with calculating your expected signal?

1. Go to Skyview and observe Vega (or some other star of known magnitude) for a fixed number of seconds in a certain filter.
2. Compute how many counts you get.
3. You can then directly calculate the expected number of counts for any other object for which you know the magnitude in that filter.

The above is also how one calibrates photometry. *Any time you go observing and want to measure how bright an object is, you need to during the same night observe objects of known brightness.*

- The important aspect of this approach is that it is *differential*. You don't have to worry about calculating quantum efficiency of your detector, atmospheric transmission, ...

Magnitude Systems

The signal (number of counts) from your target will be:

$$S = S_r 10^{-0.4(m - m_r)} \times (t / t_r)$$

Reference signal
Target mag
Time on target
Reference mag
Time on reference

Remember though, that the above will give you the flux in counts in your digital image, also known as **ADU (Analog-to-Digital Units)**. This is related to the number of electrons recorded in the CCD by the **Gain** (G, also sometimes more appropriately called inverse-gain). For example, for a detector set at G=2, e^-/ADU, there is one count recorded for every 2 electrons detected. The equation above only holds if both objects are observed with the same gain.

Another way of writing the above, once you've calculated the appropriate normalization, is simply

$$S = f \times t$$

where S is the signal, f is the flux from the object (in photons/s, electrons/s, or ADU/second) and t is the integration time.

Magnitude Systems

Typically, you will derive or use what is called a *zeropoint*.

The zeropoint is the magnitude of an object with a flux of 1 ADU/s. In this case, the equation for the expected flux,

$$S = S_r 10^{-0.4(m - m_r)} \times (t / t_r)$$

becomes

$$S = 10^{-0.4(m - ZPT)} \times t$$

Noise

There are multiple sources of noise:

1. Poisson Noise: For large N, $\sigma = \sqrt{N}$ where N is the number of *detected events (electrons).*
   - All sources of light (sky and target object) contribute to Poisson noise
   - Normally, one takes N′ to be the number of counts in ADU rather than electrons…
   - In this case,

     In electrons: $$\sigma = \sqrt{N' \times G}$$

     In ADU: $$\sigma = \sqrt{N' \times G}/G = \sqrt{N'/G}$$

The contributions to the Poisson noise from the sky and target source are treated separately.
For the target source, if we define f_t as the target flux per second in ADU, then the noise in ADU is

$$\sigma = \sqrt{f_t \times t/G}$$

For the sky, if we define s_{sky} as the sky brightness in ADU/second/pixel and n_{pix} as the area over which we are measuring light from the target, then the noise in ADU is

$$\sigma = \sqrt{s_{sky} \times n_{pix} \times t/G}$$

Noise

There are multiple sources of noise:

2. Read Noise (RN): Noise introduced when you read out your CCD -- always quoted in electrons.
   - When you average *m* frames together, read noise will decrease as sqrt(*m*).
   - RN is defined per pixel. If you are looking at an object that covers n pixels, the associated read noise is:

$$\sigma_{RN} = \sqrt{n_{pix}} \times RN$$

3. Dark Current Noise: This is noise introduced by thermal excitation of electrons within your detector. Because the number of such excitations will increase with the length of your exposure, the dark current (D) is quoted in electrons/sec/pixel. The equation for D is:

$$\sigma_{DN} = \sqrt{D \times n_{pix} \times t}$$

Signal-to-Noise

Sources of noise add in quadrature if they are independent, so the total noise is

$$\sigma^2 = \sigma^2_{source} + \sigma^2_{sky} + \sigma^2_{RN} + \sigma^2_{DN}$$

or

$$Noise = \sigma = [(f_t \cdot t) + (s_{sky} \cdot n_{pix} \cdot t) + (RN^2 \cdot n_{pix}) + (D \cdot n_{pix} \cdot t)]^{1/2}$$

Putting it all together,

$$S/N = \frac{(f_t \cdot t)}{[(f_t \cdot t) + (s_{sky} \cdot n_{pix} \cdot t) + (RN^2 \cdot n_{pix}) + (D \cdot n_{pix} \cdot t)]^{1/2}}$$

Poisson-limited   Background-limited   Read-Noise limited

In the limiting case of Poisson noise for the target being the only noise source, we recover $S/N \propto t^{1/2}$

In the read noise dominated limiting case, we obtain $S/N \propto t$

S/N vs time

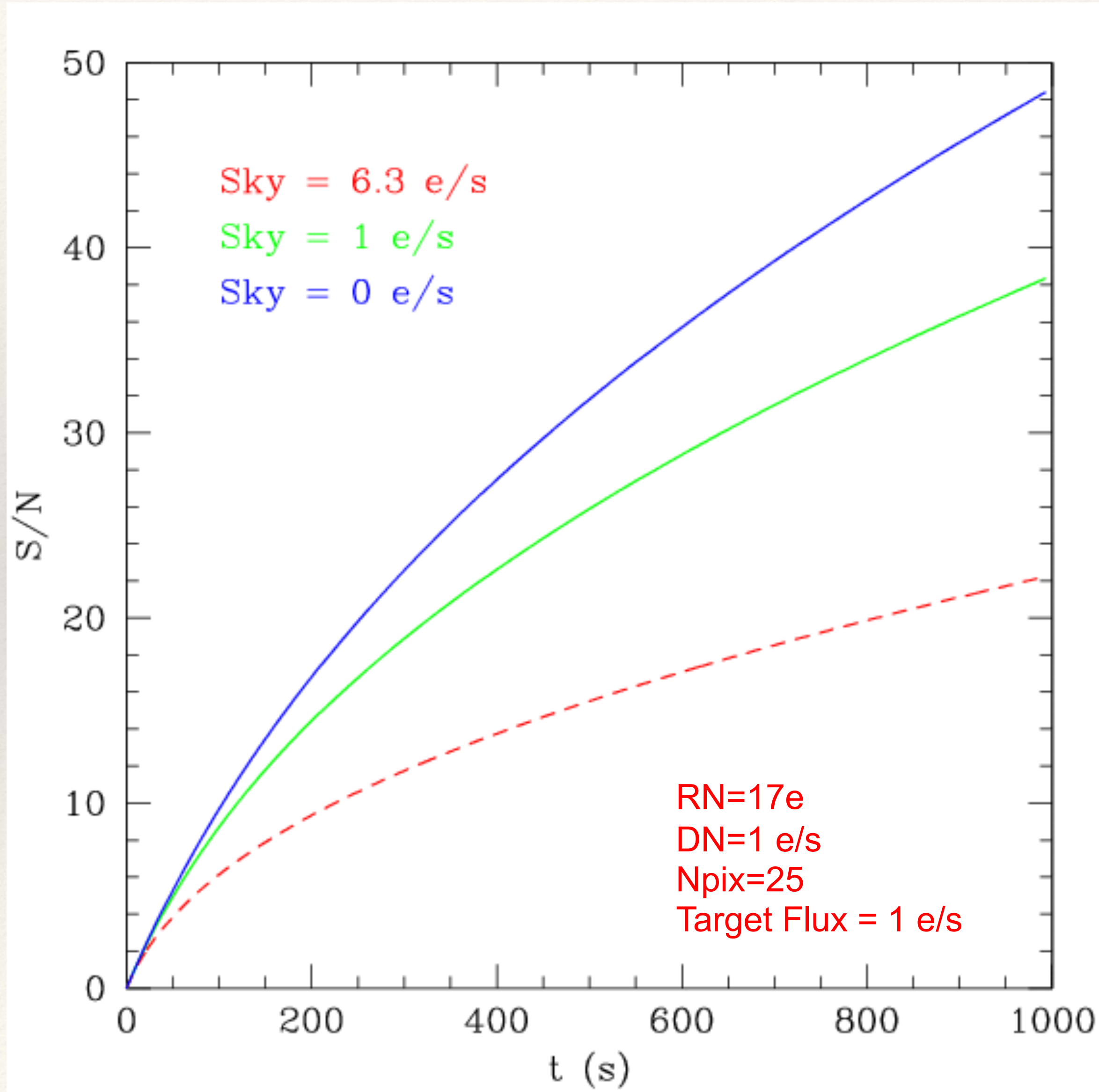
For background-limited (or Poisson):

2 times longer integration gives
 sqrt(2) higher S/N

In magnitudes,
2.5 log(sqrt(2)) = 0.38 mag

Equivalently, going 1 mag deeper requires integrating 6.3 times as long.

Image on Right: Comparison of required exposure times to observe an object for two cases where the sky differs by 2 mag/sq arcsec in brightness (factor of 6.3), and the case of no sky.



S/N vs time

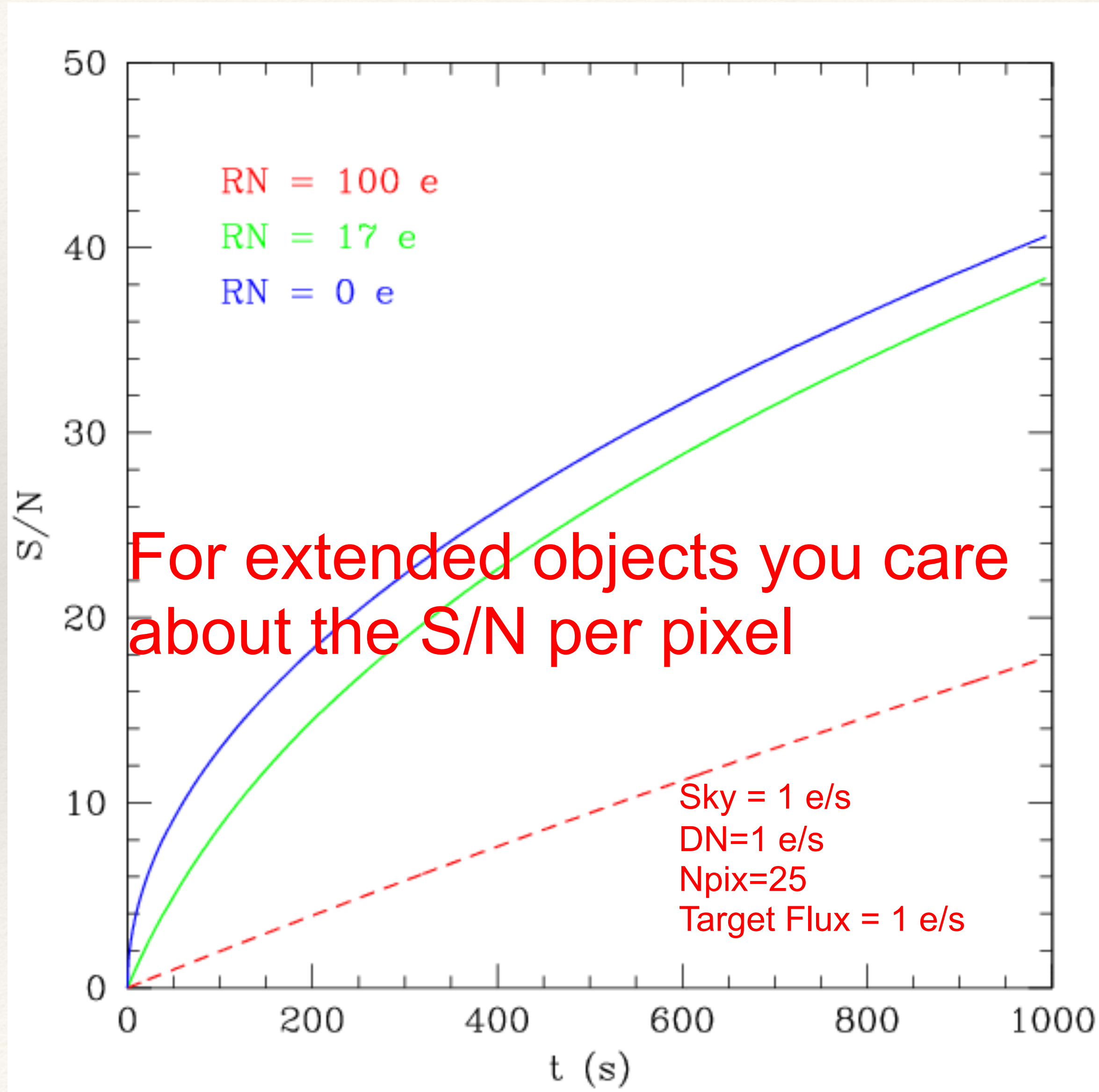
For Read-Noise limited:

2 times longer integration gives
2 times higher S/N

In magnitudes,
2.5 log(2) = 0.75 mag

Equivalently, going 1 mag deeper requires integrating 2.5 times as long.

Image on Right: Comparison of required exposure times to observe an object for different read noise levels



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$$\sigma^2 = \sigma^2_{source} + \sigma^2_{sky} + \sigma^2_{RN} + \sigma^2_{DN}$$

or

$$Noise = \sigma = [(f_t \cdot t) + (s_{sky} \cdot n_{pix} \cdot t) + (RN^2 \cdot n_{pix}) + (D \cdot n_{pix} \cdot t)]^{1/2}$$

Putting it all together,

For Extended Sources:
$n_{pix} = 1$
f=flux per pixel

$$S/N = \frac{(f_t \cdot t)}{[(f_t \cdot t) + (s_{sky} \cdot n_{pix} \cdot t) + (RN^2 \cdot n_{pix}) + (D \cdot n_{pix} \cdot t)]^{1/2}}$$

Poisson-limited Background-limited Read-Noise limited

In the limiting case of Poisson noise for the target being the only noise source, we recover $S/N \propto t^{1/2}$

In the read noise dominated limiting case, we obtain $S/N \propto t$

Practical observing tips

- **Use the calculations as a rough guide**
- **Adjust at telescope based upon what you actually see**

Calibration Images

Calibration images include all the non-science images that must be taken for use in reducing your data. ***Obtaining good calibration data is an essential element of a successful night of observing***.

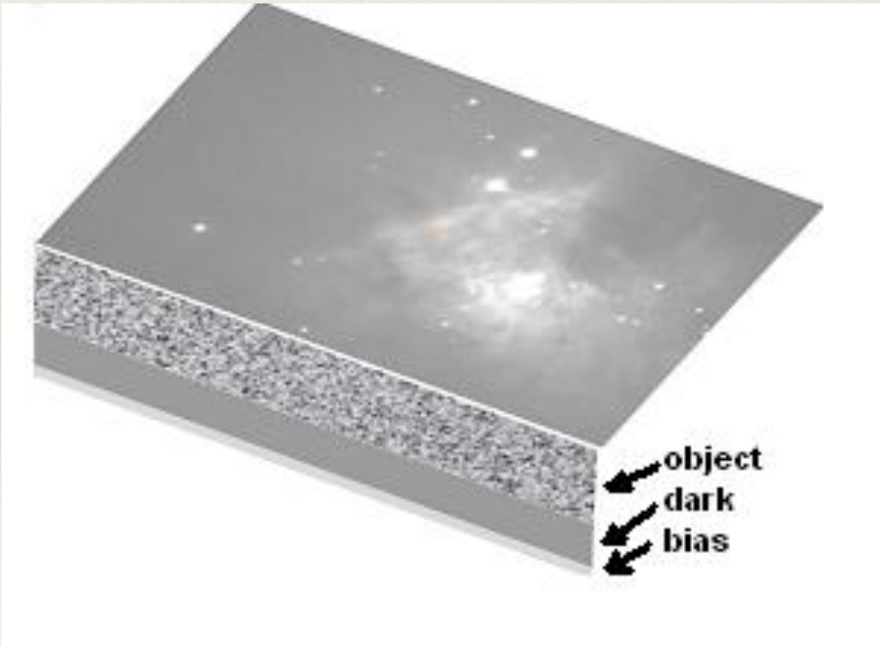
The types of calibration images taken on a normal night of imaging include:

- Dark Frames and/or Bias Frames
- Flat-fields (Dome, Twilight, Sky)
- Standard Stars (for photometric calibration)

Calibration Images

An observed CCD image includes signals from three sources:

1. Photons imaged onto CCD by telescope
   - Sources: Astronomical objects and sky
   - Generated by photoelectric effec*t*
2. Dark current
   - Source: thermal electrons collected in each pixel during the exposure
3. Bias
   - A signal added to each pixel during readout



Must subtract off dark current and bias.

Calibration: Dark Frames

What: Exposures taken with the shutter closed (hence “dark”)

- Darks should have the same exposure time as your science images.
- Darks should also be taken at the same temperature as your science images .
- You want to take multiple dark images and (median or average) combine them.
  - Reduces the noise
  - Eliminates spurious pixels in individual frames
  - Combined image typically called the “master dark”.

Purpose: Remove the dark current from thermally excited electrons.

Application: The master dark frame is subtracted from the science image.

Calibration: Bias Frames

What: Zero second dark exposures

- You want to take multiple bias images and (median or average) combine them.
    - Reduces the noise
    - Eliminates spurious pixels in individual frames
    - Combined image typically called the "master bias".

Purpose: Remove the bias signal

- The bias is an offset level introduced when the detector is read out.
- Even if the output from the CCD were 0 electrons, there would still be a bias signal that varies from pixel to pixel in a repeatable fashion.
- This is an additive offset.

Application: The master bias frame is subtracted from the science image.

Calibration: Flat-fields

Purpose: Correct for pixel-to-pixel sensitivity variations

- Each pixel has a different response
  - Quantum efficiency variations, dust on the optics, vignetting, ...
  - If illuminate all pixels with the same brightness, then you can measure and correct for these variations

Application: Divide the science frame by the master flat.

Calibration: Flat-fields

Flat-fields

What: Exposures of a uniformly illuminated source

- You want to take multiple flat-field images and median combine them.
  - Reduces the noise and eliminates spurious pixels in individual frames.
  - Eliminates objects for twilight and sky flats
  - Must normalize all images to same mean value before combining
  - Combined image typically called the “master flat”.
- Normalized to have a mean value of 1.
- Taken in each filter
- For dome and twilight flats, you want to have as many counts per pixel as possible to reduce noise, but not so bright as to saturate or have concerns about nonlinearity.

Calibration: Flat-fields

Flat-fields

Dome Flats

Images of a uniformly illuminated white screen inside the dome.

Twilight Flats

Images taken at twilight, when the sky is much brighter than astronomical sources.
Effectively using the sky as your uniformly illuminated screen.

Sky Flats

Median combination of many science exposures during the night, again using the sky as your uniformly illuminated screen.

...each has advantages and disadvantages...

Calibration: Flat-fields

Flat-fields

Dome Flats

Images of a uniformly illuminated white screen inside the dome.

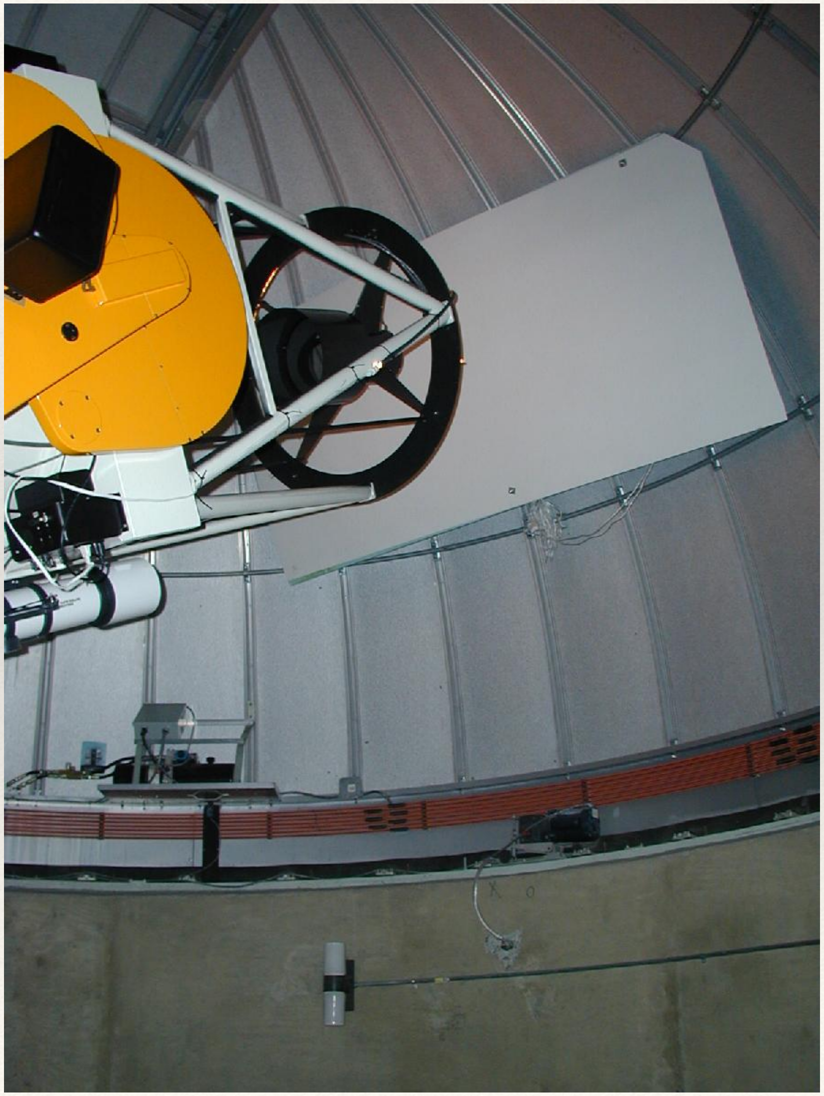
Advantages:

Can be taken at any point, including during the day.

Can us a lamp to make the images as bright as you wish

Disadvantages:

Least similar to what you are actually observing. Illumination of the detector may be different



Calibration: Flat-fields

Flat-fields

- Twilight Flats
- Images taken at twilight, when the sky is much brighter than astronomical sources.
- Effectively using the sky as your uniformly illuminated screen.

Advantages:

- Very similar to your actual observations.
- Lots of brightness

Disadvantages:

- Very short window of time to take flats.

Calibration: Flat-fields

Flat-fields

Sky Flats

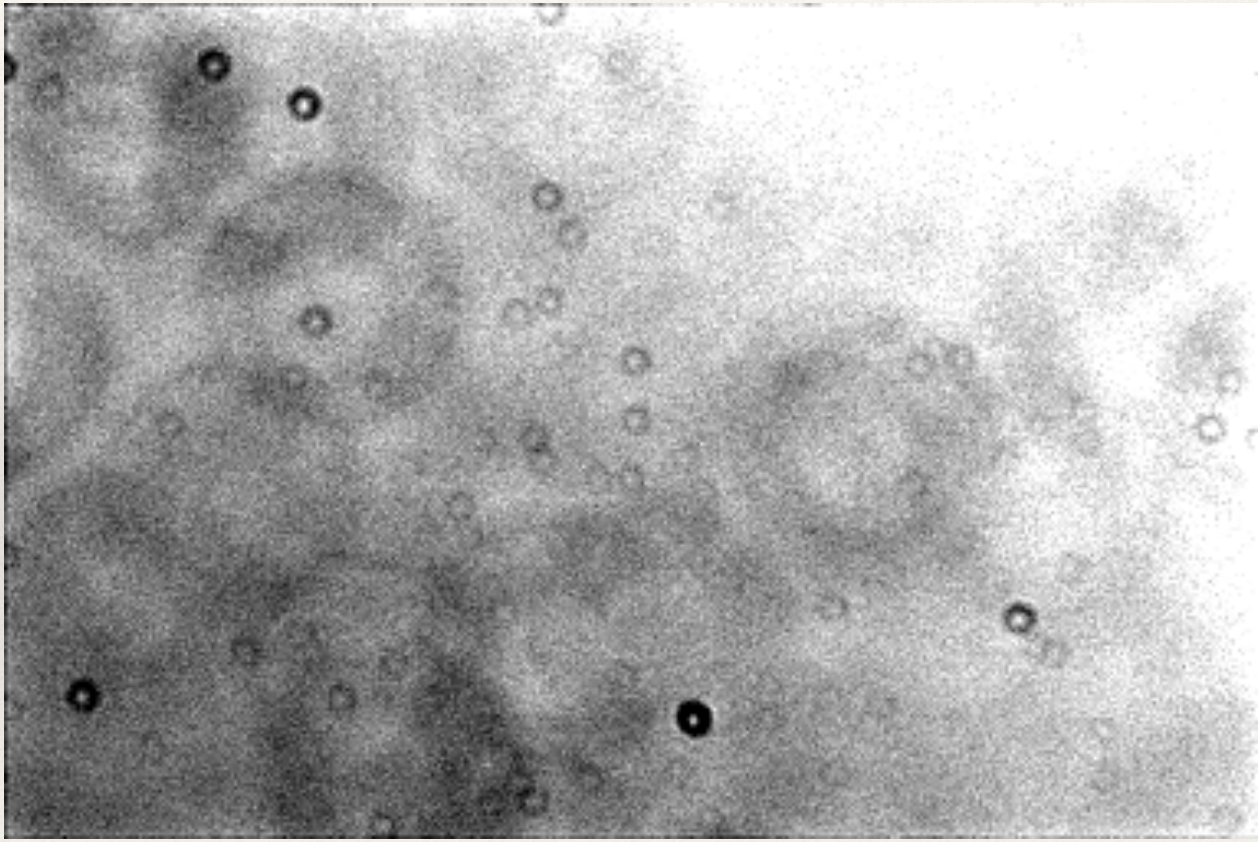
Median combination of many science exposures during the night, again using the sky as your uniformly illuminated screen.

Advantages: Exactly the same set-up as your actual data (because it is your actual data)

Disadvantages: Need a lot of images, because the sky is very faint.

Calibration: Flat-fields

- Why take (dome) flats at the start and end of the night?



Before observing (General Info)

- Know the start-up and operating procedures
  - Read the manuals for the telescope and instrument that you are using
- Know the capabilities of the instrument
  - FOV
  - CCD Gain
  - CCD Full Well Depth
  - CCD Readout time
  - Sensitivity

Start of the night:
Large Research Telescope

- **Take Dark and/or Bias Frames** (a few hours before sunset)
- **Take Dome Flats** (a few hours before sunset)
- **Open Dome** (before sunset)
- **Take Twilight Flats** (at sunset)
- **Check the Pointing**
  - Aim at a bright star and sync ("zero") the telescope
  - Double-check on a second bright star
- **Adjust the focus**
  - Pick a moderately bright star
  - Step through focus and measure the FWHM of the star for different values of the focal length.
    - Use focus data from previous nights as a rough estimate
    - Record as you go
    - Always go from one direction, as there may be hysteresis
- **Proceed to science observations**

Start of the night:
Skyview (very similar)

- **Open Roof/Dome**
- **Take Twilight Flats**
- **Check The Pointing**
  - Aim at a bright star and sync ("zero") the telescope
  - Double-check on a second bright star
- **Adjust the focus**
  - Pick a moderately bright star (~4th-7th magnitude – good to look for a useful star near your science field.)
  - Set the detector to focus loop mode and adjust the focus while taking exposures.
  - Adjust until you achieve the best possible focus (but don't spend too long).
- **Proceed to science observations**

During the night

- Take the desired images of your targets
  - Be sure to keep a careful written log of your observations!
    - This log should ideally be in your notebook or on log sheets which you can keep in your notebook.
    - Information that the log should include (for example)

Frame	Object	UT	Airmass	Filter	Exptime	Comments
001-010	**Dark**	**0:51**	**--**	**--**	**10s**	**Partly Cloudy**
011-020	**Flats**	**1:15**	**--**	**R**	**10s**	
021	**M31**	**1:35**	**1.53**	**R**	**60s**	**2.5″ seeing**

  - Check the images as you go to make sure nothing odd is happening
  - Occasionally dither (slightly move the telescope) between images.
- If the weather is photometric and you are doing photometry:
  - Observe stars with known magnitudes (Standard stars) that can be used to calibrate your photometry

End of the night

- Close roof / dome
- Take dome flats (not at Gott)
- Take dark frames for every exposure time used
- Stow everything

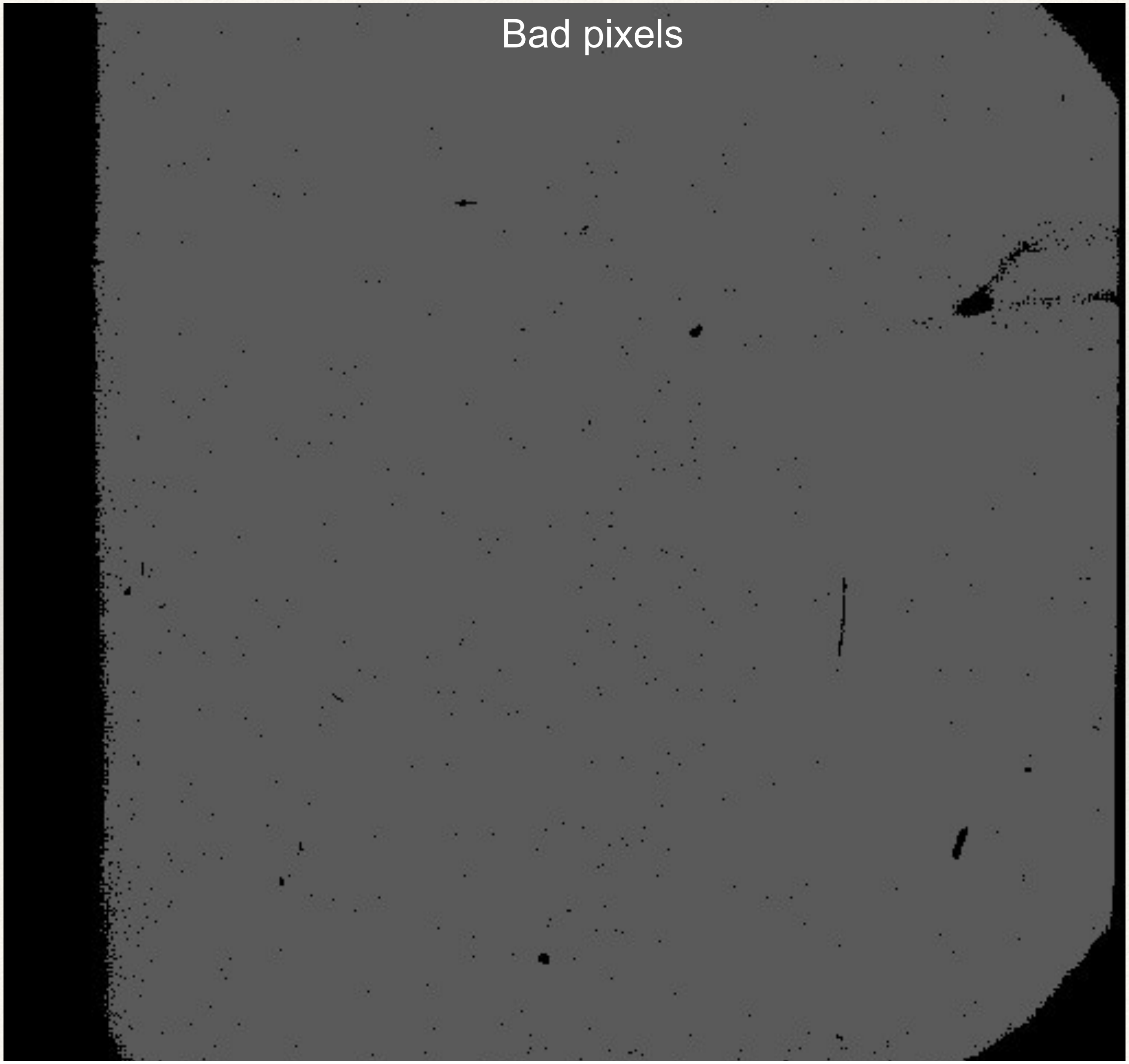
Problems with your Data

So what will the data look like when things go wrong?

Defects that are always present:
- Bad Pixels
- Cosmic Rays
- Bleed Trails

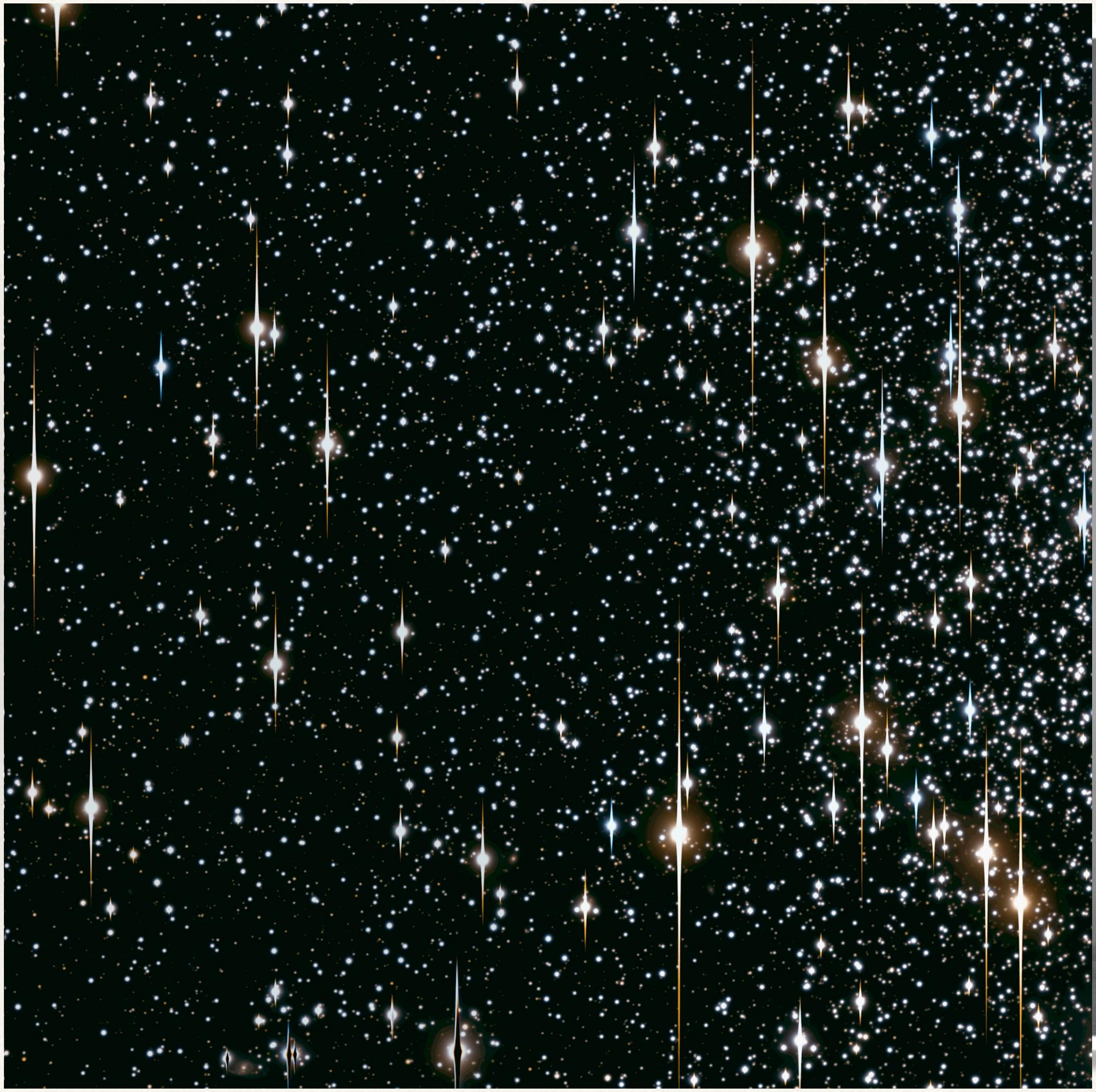
More serious issues
- Saturated Image
- Vignetting (sometimes unavoidable)
- Out of Focus
- Bad Tracking
- Scattered light

Problems with your Data



Problems with your Data

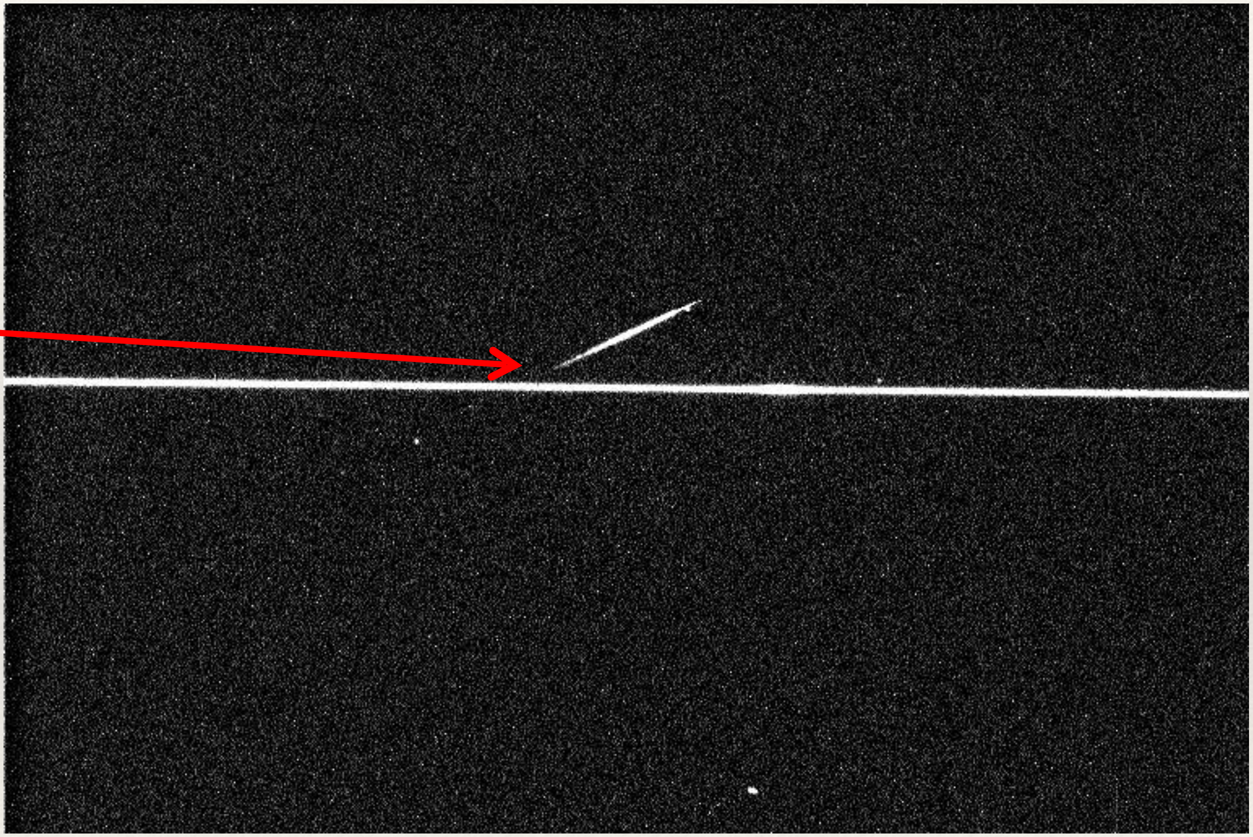
Bleed Trails



Credit: Kurtis Williams

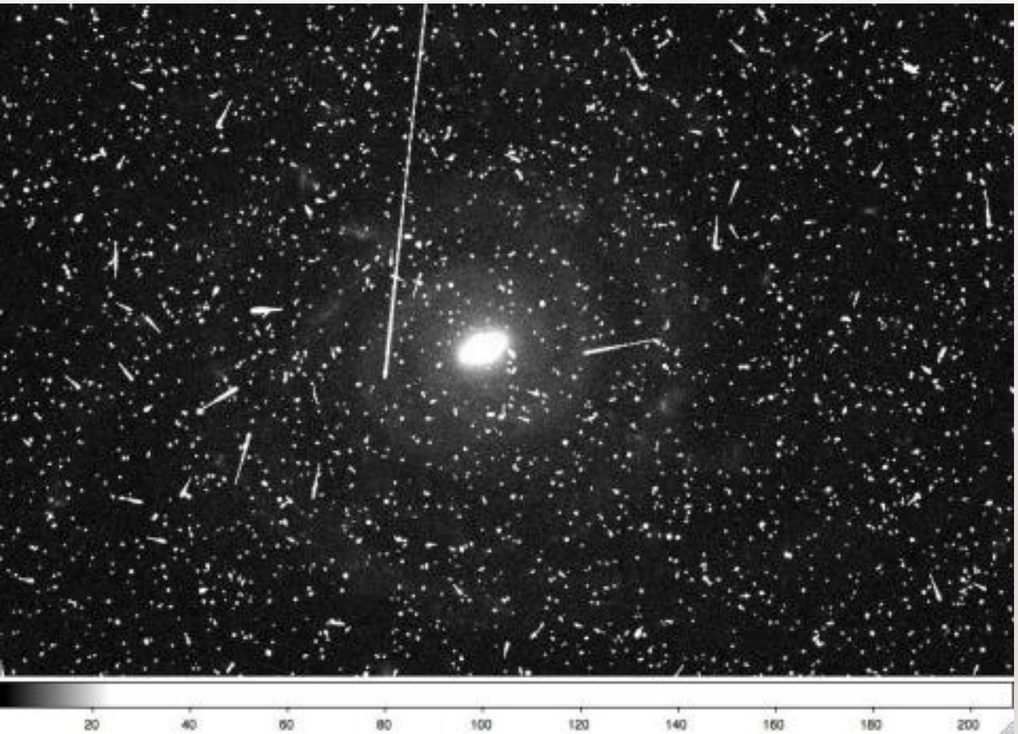
Problems with your Data

Cosmic Rays

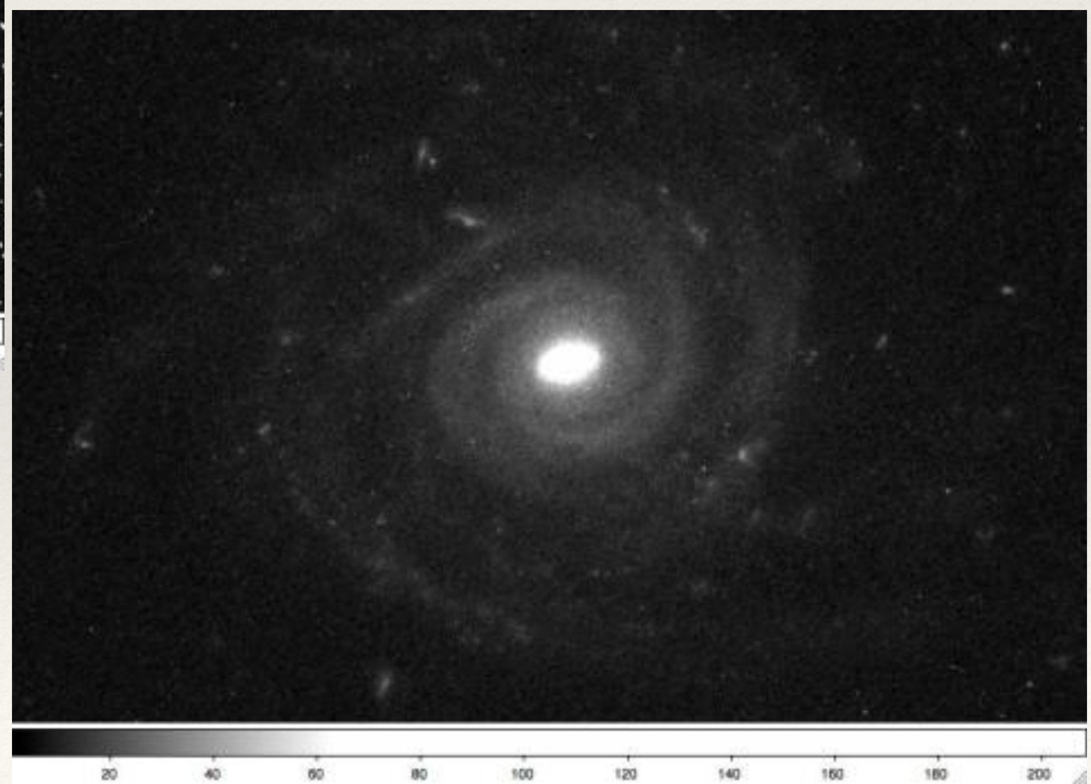


Problems with your Data

Cosmic Rays

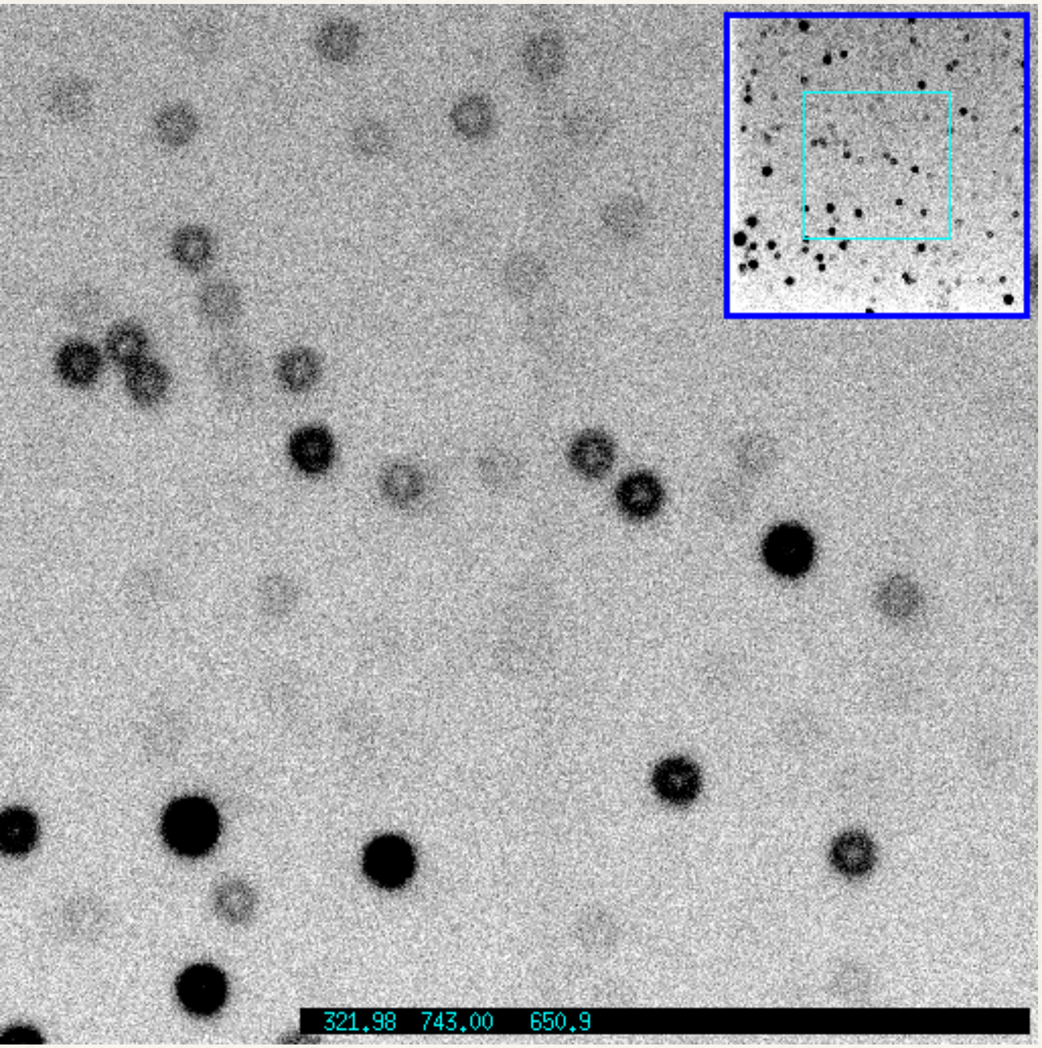


Courtesy: http://blog.galaxyzoo.org/2010/04/12/how-to-handle-hubble-images/

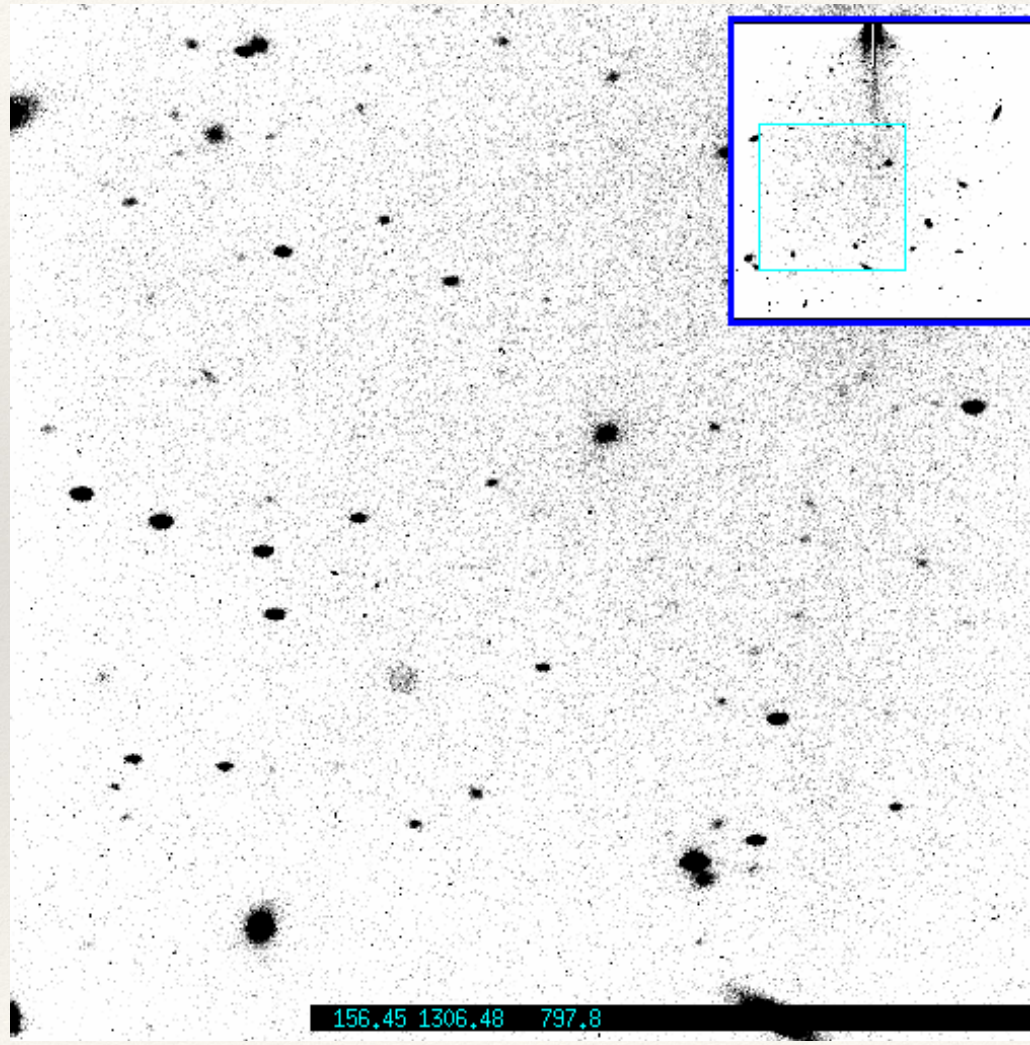


Problems with your Data

Out of focus



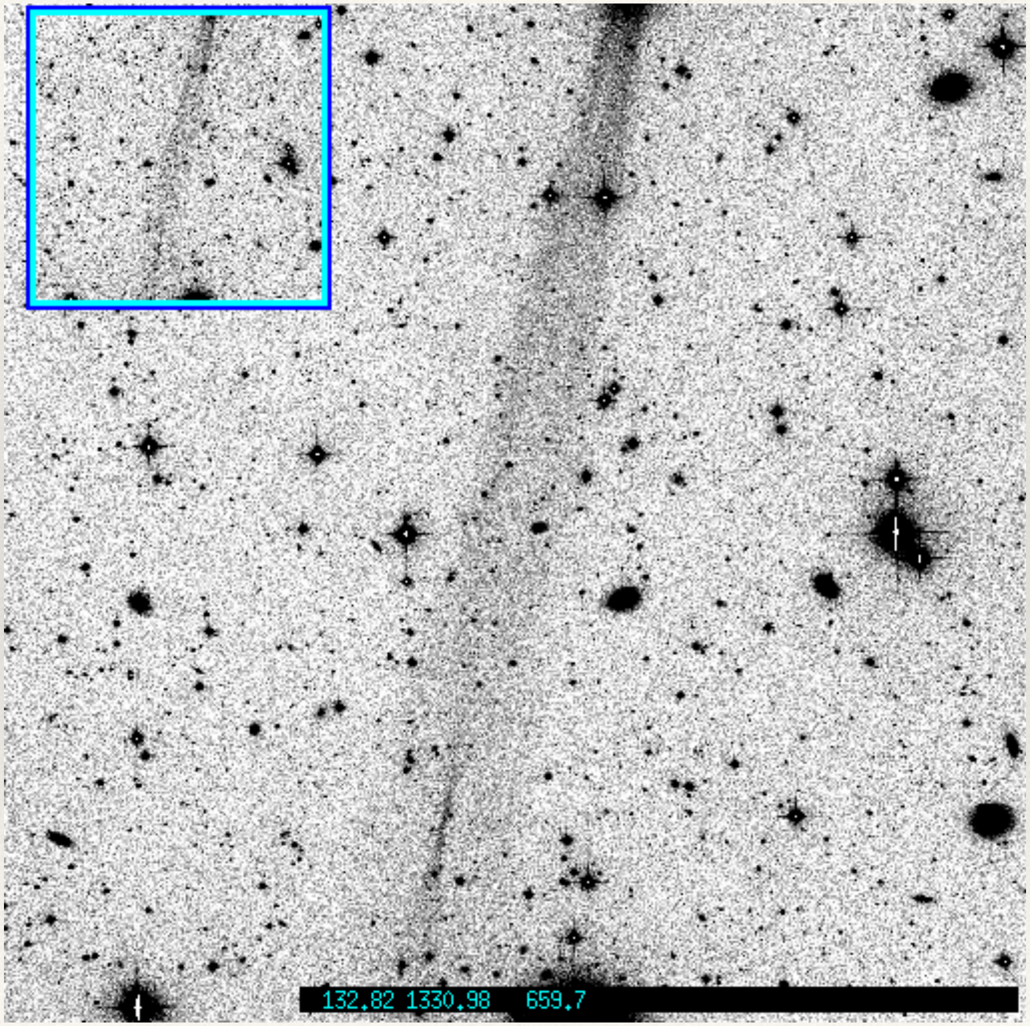
Bad tracking



Courtesy http://www.dtm.ciw.edu/vonbraun/obs_mishaps/mishaps.html

Problems with your Data

Scattered Light



Courtesy http://www.dtm.ciw.edu/vonbraun/obs_mishaps/mishaps.html

Problems with your Data