III. CCD Basics [v1.3.3]

A. Overview

- In observational astronomy, an experiment is often only as good as its detector
  - ◇ e.g. Efficiency of UV detectors remains at $\sim 20\%$
  - ◇ Advances in detectors (e.g. energy resolving devices in the topcial) can lead to major leaps in the science
- Optical astronomy (and essentially IR) is dominated by the CCD
  - ◇ An intuitive knowledge of the inner workings is vital to gauge the quality of your data
  - ◇ And to analyze it!
- A CCD is similar to a postage stamp with a grid on it.
  - ◇ Each cell can detect photons, holding electrons like rain buckets (or egg cartons)
  - ◇ You can read the charge one time, any time, which then empties each bucket.
    - ▲ IR detectors can read without 'destroying' the charge
- Goals
  - ◇ Understand how detectors collect and report signal
  - ◇ Understand the primary sources of "noise" (a.k.a. error)
- References
  - ◇ Léna, "Observational Astrophysics"
  - ◇ Howell, "Astronomical CCD Observing and Reduction Techniques"

B. The "Detector"

- Lecture II (Detectors) describes the basic physics of a semi-conductor detector
  - ◇ Photons strike the silicon
  - ◇ A fraction η generate charge in the conduction band which move freely in the metal
  - ◇ The charge is then stored as voltage in a capacitor (in a 'well' across the surface of the detector)
- Key quantities
  - ◇ Device
    - ▲ Efficiency (η or QE): Ratio of the number of electrons generated divided by the number of photons incident
    - ▲ Dark current: Current generated by thermal motions of electrons in the device
  - ◇ Electronics
    - ▲ Counts: Number recorded to the file [this is all you get!]

    - ▲ Gain (g): Ratio of electrons generated to counts recorded
    - ▲ Bias level: 'Artificial' charge added to properly measure zero signal
    - ▲ Read noise: Uncertainty in measuring the charge imposed by the electronics
- We will refer to one unit of this "detector" as a cell or a pixel

C. Pixel

- Refer to each cell in the CCD array as a pixel
- Each pixel collects photons independently of all other pixels
  - ◇ The charge is confined by "gates"
  - ◇ The charge is stored in a "well" akin to a zero time-constant capacitor
- Physical parameters
  - ◇ Area of the pixel (size, e.g. μm^2)
  - ◇ x, y position – Spatial information
  - ◇ Charge (voltage) – photon counting
- The "full well"
  - ◇ The gates on the pixel can hold a finite charge
  - ◇ If you exceed this full well design, the charge bleeds to adjacent pixels
  - ◇ In an array, bleeding occurs preferentially along the columns, not the rows, because the gates are weaker there (by design)

D. CCD Array

- With modern photo-lithography, it is possible to generate an array of pixels
  - ◇ The silicon is inlaid with other metals that hold voltage and become clocking "gates"
  - ◇ These gates separate the pixels, and can prevent charge from being transferred between them.
  - ◇ They also can be used to shift charge around
    - ▲ In a standard CCD, charge may be moved down the columns (high to low by convention)
    - ▲ It may also be moved across the row (typically only on the bottom row), to an amplifier
    - ▲ Fancy clocking on CCDs can shuffle charge up and down columns and side to side. These often have poorer performance.

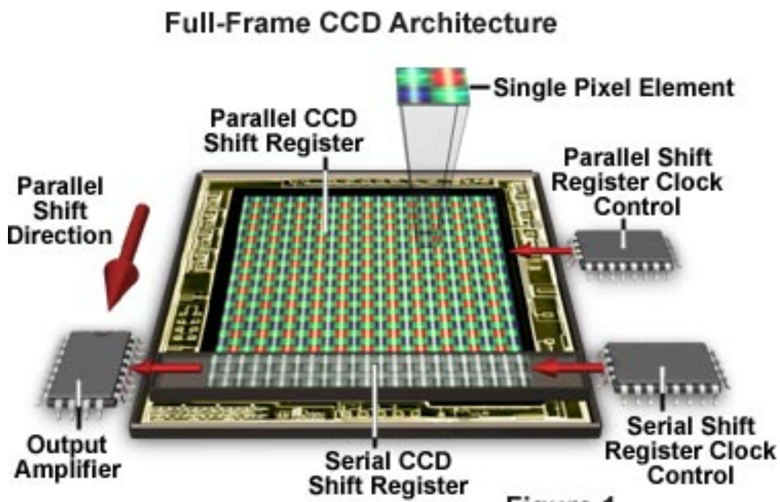


Figure 1

- Modern CCDs may have 4096x4096 pixels
  - ◇ At 18μm per pixel, that implies approximately 1 cm on a side
  - ◇ These large format devices enable imaging huge areas of the sky and high-dispersion spectroscopy
- A high QE $\eta > 0.8$, low noise device costs over $200k each
  - ◇ Current technology is tuned to wavelength, e.g. < 4000Å or > 8000Å
  - ◇ Devices are buttable enabling large mosaics (1 Gigapixels!)
- The device is generally covered with a shutter to avoid charge accumulation in-between exposures and during readout

E. Readout Basics

(a) Expose (with shutter open, presumably) and accumulate charge
- At the end of the exposure, each pixel has its own set of charge
- Ideally, one electron per photon
- Hopefully, it is at least proportional to the number of photons that hit it

(b) Readout means measuring the charge accumulated in each pixel
- Use electronics attached to the CCD to "read" (i.e. count) the charge
- In simplest form (e.g. our figure), the readout electronics are attached to **one** pixel at one corner of the CCD
- One reads charge only from this single pixel!

(c) Read one row at a time
- The gates are able to shift the charge along a row
  - ◇ Modulate the voltages on each gate
  - ◇ This is a highly orchestrated (clocked) procedure
- Read, shift, read, shift, read, shift

(d) After reading the bottom row, shift all the remaining rows down one
  - This utilizes the other set of (parallel) gates
  - This timing is simpler

(e) Consider the charge in the far corner from the readout
  - By the end, it has moved $n + m$ times (for $n \times m$ pixels)
  - Charge Transfer Efficiency (CTE) – Accuracy with which one moves charge on the CCD
    - ◇ For a large device, the CTE must be better than 1 part in 99,999
    - ◇ 0.001% losses are unacceptible
    - ◇ This scales with the size of the detector (divided by the # of readout amplifiers)

F. Readout Electronics

- Amplifier (amp)
  - ◇ Amplify the tiny charge in each pixel into a manageable value
  - ◇ This ampifies the error too!
  - ◇ And introduces new error
- Analog to Digital Converter (ADC or A/D)
  - ◇ Convert an analog voltage into a digital number (Counts)
  - ◇ Often restricted to a 16-bit value
    - ▲ Data storage was expensive (still can be, e.g. space missions like Kepler)
    - ▲ If unsigned, then the values range from $0 - 64,000$
  - ◇ Beware of non-linearity
    - ▲ Depends on how charge accumulates with photon number
    - ▲ Depends on how voltages are converted to numbers
- Bias level
  - ◇ Essential to properly counting zero photons
    - ▲ One never measures a truly zero voltage, only values near zero
    - ▲ If each of the ‘negative’ voltages were given 0 counts, then you would bias the measurement high
  - ◇ Solution
    - ▲ Convert a zero voltage to a significant, positive value of counts (e.g. 1000)
    - ▲ A series of pixels with nearly ‘zero’ voltage will then give values that fluctuate around 1000
    - ▲ This intential offset in counts from zero is the bias level
  - ◇ Assessing the bias level
    - ▲ Overscan: After reading the row of charge, one may read a series of ‘fake’ pixels expected to have zero charge

- ▲ Bias image: Take a series of 0s exposures and analyze

- Gain (g)
  - ◇ Ratio of electrons produced to the counts recorded
    - ▲ Usually, $g > 1$
    - ▲ e.g. 2 electrons per count
  - ◇ How would you measure the gain of a CCD?
    - ▲ Electrons follow Poisson stats, not counts!
- Read Noise (RN)
  - ◇ The readout electronics contribute a source of noise to the measured counts
  - ◇ Usually close to a Gaussian, random 'signal'
    - ▲ Typical values are $3 - 10$ electrons
    - ▲ Easily assessed from analysis of a bias frame
- Connect to a storage device
  - ◇ e.g. a computer with a hard-drive
  - ◇ The modern standard is to write all of the pixel values into a single binary (FITS) file

G. Dark Current

- As described in the Detectors lecture, our semi-conductor devices are designed to enable charge to flow when a photon strikes them
  - ◇ One generally designs the device so that electrons are very close to conducting
  - ◇ This maximizes efficiency η
- If the device is too warm (high T), charge may flow without photons
  - ◇ i.e. the tail of the Maxwellian distribution has sufficient energy to 'cross the gap'
  - ◇ This is referred to as Dark Current
  - ◇ One mitigates against this unwanted charge by lowering the CCD temperature
  - ◇ This also reduces the device's efficiency
- Modern CCD devices have low dark currents
  - ◇ Modern IR devices continue to have non-negligible values
  - ◇ Best to characterize this yourself on whichever detector you use

H. QE and Flat Fields

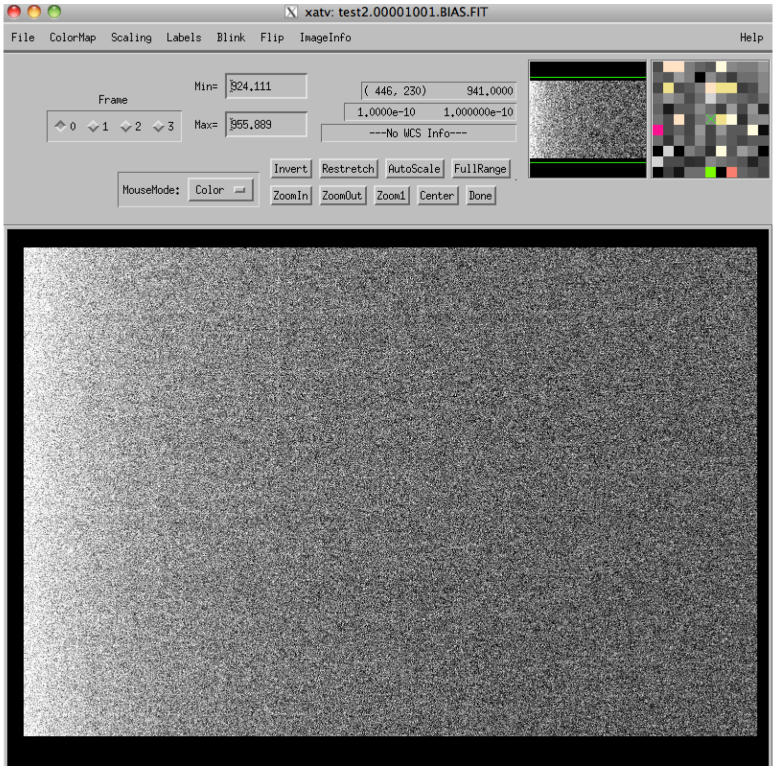
- The QE defines the probability that a pixel generates an electron when struck by a photon
  - ◇ Ranges from $0 - 100\%$
  - ◇ Wavelength dependent
- Generally, the pixels in a CCD array have nearly the same QE

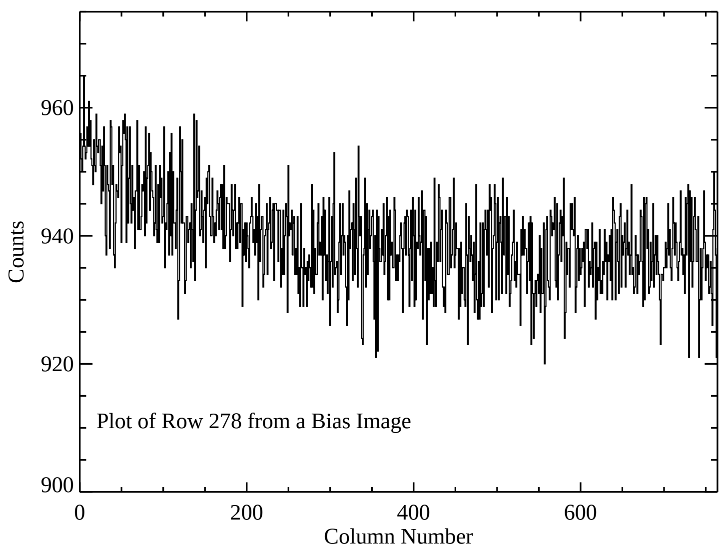
    - ◇ But it is never *exactly* the same
    - ◇ Modern devices have variations at the $\approx 0.5\%$ level

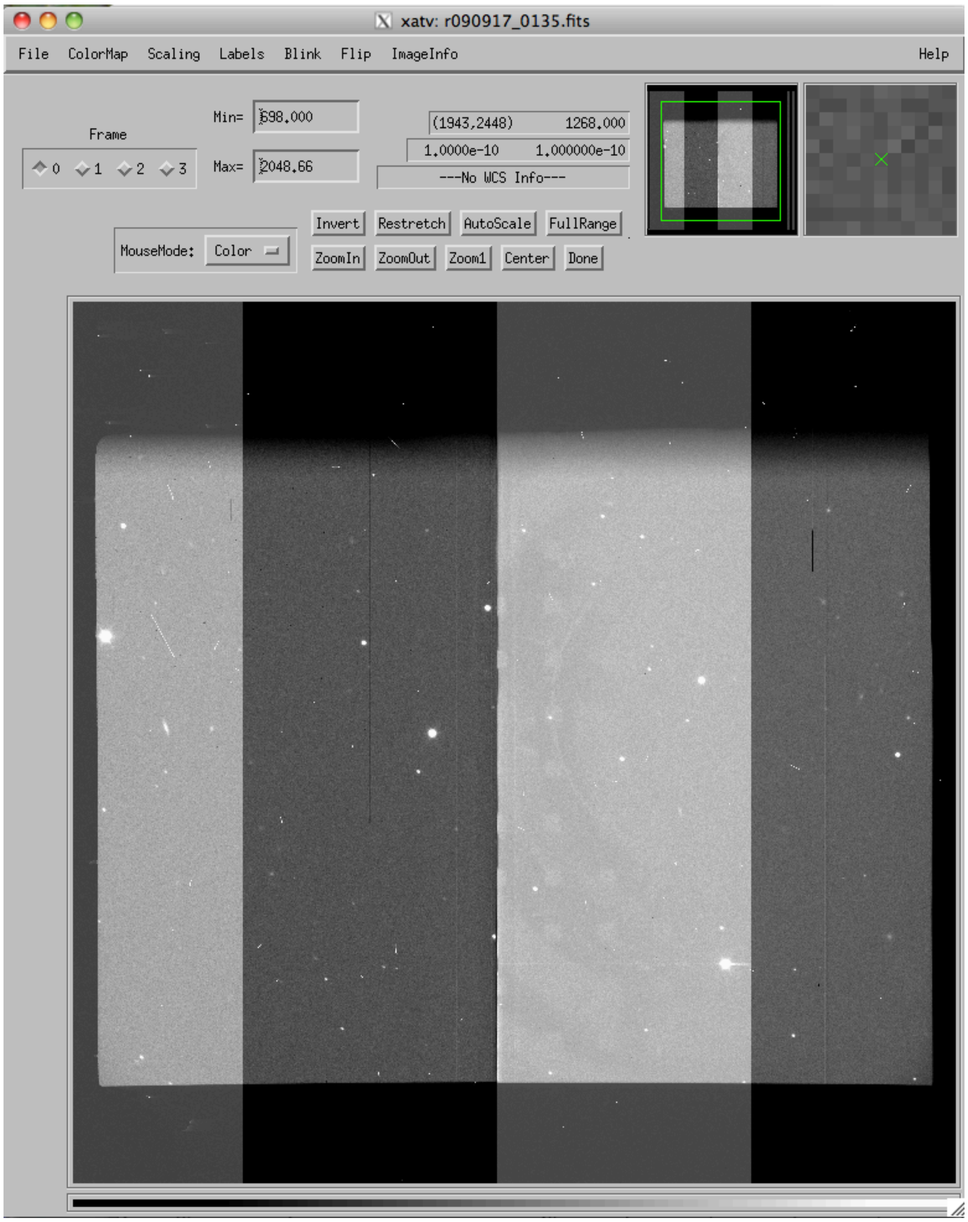
- Shine exactly the same number of photons on each pixel of a CCD
    - ◇ Observe a variation in the number recorded
    - ◇ For many reasons, one wishes to correct for these intrinisic variations in the QE
- Flat-field
    - ◇ Correct for QE variations
    - ◇ Multiplicative factor, not additive
    - ◇ Procedure:
        - (a) Uniformly illuminate a CCD with light
            - ▲ Difficult to do perfectly
            - ▲ Observe the twilight sky
            - ▲ Observe a screen in the dome
            - ▲ Observe the night sky at random positions and take median
        - (b) Take a series of exposures
        - (c) Combine the series of images
        - (d) Remove detector bias (see below)
        - (e) Normalize the resultant image to a unit value
            - ▲ Often smooth the data first
            - ▲ Reduces illumination patterns
        - (f) Divide this flat-field image into your science frames

I. Example (good) Images

- Bias frame


xatv: test2.00001001.BIAS.FIT
File ColorMap Scaling Labels Blink Flip ImageInfo Help
Frame
0 1 2 3
Min= 924.111
Max= 955.889
(446, 230) 941.0000
1.0000e-10 1.000000e-10
---No WCS Info---
Invert Restretch AutoScale FullRange
MouseMode: Color
ZoomIn ZoomOut Zoom1 Center Done

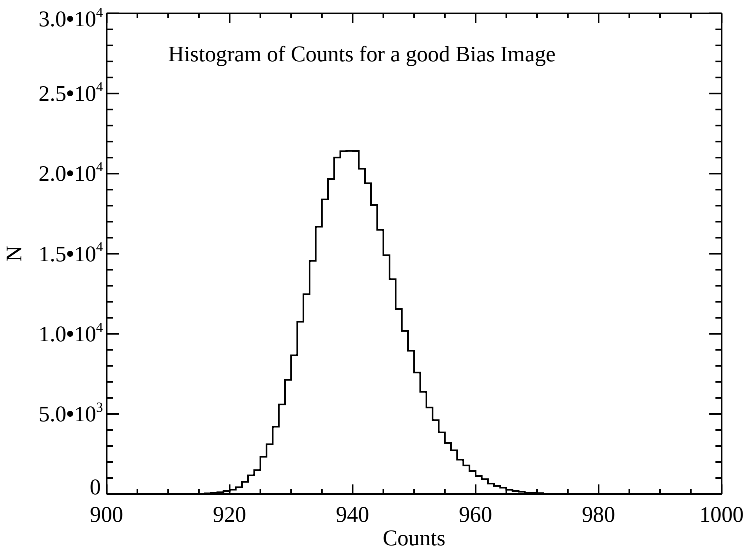

960
940
920
900
Counts
0
200
400
600
Column Number
Plot of Row 278 from a Bias Image



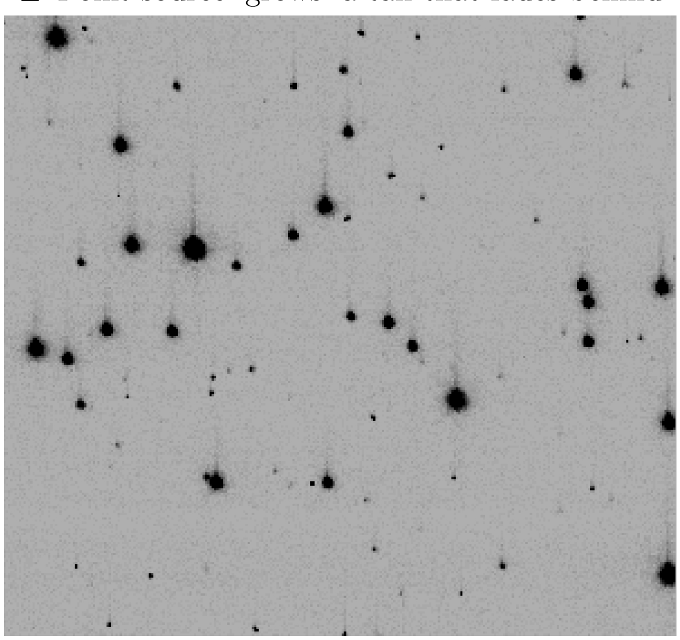
- Raw image of the night sky (Keck/LRIS)
  - ◇ The striping is due to the different bias levels for the 4-amplifier read-out
  - ◇ The well illuminated region is the unvignetted portion of the camera
  - ◇ Note the (partially) bad columns in the 2nd and 4th amps
  - ◇ Note the odd flat pattern in the 3rd amp

J. CCD "failure" modes

- A/D failure
  - ◇ Improper bias level (e.g. non-Gaussian)
  - ◇ Dropping bits



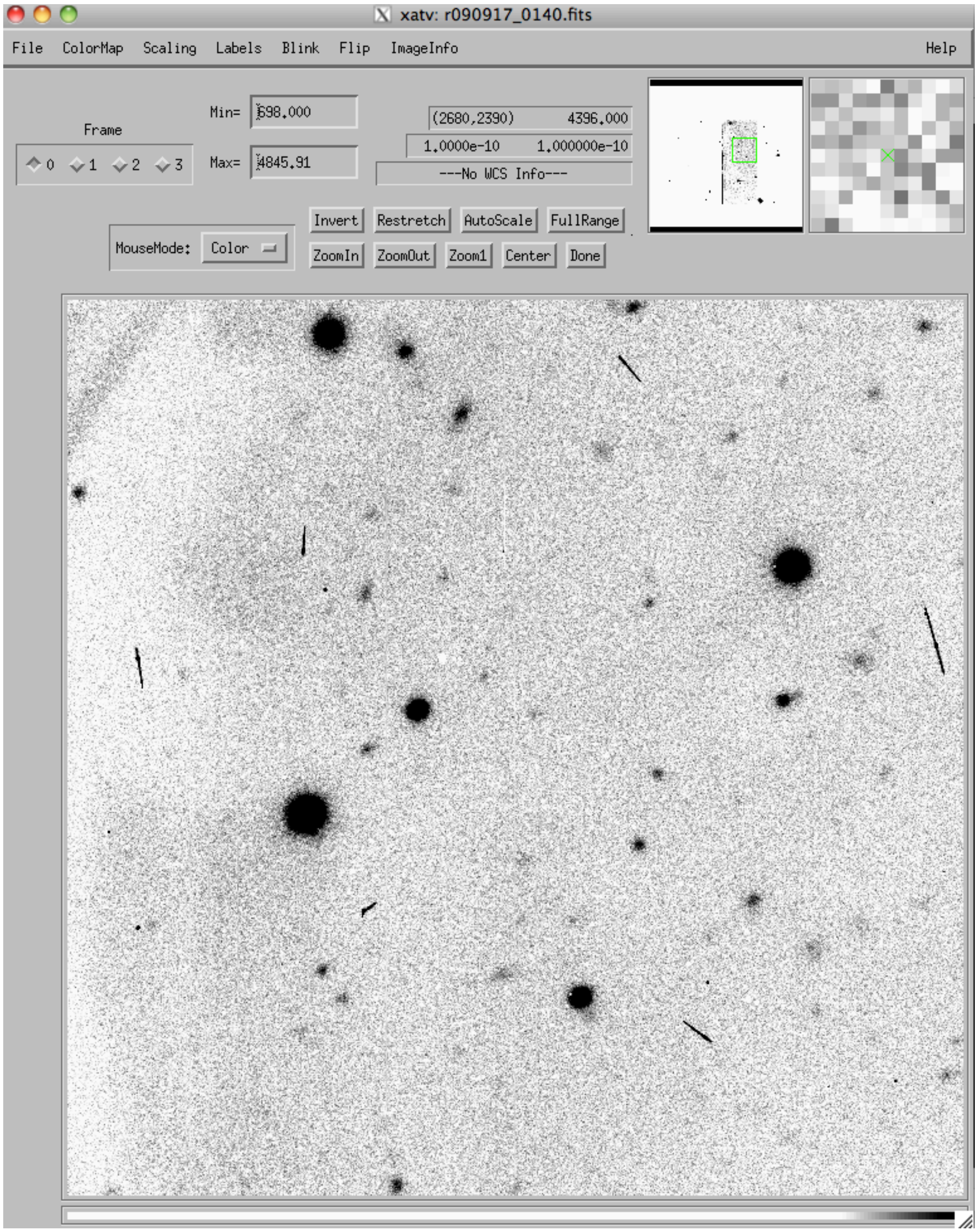
- CTE
  - ◇ Shift register not accurate to 99.999%
  - ◇ Typically in the parallel shift (along the column)
  - ◇ Charge is left behind from pixels with large values
    - ▲ Same fraction any time the charge is shifted
    - ▲ Point source 'grows' a tail that fades behind



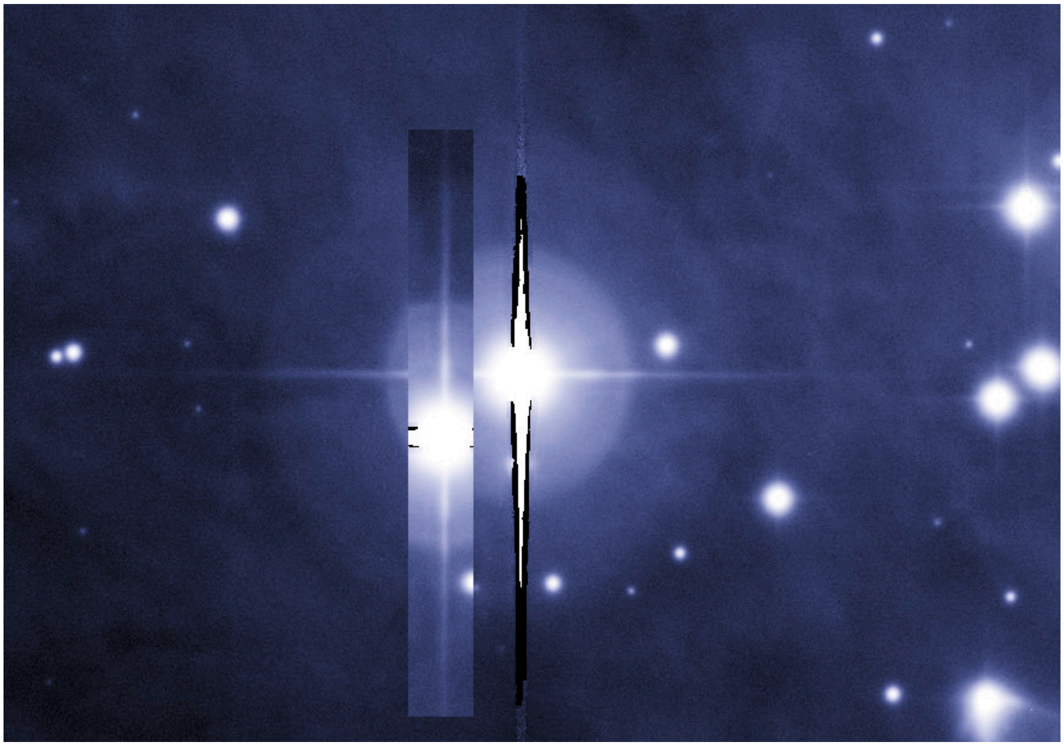
- Defects
  - ◇ Difficult to manufacture a device without blemish
  - ◇ Military buys the perfect ones
  - ◇ Scientists pay a much cheaper price for the imperfect devices

- ◇ Bad columns, quadrants, etc.

- Cosmic-rays
  - ◇ CCDs also record cosmic ray events
  - ◇ Bright and localized charge concentrations
  - ◇ Often show up as little 'streaks' as in the image below



- Saturation
  - ◇ Bleeding: Exceed the full-well of a pixel
  - ◇ Over-expose: Exceed the A/D bit-level (e.g. 64,000)
  - ◇ Non-linearity: Exceed the linear regime of the system



- Fringing
  - ◇ Patterened response of the CCD to longer wavelength light
  - ◇ Systematic and highly wavelength dependent