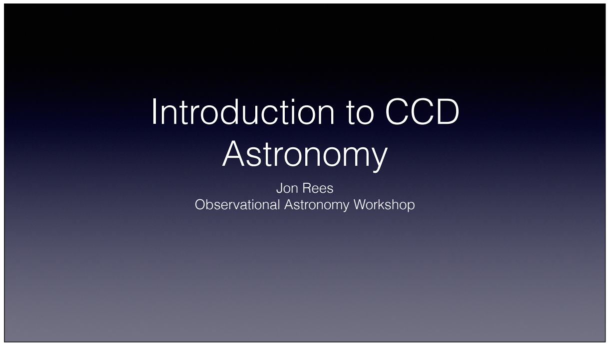
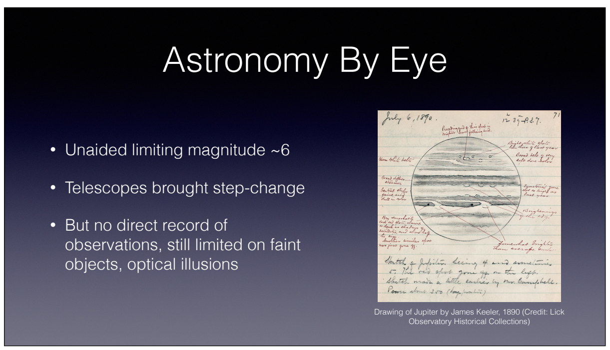
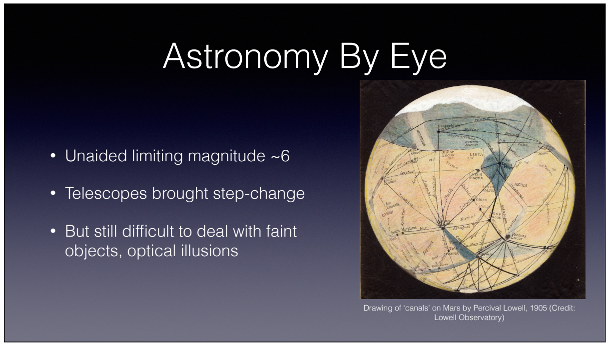


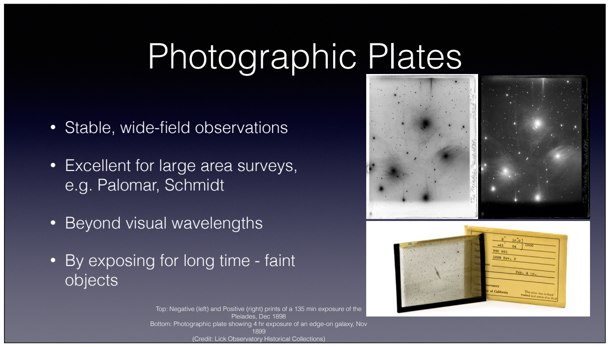
This talk/document will hopefully give you a short overview over how we use CCDs in astronomy, and some of the pitfalls and caveats associated with their use



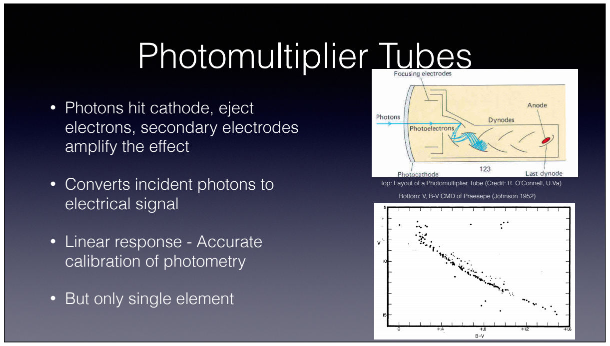
Before talking about CCDs, let's look at astronomy before CCDs.
Of course the first observations were made simply by eye. Unaided, your eyes have a limiting magnitude of around 6 (depending on quality of your sight and location).
Telescopes massively changed things. Galileo famously discovered the Galilean moons of Jupiter in 1610 using a telescope.
But you have no direct record when observing by eye. You can draw what you see (see the image on the right of Jupiter by James Keeler using the Lick 36-inch refractor), but you're still somewhat limited.



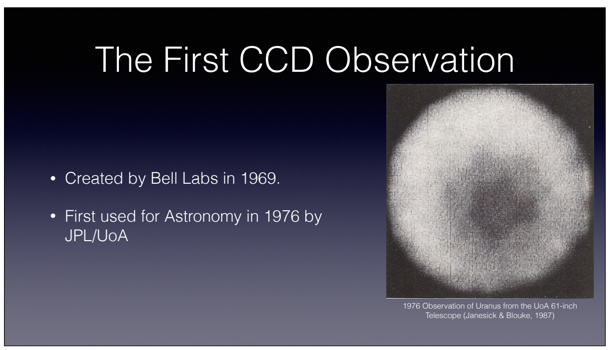
You also have to deal with the potential for people drawing things that simply aren’t there.
In the late 19th and early 20th century, some observers thought they saw evidence of ‘canals’ on Mars, with some even suggesting it was evidence of an advanced civilization on Mars (see the drawing on the right made by Percival Lowell of the canals he thought he saw).
Better telescopes and better instruments later showed this was simply an optical illusion, likely created by dust collecting along the bases of mountains.



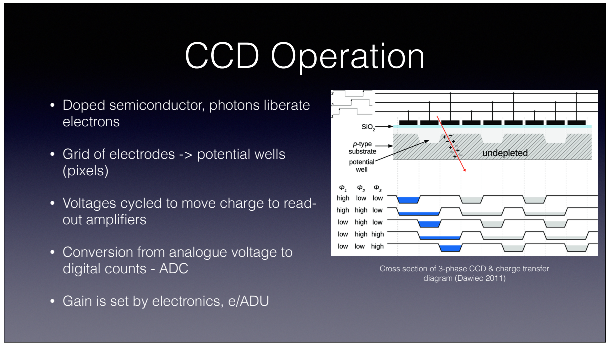
Photography revolutionised things again. Photographic plates provide stable records of observations, and can cover wide areas on the sky.
You can also use photographic plates to look at wavelengths beyond the visual portion of the spectrum, opening up new possibilities.
Exposing the plates for long time periods allows you to detect fainter objects than you could by eye (see the image on the bottom right of an edge-on galaxy, taken with 4 hours of exposure time for example)
But photographic plates do not respond linearly to changes in light, making overall calibration difficult.



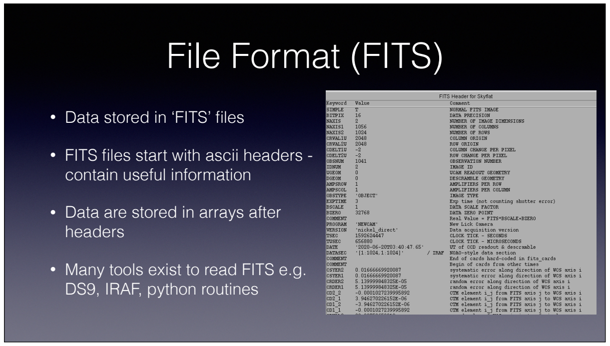
With photomultiplier tubes we enter the age of electrical astronomy. In a PMT, photons hit a cathode at the front of the device and eject electrons. These electrons are accelerated down the tube, hitting successive secondary electrodes and ejecting yet more electrons.
By the time you read out the signal at the end (as a voltage), you can have millions of electrons from an initial photon event. So PMTs are great for looking at faint sources.
PMTs also have very linear responses - if you double the number of photons hitting them, you double the number of electrons you get at the end. This means you can calibrate your measurements very accurately (see the excellent colour-magnitude diagram of Praesepe)
But PMTs are effectively a single pixel, if you want to observe 100 stars you need to make 100 (or more) observations. Time consuming!



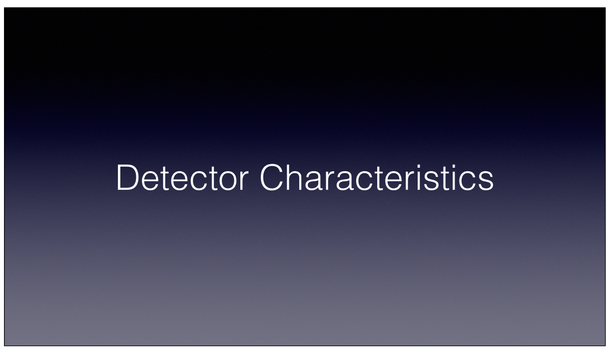
Charge-Coupled Devices (CCDs) were created by AT&T Bell labs in 1969.
First used for astronomy observations by a team from JPL and University of Arizona in 1976.
You can see the first astronomical CCD image on the right, an image of Uranus taken using a filter centered on Methane. The dark spot you see was evidence of methane in the atmosphere.

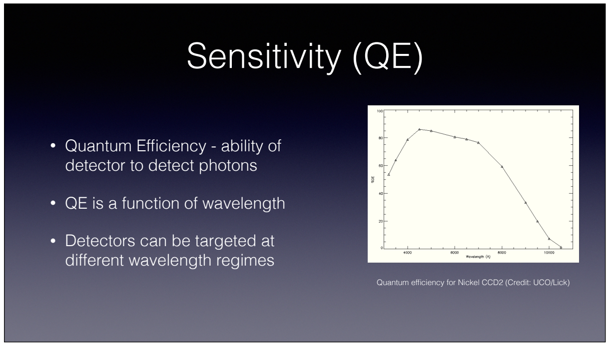


As a basic introduction to CCD operation, photons that hit the CCD liberate electrons, allowing them to move from the valence to conduction band.
Laying down a grid of electrodes allows us to create potential wells, confining these liberated electrons and prevent them falling back to the valence band. This grid of potential wells is our grid of pixels.
By cycling the voltages applied to these electrodes, we can move the charges around the chip and shuffle them over to read-out electronics. Measured as an (analogue) voltage.
This voltage measurement is converted to digital counts using an Analogue-to-Digital converter (ADC)
The relationship between the number of electrons and the resulting counts is termed the gain (e.g. gain for the Nickel CCD is ~2 electrons per ADU). Gain is a balancing act between having resolution to detect electrons(photons) and dynamic range of detector (max counts)

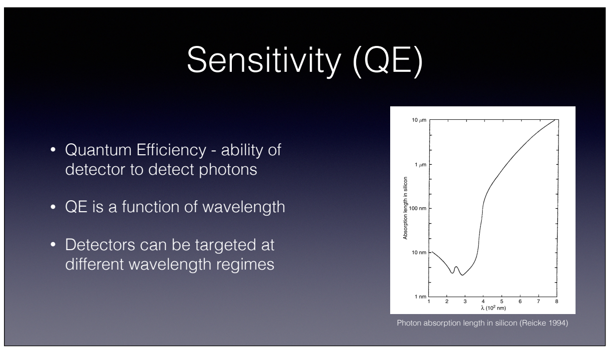


Once you've read out your data you need somewhere to store it. We use FITS files (Flexible Image Transport System).
FITS is an open format, and always backwards compatible (updates to the format must never break old files).
FITS files start with a human-readable header, which generally contains useful information about the observations. E.g. exposure time, co-ordinates the telescope is pointing at, instrument, filters.
Then the data are stored in arrays after the header.
Many tools exist to read FITS files, some of which you'll encounter in this workshop.





Quantum efficiency (QE) is defined as the ratio of incoming photons to those actually detected or stored in the device.
A QE of 100% would be an ideal detector with every incoming photon detected and recorded in the data. Of course things aren't perfect.
The CCD on the Nickel had a QE that peaks at ~85-90% at 4000 Angstroms, rapidly declining as you move to the red. It drops to almost zero by the time you get to the micron near-infrared regime.



You can target your CCD at specific wavelength regimes.
On the right you can see absorption length of photons as a function of wavelength. Absorption length is distance over which 63% (1/e) of photons will be absorbed.
So blue photons only travel a short distance in silicon before being absorbed, but red photons travel much larger distances.
If you thin out your detector, you make yourself much more sensitive to blue photons (while red photons will travel through without detection).
If you have a much thicker CCD you'll be more sensitive to red photons.

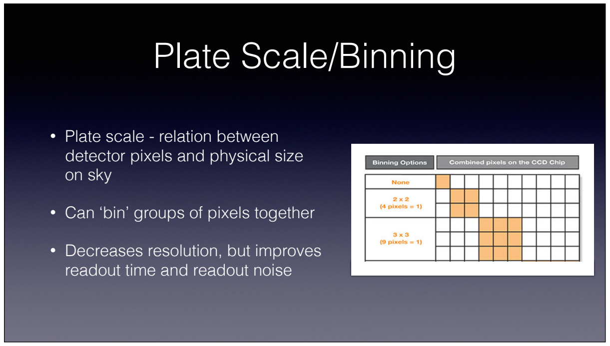
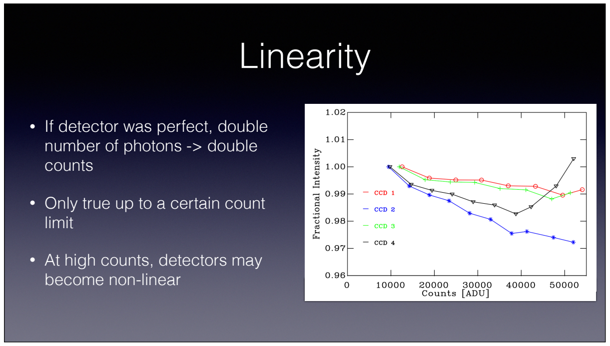
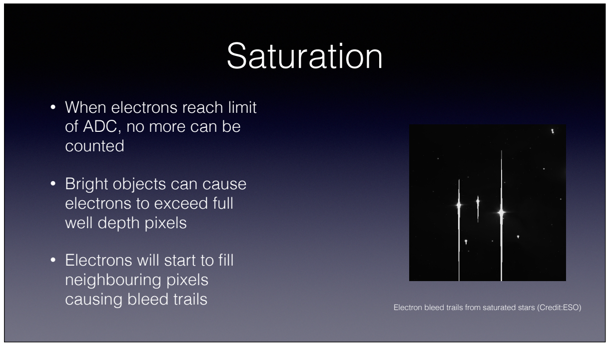


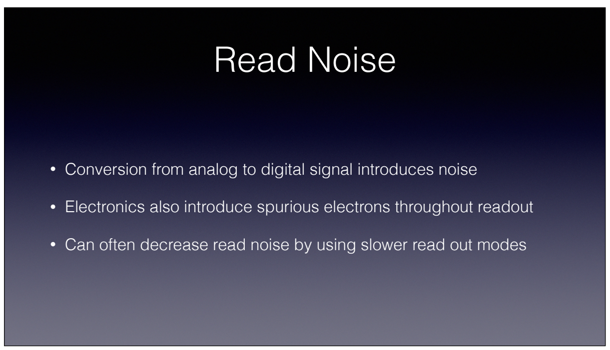
Plate scale is a term that originates from when photographic plates were used as the main imaging device. It relates the physical size of your detector to the size it covers on the sky.
For a CCD a convenient unit for the plate scale is arcsec/pixel. For the Nickel CCD the plate scale is 0.18 arcsec/pixel, so each pixel covers an are on the sky of 0.18x0.18 arcseconds.
You can also 'bin' pixels on your CCD, reading out groups of pixels as if they were a single pixel (see image on the right).
For 2x2 binning you read out groups of 4 pixels as if they were one larger pixel.
Binning of CCD pixels decreases the image resolution, but usually increases the final signal-to-noise value of a measurement, and reduces the total readout time (because you're reading out fewer effective pixels)
Binning is usually a good idea in imaging, where your plate scale is significantly smaller than typical sky conditions (e.g. seeing).
Usually avoided in spectroscopy, where you will lost spectroscopic resolution, but sometimes there's a useful science case for doing so.



Linearity of a detector refers to how it reacts to changes in the incident light.
In an ideal detector, if you double the number of photons you would get double the signal at the end (double the counts).
Of course, detectors are not perfect, and this linearity is often only true over a certain range.
On the right, we have measurements of the linearity for the CCDs on the Isaac Newton Telescope on La Palma. You can see it’s linear to within ~2% over most count ranges. But it does become worse at hight counts.
In general, you want to stay within the linear regime of your detector. This will vary from detector to detector, e.g. Nickel CCD is linear up to ~50,000 counts. Kast Blue is linear all the way up to ~65,000 counts. Kast Red is only linear to ~30,000 counts (at least in slow read out).
So be aware of your linearity limit, and try to keep under that level of counts (otherwise you’re never really sure how bright your target is).

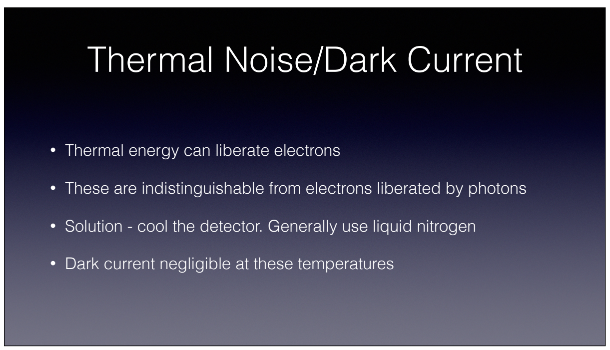


If you go beyond the non-linear regime, you can reach a point at which the detector is no longer able to count any more electrons.
For a 16-bit ADC, the maximum counts is 2^16: 65,536. Once you reach this point, it doesn’t matter how many electrons are left in your pixel, you can’t count them.
If you have brighter stars, you can actually fill up your potential well and electrons will spill over into neighbouring pixels. When this happens you get bleed trails (see image on the right).
Again, avoid saturation, because you’re no longer able to tell how many photons you’re actually receiving.



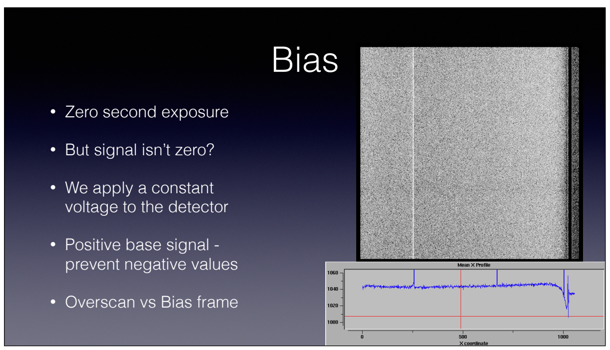
Conversion from an analog signal to a digital number is not perfectly repeatable.
Each on-chip amplifier and A/D circuit will produce a statistical distribution of possible answers centered on a mean value.
Electronics also introduce spurious electrons, which are indistinguishable from electrons excited by photons.
This noise is your readout noise, which is unavoidable. Readout noise is typically ~10 e per pixel for Nickel as an example.
But you can decrease the readout noise by reading out your detector over a longer time, because readout speed, and thus the rate at which currents flow through the on-chip amplifier, can cause thermal swings in the amplifier temperature.
Observatories will typically offer a choice of readout speeds.

Typically here at Lick we stick to slow readout speeds, although we do have faster readout speeds for when there's a legitimate science case for it.



Every material at a temperature much above absolute zero will be subject to thermal noise. For silicon in a CCD, this means that when the thermal agitation is high enough, electrons will be freed from the valence band and become collected within the potential well of a pixel. When the CCD is readout, these dark current electrons become part of the signal, indistinguishable from astronomical photons. Fortunately, there's a simple solution. Cool the detector. At professional observatories we typically use liquid nitrogen to cool the detectors down to ~-100C, which makes the dark current negligible.

Now let’s talk about the calibration files we can use to deal with CCD imperfections.

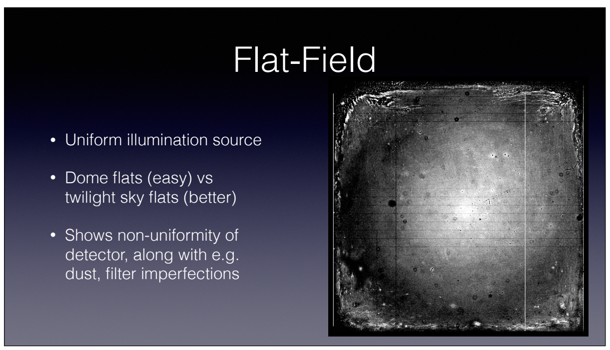


If we take a zero second exposure, we don’t see zero signal. Why? We actually apply a constance voltage to the detector, which results in a non-zero base signal. For Lick instruments, this bias level is typically around 1000 pixels.

This positive bias level has a big plus: we avoid negative values in our data.

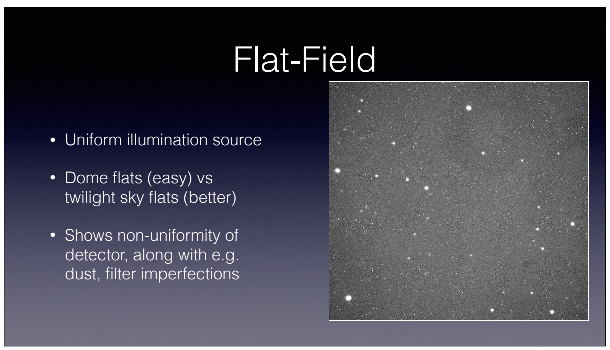
To account for this bias signal you can either use overscan regions, or bias frames. After reading out all of the pixels, we can continue to poll the readout electronics. These extra reads don’t correspond to physical pixels, but instead simply give you a measure of the bias level. These extra reads are appended on to the side of the data as extra columns (see e.g. the far right hand of the bias frame shown above).

The downside of overscan regions is that it doesn't tell you about the variation of the bias level over the CCD. For example in the bias shown on the right, we have a bad column, shown as a long white column in the data. We can also have a bias level that varies slightly over the field. If you simply used the overscan region, you would not be able to deal with this.
Instead, we use bias frames - zero second exposures. Typically, you'll take a number of bias frames during an afternoon before your nighttime observations.

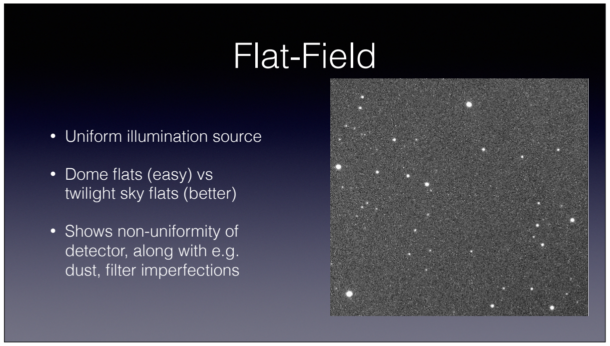


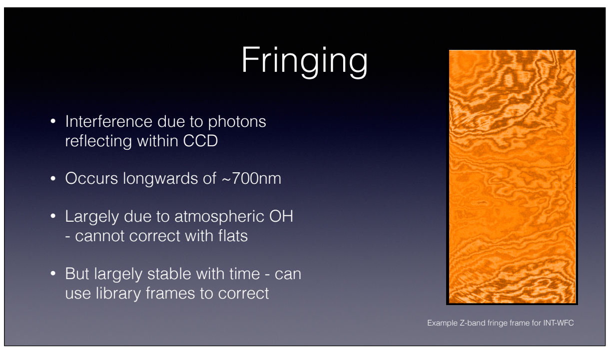
Once again, CCDs are not perfect. CCD pixels do not all respond equally to incident light. To account for the non-uniformity in pixel response, you can use flat field observations.
These are observations of a uniformly illuminated field. If everything were ideal, a flat-field would be a simple blank white image. You can see from the image on the right (a Nickel flat-field), that this is not the case.
We have edge effects from imperfections in the filter. The image is brighter in the center, darker at the edges, and we can see out-of-focus dark circles throughout the image, which is actually dust (either on the mirror, filter, or CCD dewar).
To correct for this, you can either use dome flats (observations of an illuminated white screen in the dome) or twilight flats (observations of

the sky at sunset/sunrise)
Dome flats are easy to take, but imperfect - usually shadowing/non-uniform illumination.
Twilight flats are better, but very intense to get these observations (as you'll see this evening) because you have short time to get many observations.



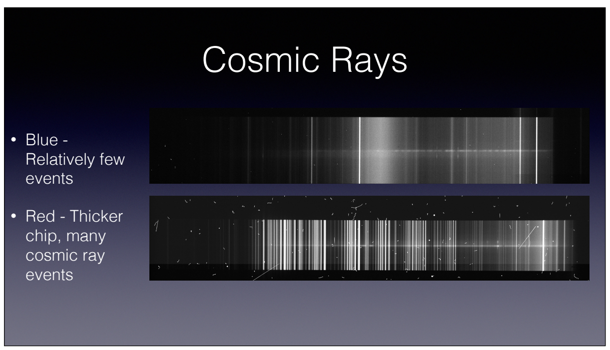
Applying flat-fields is done by dividing your data by your flat-field observation. Doing this doesn't (or shouldn't) have a massive effect.
It simply evens out responses over the field of your CCD. For example, compare between this image (before flat-fielding) and the one on the next slide (after flat-fielding).





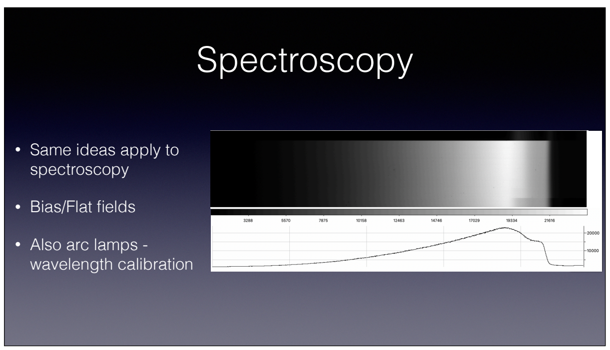
Depending on your science, you may encounter fringing.
Fringing refers to the interference pattern that can occur on CCD images taken at long optical wavelengths.
It is produced when photons reflect within a CCD leading to constructive or destructive interference.
In broadband and narrowband imaging fringing typically occurs due bright night-sky emission lines from atmospheric OH molecules and cannot be corrected using dome flats (which are illuminated using polychromatic lights) or twilight sky flats (in which the scattered sunlight will dominate over the sky emission).
The image on the right is an example of fringing on the INT-WFC on La Palma, created using 7x500 second exposures of the night sky (almost 1 hour of on-sky time).

Fortunately fringing is generally stable with time. This means you can use library frames, and often won't have to create your own. And certainly won't have to create a new one each observing run, unlike bias/flat-fields.

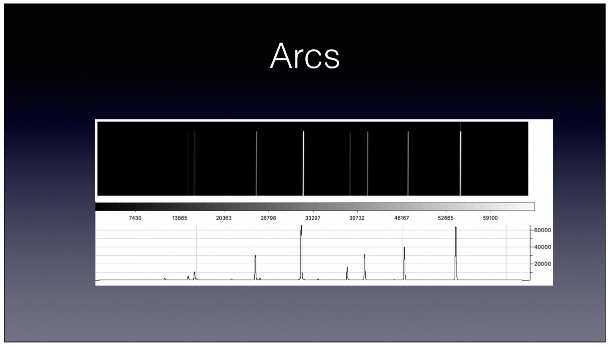


Cosmic rays can also affect your observations. These are high-energy particles coming from space (or from radioactivity of the CCD dewar glass) that cause detection events in your CCD.
The top image is an 1800s Kast blue exposure. You can see a couple of cosmic rays, but it's not really a major issue.
The bottom image is a 600s Kast Red exposure, with many more cosmic ray events. This is because the Red CCD is a thicker chip (to make it sensitive to red photons), so cosmic rays are more likely to cause a detection.
To correct for this, take multiple exposures and combine them. Your signal will be the same in each exposure, whereas the cosmic rays will be at different locations.
For the Kast observations above, the observer took 1x 1800s

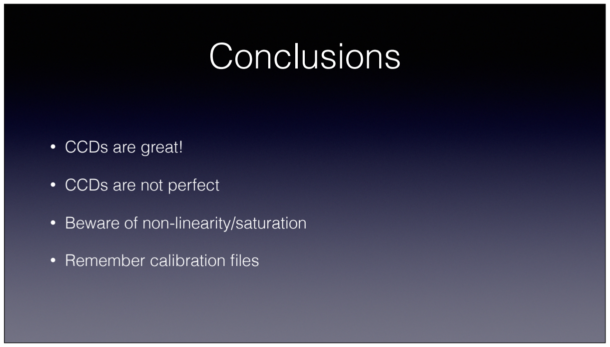
exposure in the blue (where cosmic rays aren't a major issue), but 3x600s in the red (where they are a big problem).



All of the things we've discussed so far apply to spectroscopy as well as imaging data.
You still need bias and flat-field observations (see an example for a spectroscopic flat-field on the right).
But you'll also need an extra calibration file for spectroscopy - Arcs



Arcs are observations of arc lamps. Arc lamps use bulbs filled with specific gases, which results in emission lines with known wavelengths.
An example for Kast Blue is shown above. By comparing the locations that the emission lines fall on your CCD you can figure out what pixel corresponds to a given wavelength, giving you a wavelength solution for your spectra.



Conclusions

- Calibration Files:
  - Bias (Bias Voltage)
  - Flat Field (Non-uniform response)
  - Arcs (Wavelength Calibration)
  - Fringe Frame, Standard Star