Lecture 12

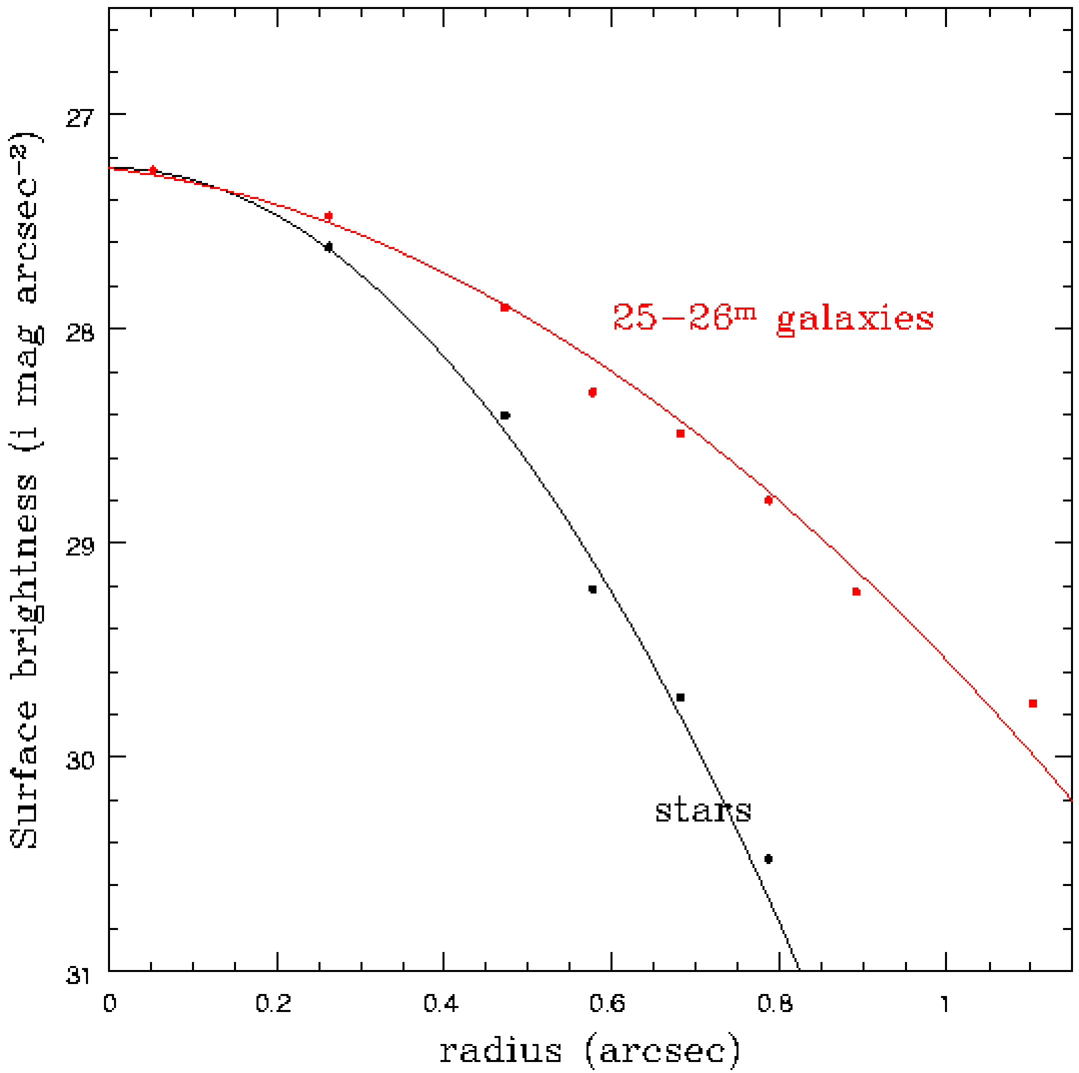
# Imaging with CCDs

Sources of noise and systematic error

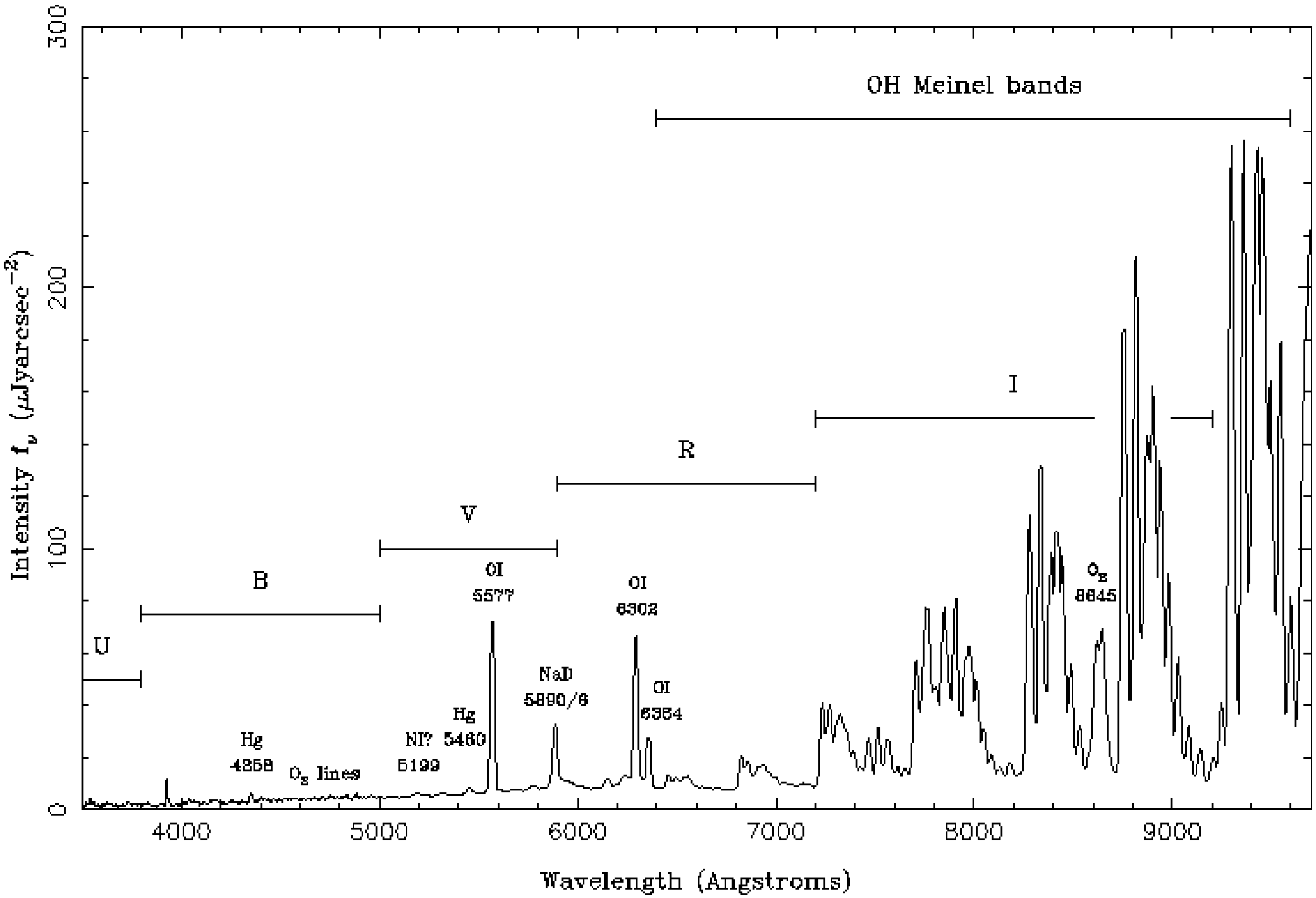
Calibration techniques

Image pre-processing

# The challenge: measure ultra-faint galaxy surface brightness

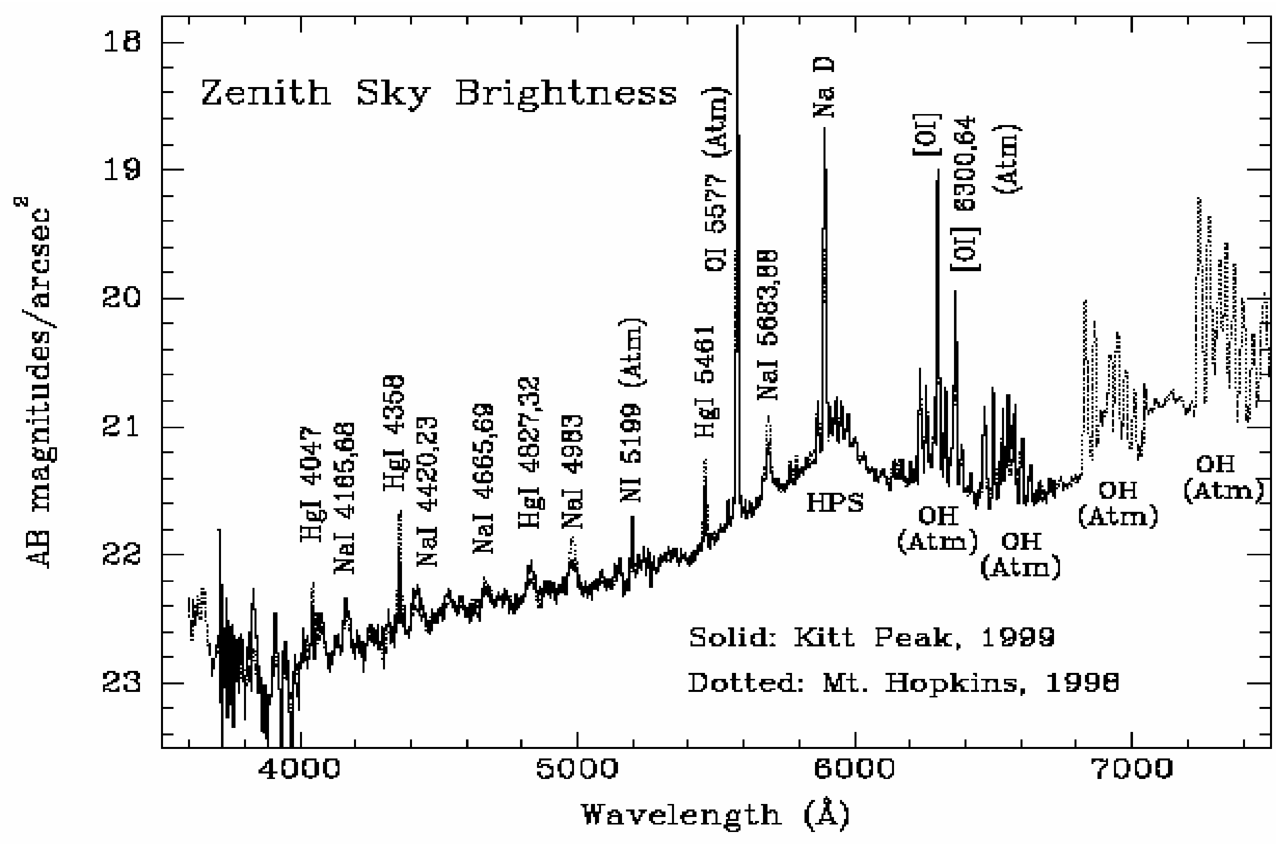


# The optical spectrum of the night sky



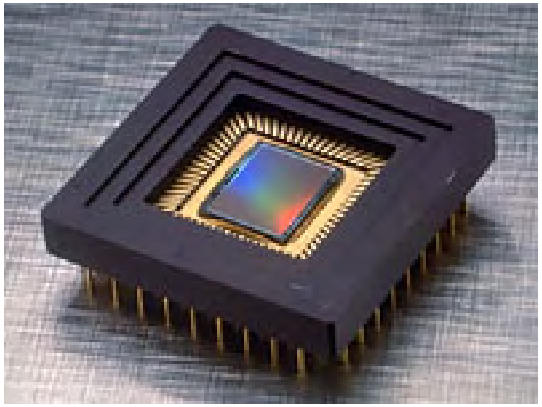
# The optical spectrum of the night sky

To get to galaxy surface brightness of 29 mag/sq.arcsec, we must do photometry at 7-8 magnitudes fainter than the typical dark night sky background.  i.e. we must eliminate systematic errors at the level of 0.0006 of the background, as well as average enough exposures to reduce the shot noise from this background.

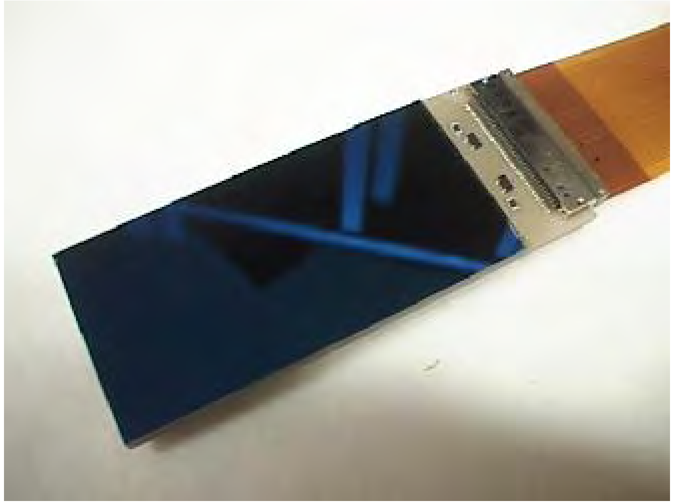


# Front and back-illuminated CCDs

The fine surface electrode structure of a front-illuminated CCD is clearly visible as a multi-colored interference pattern. Backside Illuminated CCDs have a much planer surface  appearance.
The other notable distinction is the higher QE in the AR-coated chip on the right. At the level of a few parts per thousand (our science challenge) every CCD is unique, and the gain and other properties of every pixel must be understood in each exposure.  Luckily, CCDs are linear over a wide range.



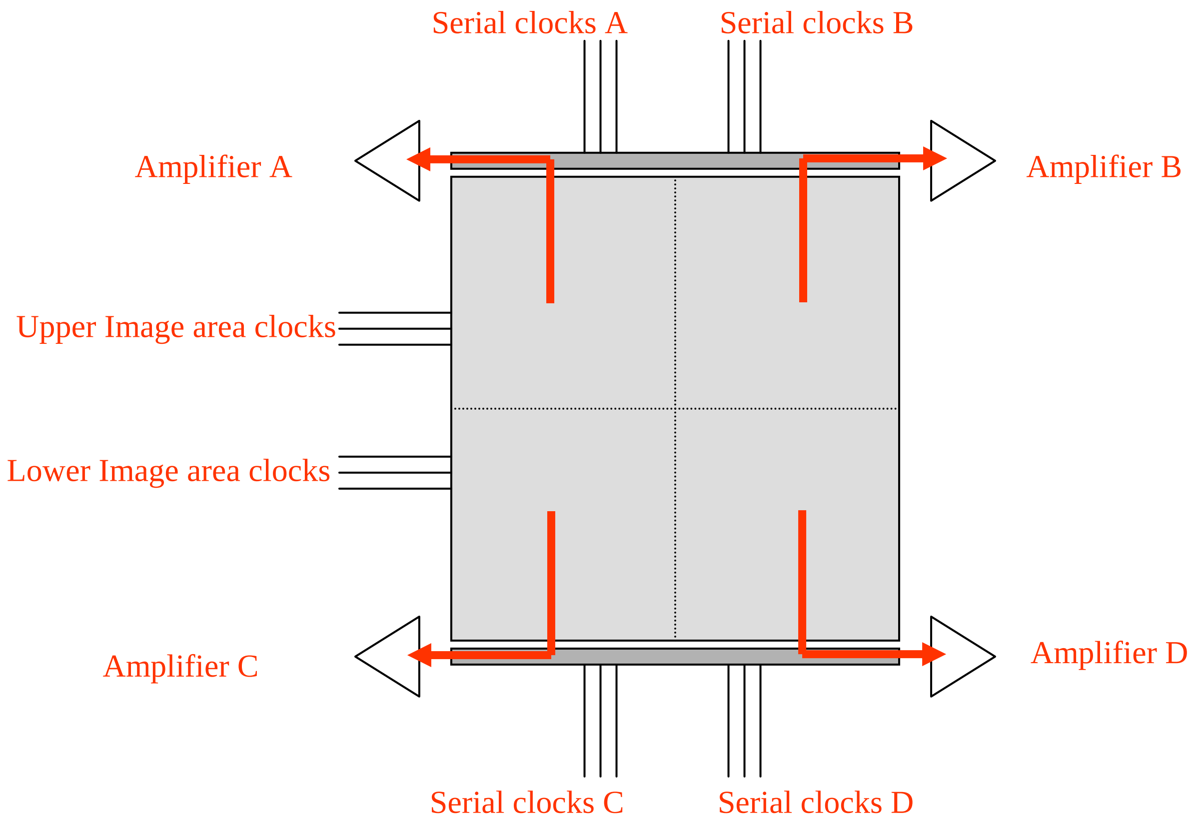
Frontside-illuminated CCD



Backside-illuminated CCD

# Slow Scan Frame Transfer CCDs

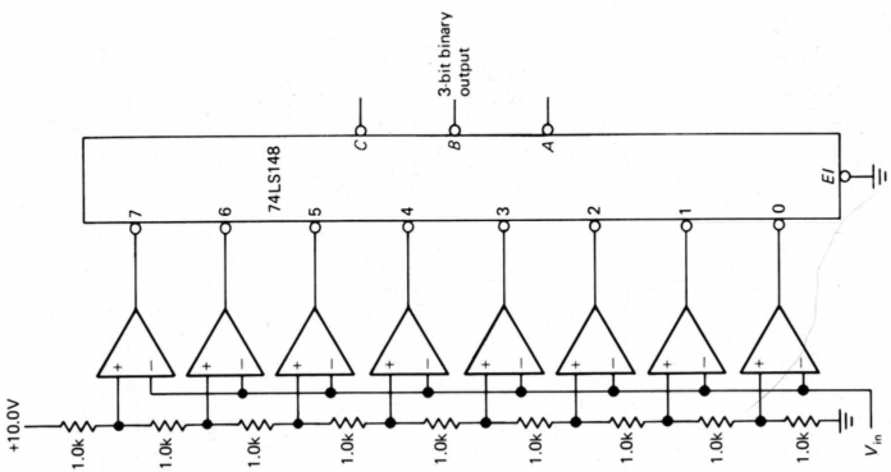
A common science-grade design uses 2 serial registers and 4 output amplifiers. Extra clock lines are required to divide the image area into an upper and lower section. Further clock lines allow independent operation of each half of each serial register. It is thus possible to read out the image in four quadrants simultaneously, reducing the readout speed by a factor of four.

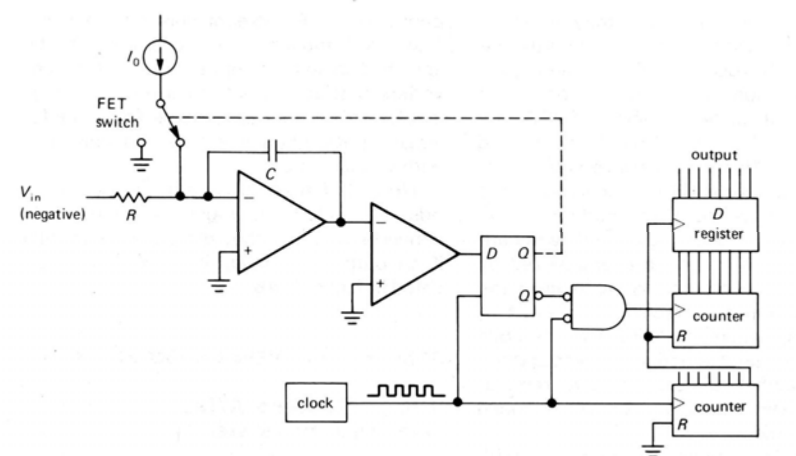


# Dynamic Range and A/D Conversion

**DYNAMIC RANGE:** The useful range of charge per pixel (at the input of the sense node amplifier is set by the read noise per pixel of this amplifier and the number of electrons per pixel in the brightest object in the exposure. For CCDs with 10-15 micron pixels and good MOSFET amplifiers this dynamic range can be from 3 – 200,000 electrons, a factor of 67,000! This can span the noise in a shutter closed "zero" frame to a time exposure with sky background plus stars and galaxies. Far better than the factor of 50 in photography.

**ANALOG TO DIGITAL CONVERSION:** We must convert the corresponding voltage output of this on-chip amplifier to digital data. This is done with some more amplification followed by an A/D converter. A 16-bit A/D has a range of 65,000. We want the least significant bit to measure the lowest noise level expected (shutter closed): the read noise. There are half a dozen ways to do this. Here are a couple: the parallel encoder flash A/D and the delta-sigma charge-balancing A/D. Pixel conversion times must be ~1 microsecond!



# Noise Sources in a CCD Image

The main noise sources found in a CCD are :

## 1. READ NOISE.

Caused by electronic noise in the CCD output transistor and possibly also in the external circuitry. Read noise places a fundamental limit on the performance of a CCD. It can be reduced at the expense of increased read out time. Scientific CCDs have a readout noise of 2-3 electrons RMS.

## 2. DARK CURRENT.

Caused by thermally generated electrons in the CCD. Eliminated by cooling the CCD.

## 3. PHOTON NOISE.

Also called 'Shot Noise'. Photons arrive in a random fashion described by Poisson statistics.

## 4. PIXEL RESPONSE NON-UNIFORMITY.

Defects in the silicon and small manufacturing defects can cause some pixels to have a higher sensitivity than their neighbours. This "noise" source can be removed by 'Flat Fielding'; an image processing technique.

# Noise Sources in a CCD Image

Before these noise sources are explained further some new terms need to be introduced.

## FLAT FIELDING

This involves exposing the CCD to a very uniform light source that produces a featureless and even exposure across the full area of the chip. A flat field image can be obtained by exposing on a twilight sky or on an illuminated white surface held close to the telescope aperture (for example the inside of the dome). Flat field exposures are essential for the reduction of astronomical data.

## BIAS OVERSCAN REGIONS

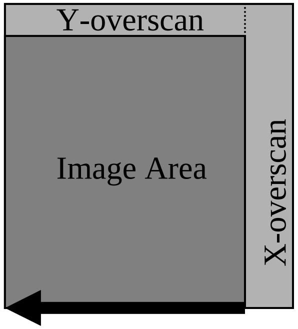
A bias region is an area of a CCD that is not sensitive to light. The value of pixels in a bias region is determined by the signal processing electronics. It constitutes the zero-signal level of the CCD. The bias region pixels are subject only to readout noise. Bias regions can be produced by 'over-scanning' a CCD, i.e. reading out more pixels than are actually present. Designing a CCD with a serial register longer than the width of the image area will also create vertical bias strips at the left and right sides of the image. These strips are known as the 'x-underscan' and 'x-overscan' regions

A flat field image containing bias regions can yield valuable information not only on the various noise sources present in the CCD but also about the gain of the signal processing electronics i.e. the number of photoelectrons represented by each digital unit (ADU) output by the camera's Analog to Digital Converter.

# Bias Overscan Regions

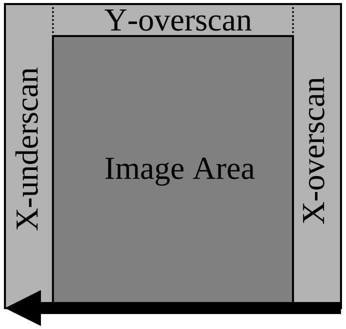
Flat field images obtained from two CCD geometries are represented below. The arrows represent the position of the readout amplifier and the thick black line at the bottom of each image represents the serial register.

CCD With Serial Register equal in length to the image area width.




Here, the CCD is over-scanned in X and Y

CCD With Serial Register greater in length than the image area width.




Here, the CCD is over-scanned in Y to produce the Y-overscan bias area. The X-underscan and X-overscan are created by extensions to the serial register on either side of the image area. When charge is transferred from the image area into the serial register, these extensions do not receive any photo-charge.

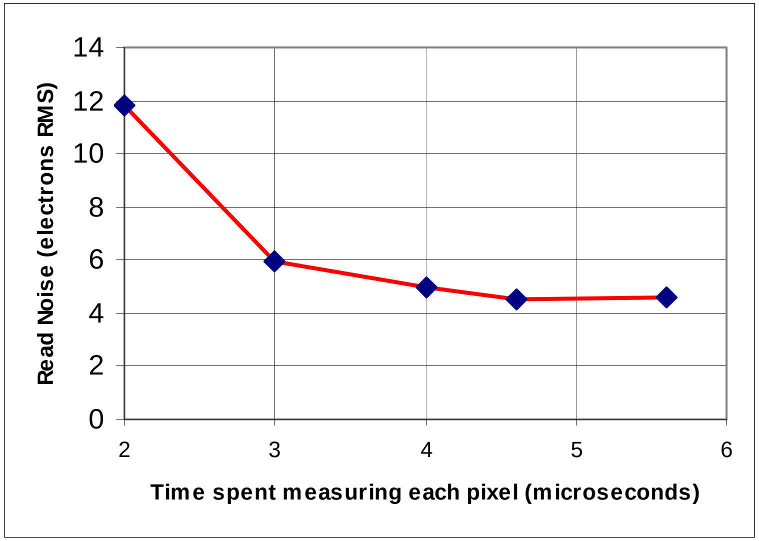
# CCD Read Noise

These four noise sources are now explained in more detail:

**READ NOISE.**

This is mainly caused by Johnson noise in the output amplifier. This noise source can be reduced by cooling the output amplifier or by decreasing its electronic bandwidth. Decreasing the bandwidth means that we must take longer to measure the charge in each pixel, so there is always a trade-off between low noise performance and speed of readout. 60Hz pickup and interference from circuitry in the observatory can also contribute to Read Noise but can be eliminated by careful design. Johnson noise is more fundamental and is always present to some degree.

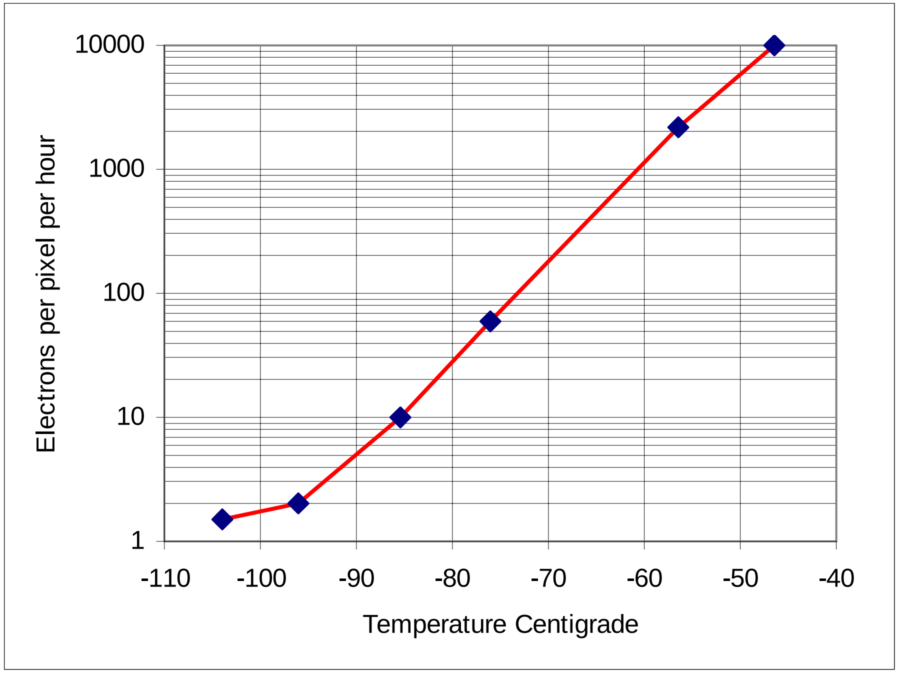
The graph below shows the trade-off between noise and readout speed for a CCD.



# CCD Dark Current Noise

## DARK CURRENT.

Electrons can be generated in a pixel either by thermal motion of the silicon atoms or by the absorption of photons. Electrons produced by these two effects are indistinguishable. Dark current can be reduced or eliminated entirely by cooling the CCD. Science cameras are typically cooled with liquid nitrogen to the point where the dark current falls to below 1 electron per pixel per hour where it is essentially un-measurable. The graph below shows how the dark current of a CCD can be reduced by cooling.



# Photon Shot Noise

**PHOTON NOISE.**

Small pixels collect very low fluxes of photons.

Poisson statistics tells us that the Root Mean square uncertainty (RMS noise) in the number of photons per second detected by a pixel is equal to the square root of the mean photon flux (the average number of photons detected per second).
For example, if a star is imaged onto a pixel and it produces on average 10 photo-electrons per second and we observe the star for 1 second, then the uncertainty of our measurement of its brightness will be the square root of 10 i.e. 3.2 electrons. This value is the ‘Photon Noise’.
Increasing exposure time to 100 seconds will increase the photon noise to 10 electrons (the square root of 100) but at the same time will increase the ‘Signal to Noise ratio’ (SNR). In the absence of other noise sources the SNR will increase as the square root of the exposure time.

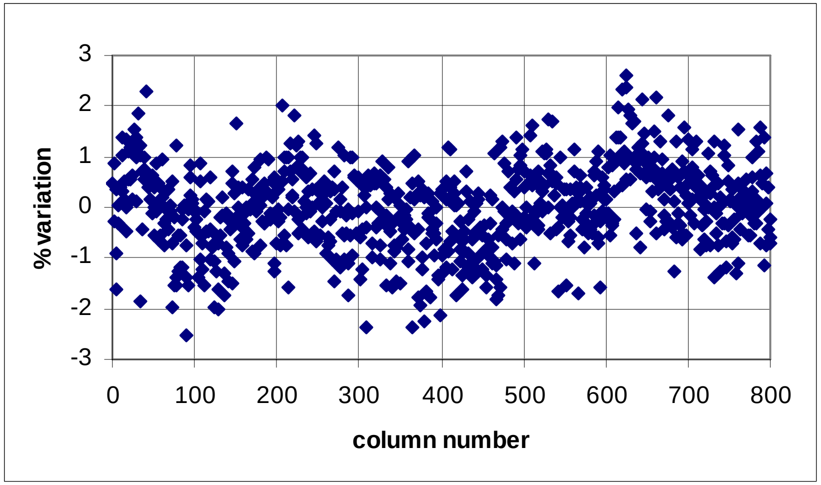
( Dark current, described earlier, is also governed by Poisson statistics. If the mean dark current contribution to an image is 900 electrons per pixel, the noise introduced into the measurement of any pixel’s photo-charge would be 30 electrons )

# Pixel QE or gain “noise”

**PIXEL RESPONSE NON-UNIFORMITY.**

If we take a bright (at least 50,000 electrons of photo-generated charge per pixel) flat field exposure, the contribution of photon noise and read noise become very small. If we then plot the pixel values along a row of the image we see a variation in the signal caused by the slight variations in sensitivity between the pixels. The graph below shows this for a CCD illuminated by blue light.

The variations are as much as +/-2%. Fortunately these sensitivity differences are constant and are easily removed by dividing a science image, pixel by pixel, by a flat field image.



# Sum Noise in a CCD Image

## HOW THE VARIOUS NOISE SOURCES COMBINE

Assuming that the pixel sensitivity variation has been removed by flat fielding, the stochastic noise sources are uncorrelated and add by quadrature sum:

$$\mathrm{NOISE}_{total} = \sqrt{(\mathrm{READ\ NOISE})^2 + (\mathrm{PHOTON\ NOISE})^2 + (\mathrm{DARK\ CURRENT})^2}$$

In CCDs made from high purity silicon the dark current is very small and often negligible. The equation then shows that read noise is only significant in low signal level applications such as Spectroscopy. At higher signal levels, such as those found in direct imaging, the photon noise becomes increasingly dominant and the read noise becomes insignificant. For example , a CCD with read noise of 5 electrons RMS will become background photon noise dominated once the sky signal level exceeds 25 electrons per pixel. If the exposure is continued to a level of 100 electrons per pixel, the read noise contributes only 11% of the total noise.

# Measuring Read Noise: Photon Transfer Method

Using two identical flat field exposures it is possible to measure the read noise of a CCD with the Photon Transfer method. Two exposures are required to remove the contribution of the pixel response variations and of small imperfections in the flat fields caused by uneven illumination.

The method actually measures the conversion gain of the CCD camera; the number of electrons represented by each digital interval (ADU) of the analog to digital converter, however, once the gain is known the read noise can be obtained directly.

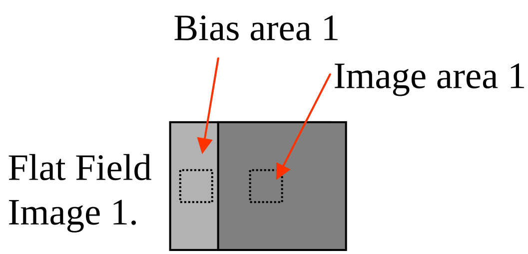
This method exploits the Poisson statistics of photon arrival. To use it, one requires an image analysis program capable of doing statistical analysis on selected areas of the input images.

The read noise and the shot noise from a uniform exposure add in quadrature:

$$\boxed{(\text{Total Noise})^2 = G^2 * \text{ReadNoise}^2 + G * \text{ExposureLevel}}$$

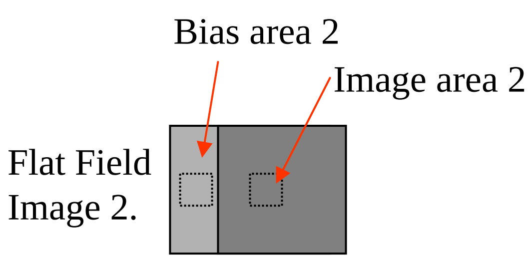
where G = gain

# Photon Transfer Method




STEP 1

Measure the Standard Deviation in the two bias areas and average the two values.
Result = $\text{Noise}_{\text{ADU}}$ [the Root Mean Square readout noise in ADU]



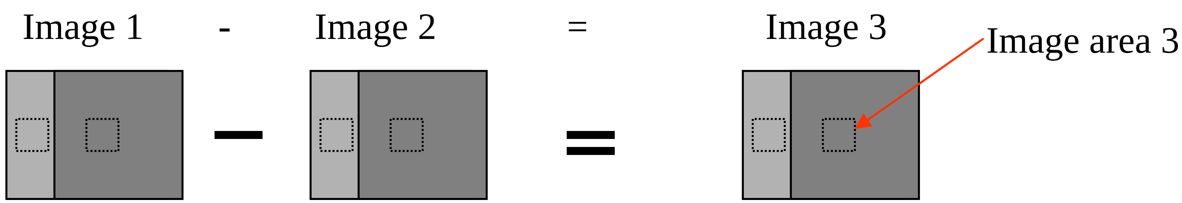

STEP 2

Measure the mean pixel value in the two bias areas and the two image areas. Then subtract $\text{Mean}_{\text{Bias area 1}}$ from $\text{Mean}_{\text{Image area 1}}$
result= $\text{Mean}_{\text{ADU}}$ [ the Mean Signal in ADU]

As an extra check repeat this for the second image, the Mean should be very similar. If it is more than a few percent different it may be best to take the two flat field exposures again.

# Photon Transfer Method

STEP 3 The two images are then subtracted pixel by pixel to yield a third image




STEP 4

Measure the Standard Deviation in image area 3
result= $StdDev_{ADU}$ .
The statistical spread in the pixel values in this subtracted image area will be due to a combination of readout noise and photon noise.

STEP 5

Now get the gain via the following equation.

$$\text{Gain} = \frac{2 \times \text{Mean}_{ADU}}{(\text{StdDev}_{ADU})^2 - (2 \times \text{Noise}_{ADU}{}^2)}.$$

The units will be electrons per ADU, which will be inversely proportional to the *voltage* gain of the system.

# Photon Transfer Method

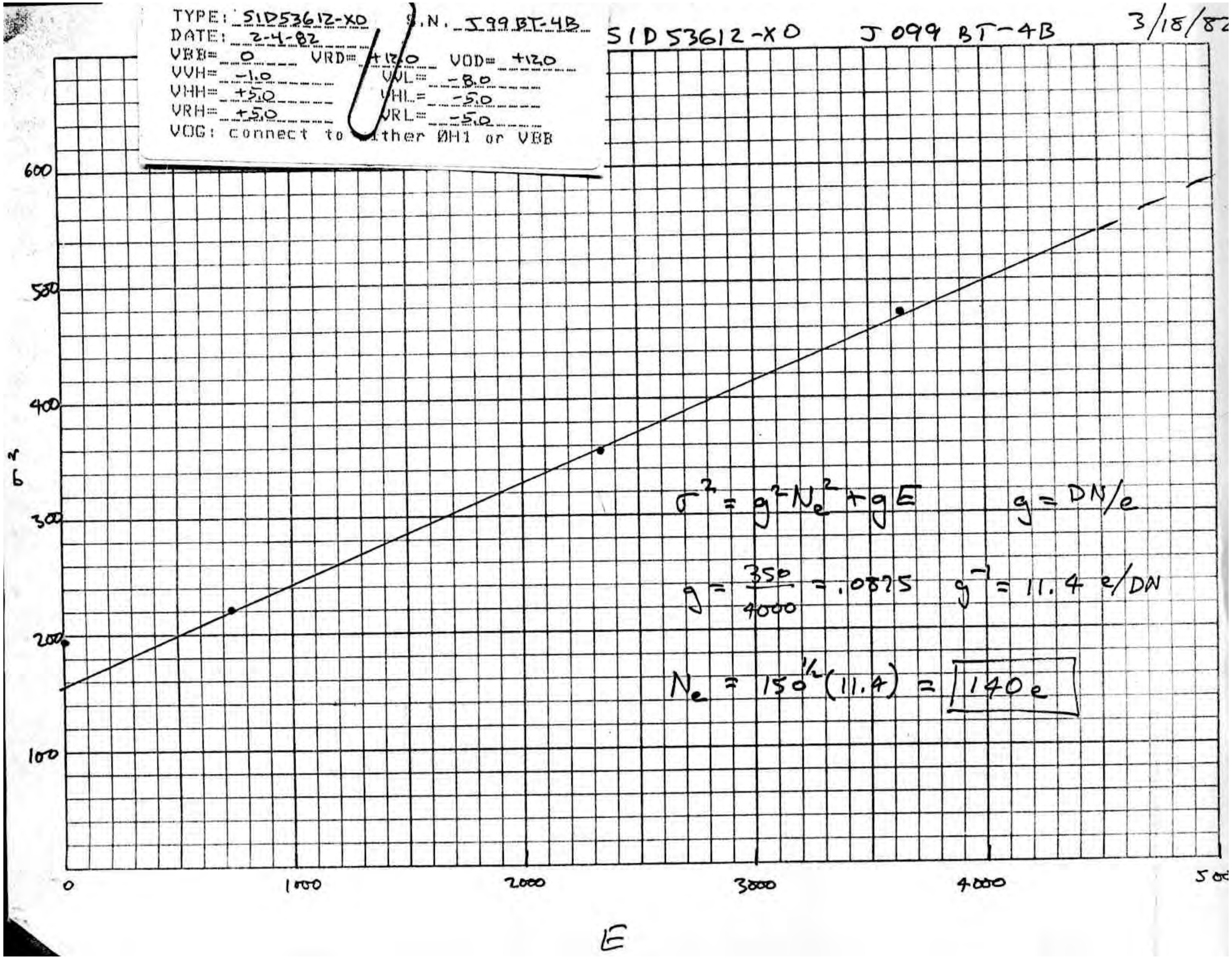
**STEP 6** The Readout noise is then calculated using this gain value :

$$\text{Readout Noise}_{\text{electrons}} = \text{Gain} \times \text{Noise}_{\text{ADU}}$$

## Precautions when using this method

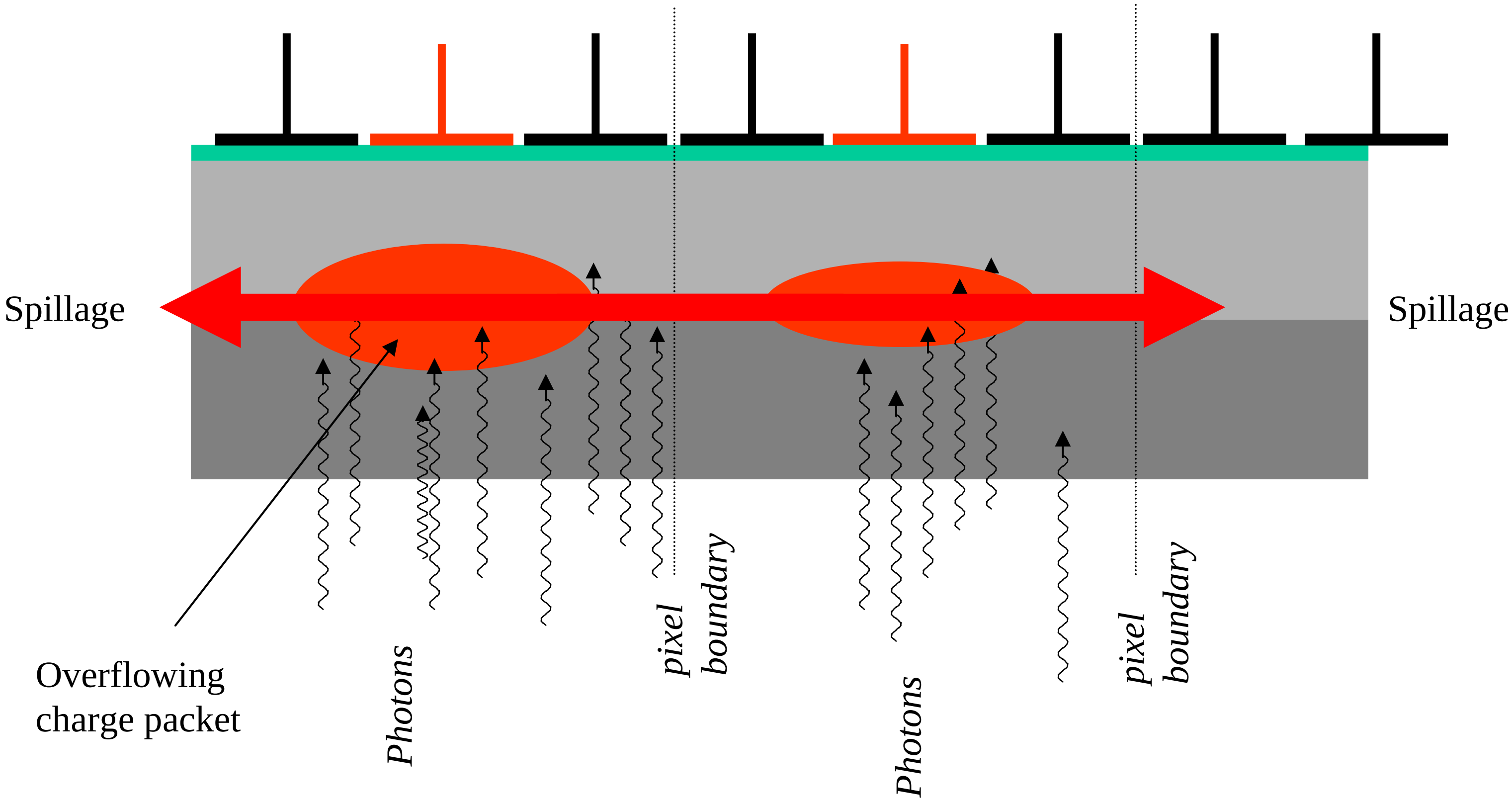
The exposure level in the two flat fields should be at least several thousand ADU but not so high that the chip or the processing electronics is saturated. 10,000 ADU would be ideal. It is best to average the gain values obtained from several pairs of flat fields. Alternatively the calculations can be calculated on several sub-regions of a single image pair. If the illumination of the flat fields is not particularly flat and the signal level varies appreciably across the sub-region on which the statistics are performed, this method can fail.

# Since 1982 the read noise of CCDs has decreased by a factor of 100



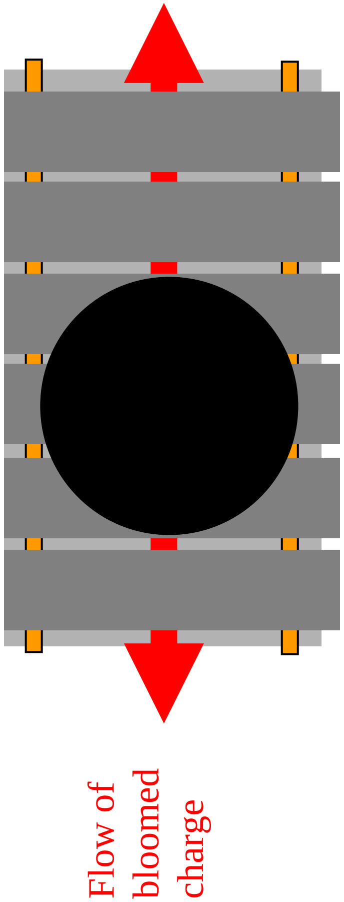
# Blooming in a CCD

The charge capacity of a CCD pixel is limited, when a pixel is full the charge starts to leak into adjacent pixels along a column. This process is known as 'Blooming'.



# Blooming in a CCD

The diagram shows one column of a CCD with an over-exposed stellar image focused on one pixel.



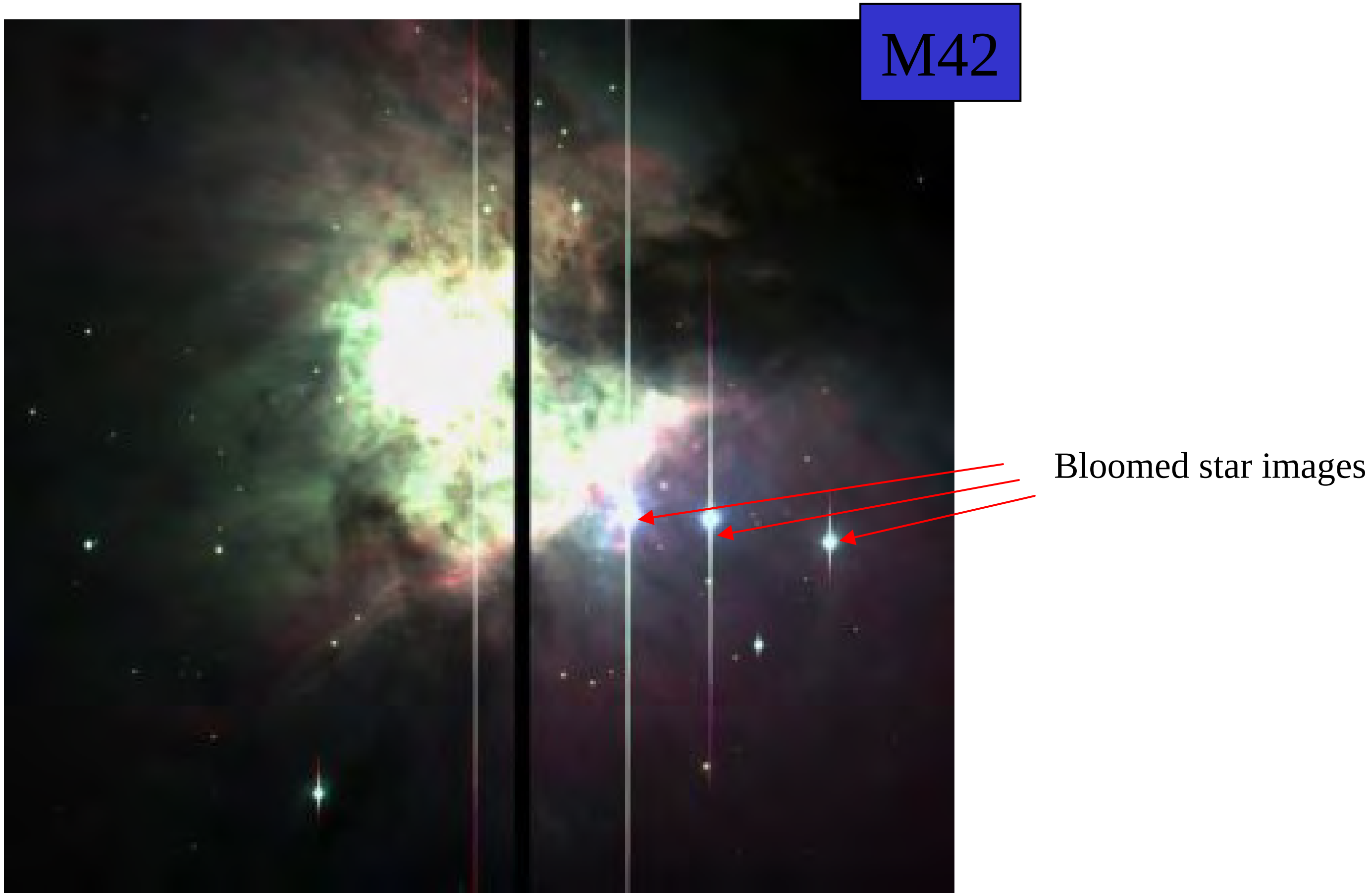

The channel stops shown in yellow prevent the charge spreading sideways along a row. The charge confinement provided by the electrodes is less so the charge spreads vertically up and down a column.

The capacity of a CCD pixel is known as the 'Full Well'. It is dependent on the physical area of the pixel. For pixels measuring 20μm x 20μm it can be as much as 300,000 electrons. Bloomed images will be seen particularly on nights of good seeing where stellar images are more compact .

In reality, blooming is not a big problem for professional astronomy.

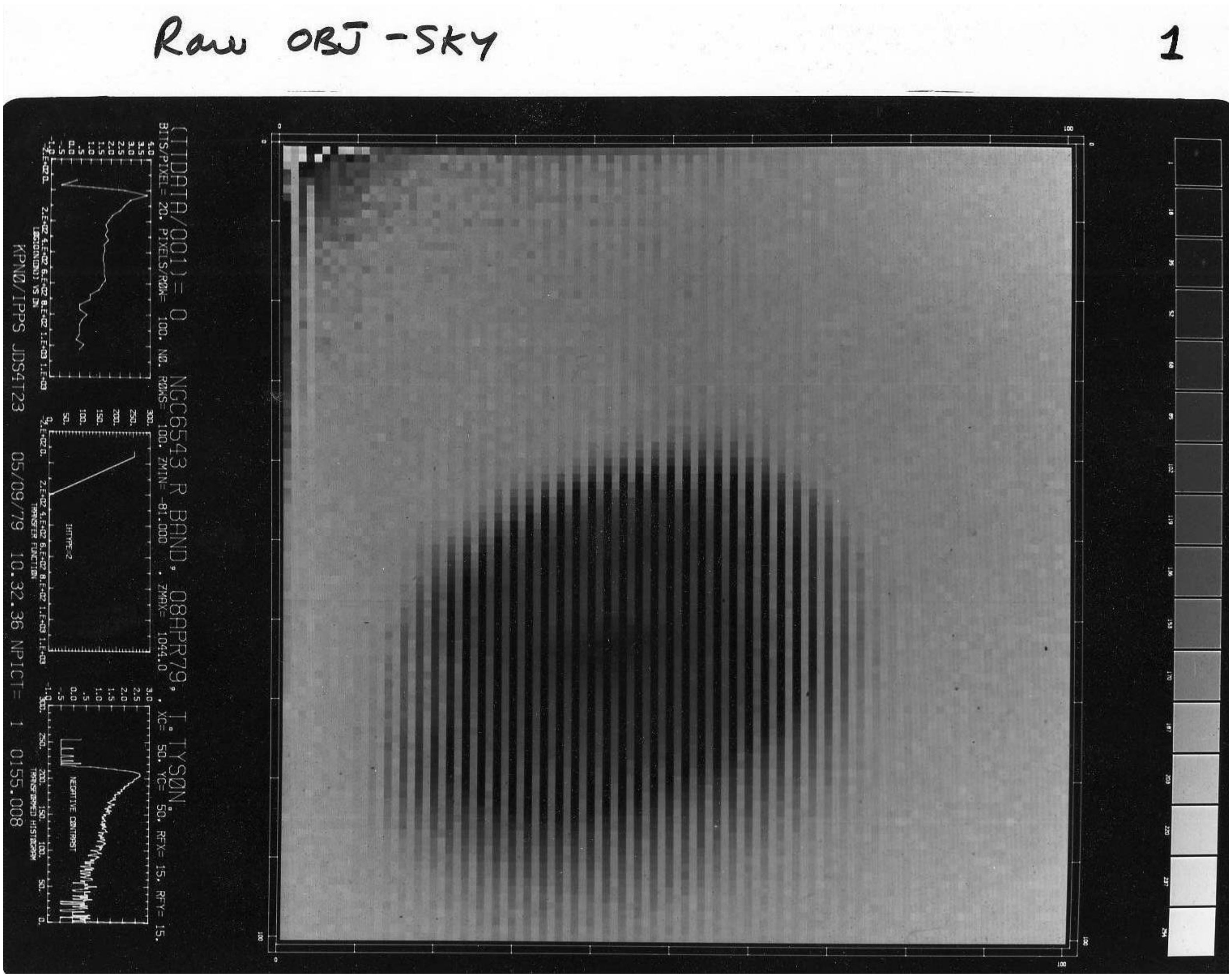
# Blooming in a CCD

The image below shows an extended source with bright embedded stars. Due to the long exposure required to bring out the nebulosity, the stellar images are highly overexposed and create bloomed images.




(The image is from a CCD mosaic and the black strip down the center is the space between adjacent detectors)

Modest beginnings: The first imaging CCD had large gain and CTE variations



# Image Defects in a CCD

Unless one pays a huge amount it is generally difficult to obtain a CCD free of image defects. The first kind of defect is a ‘dark column’. Their locations are identified from flat field exposures.

Flat field exposure of an EEV42-80 CCD

Dark columns are caused by ‘traps’ that block the vertical transfer of charge during image readout. The CCD shown at left has at least 7 dark columns, some grouped together in adjacent clusters.

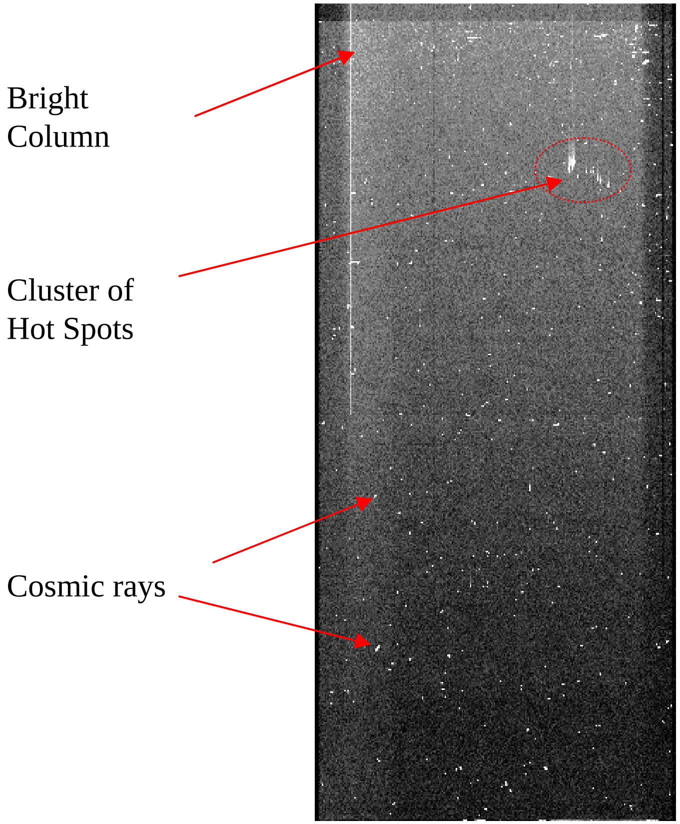
Traps can be caused by crystal boundaries in the silicon of the CCD, impurities, or by manufacturing defects.

Although they spoil the chip cosmetically, dark columns are not a big problem for astronomers. This chip has 2048 image columns so 7 bad columns represents a tiny loss of data.

**CHARGE TRANSFER EFFICIENCY (CTE):**
A related systematic error is the tendency at low light levels for incomplete charge transfer. CTE of 0.999995 per pixel transfer is common at high levels, but at low levels traps can cause many small dark columns.

# Image Defects in a CCD

There are three other common image defect types : Cosmic rays, Bright columns and Hot Spots.
Their locations are shown in the image below which is a lengthy exposure taken in the dark (a ‘Dark Frame’)




900s dark exposure of an EEV42-80 CCD

Bright columns are also caused by traps . Electrons contained in such traps can leak out during readout causing a vertical streak.

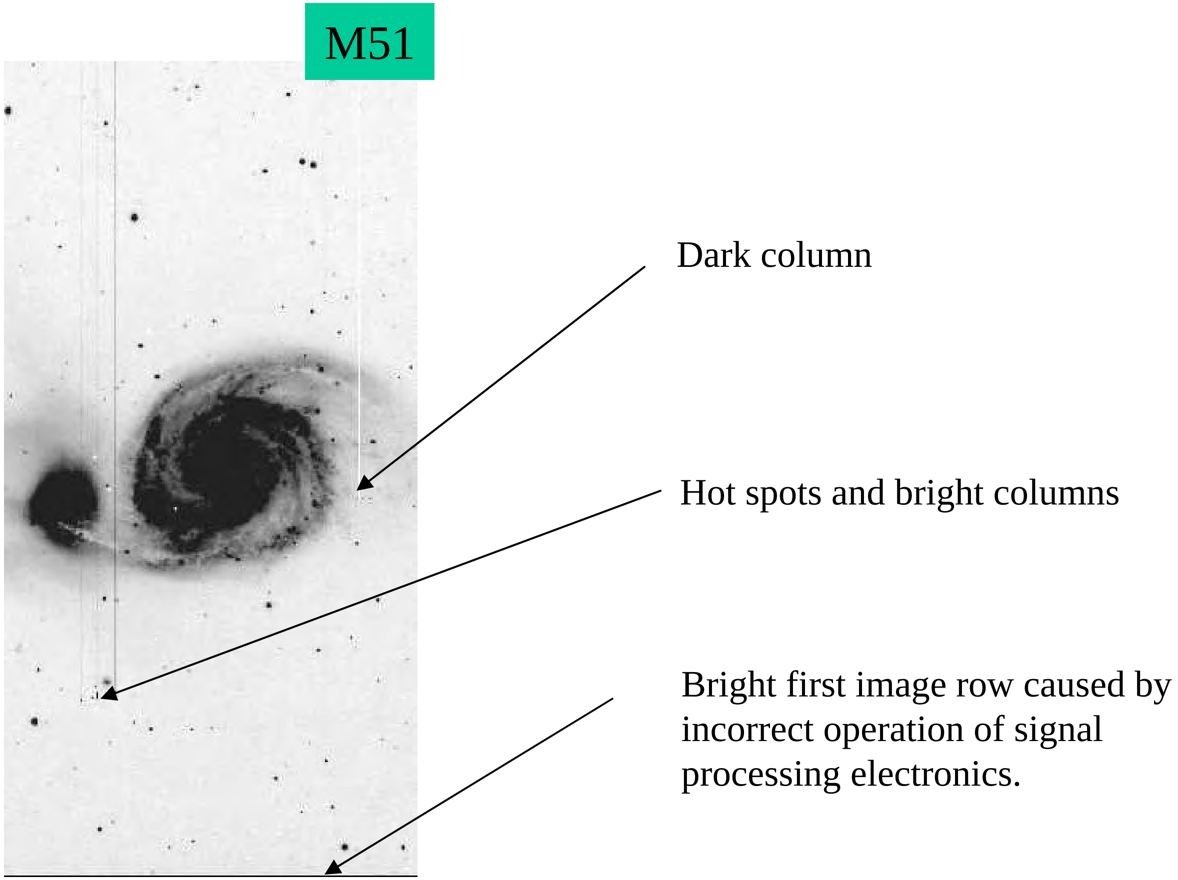
Hot Spots are pixels with higher than normal dark current. Their brightness increases linearly with exposure times

Cosmic rays are unavoidable. Charged particles from space or from radioactive traces in the material of the camera can cause ionization in the silicon. The electrons produced are indistinguishable from photo-generated electrons. Approximately 2 cosmic rays per $cm^2$ per minute will be seen. A typical event will be spread over a few adjacent pixels and contain several thousand electrons. But most are still more compact than the stellar point-spread function.

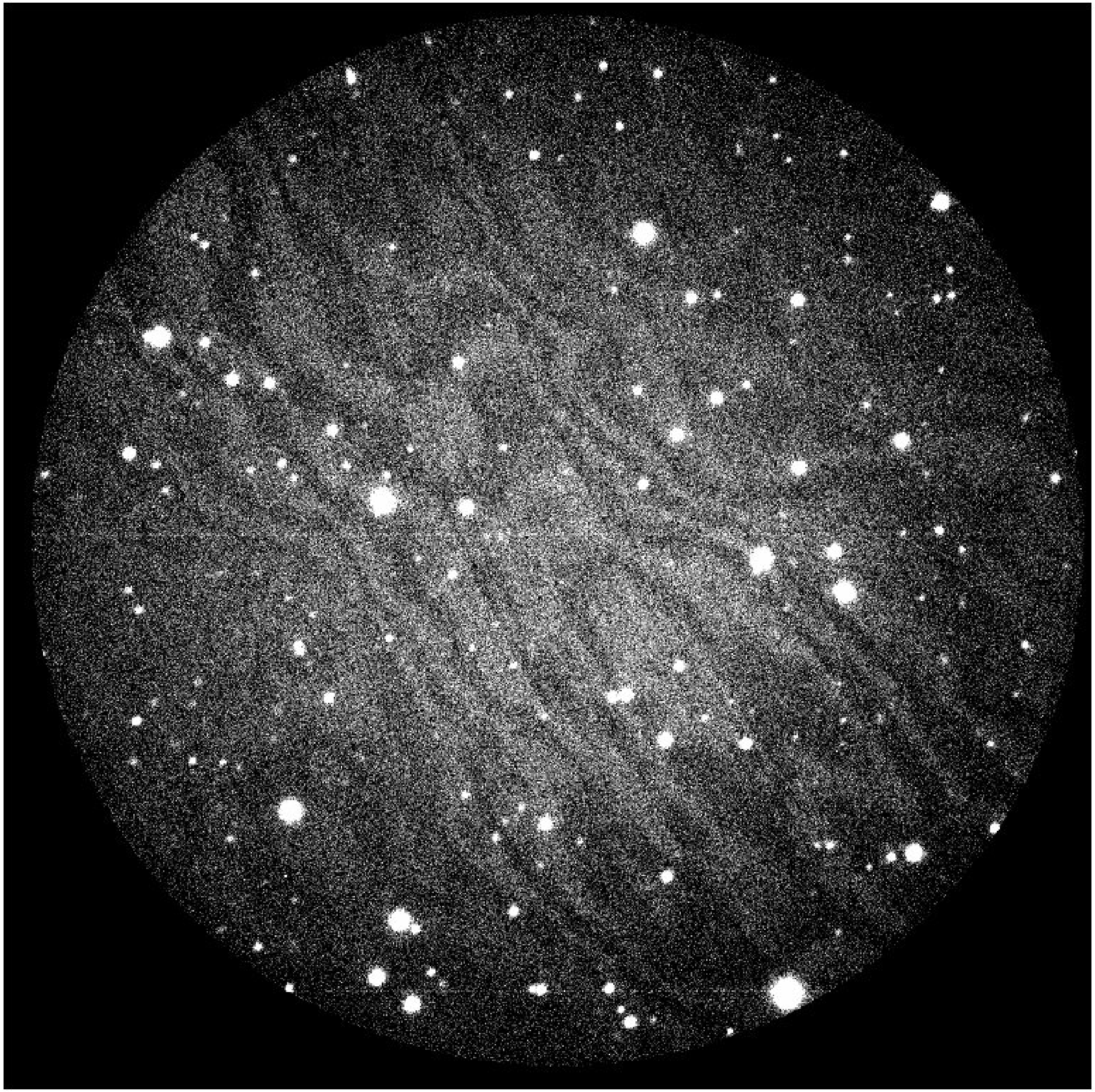
Somewhat rarer are light-emitting defects which are hot spots that act as tiny LEDS and cause a halo of light on the chip.

# Image Defects in a CCD

Some defects can arise from the processing electronics. This negative image has a bright line in the first image row.

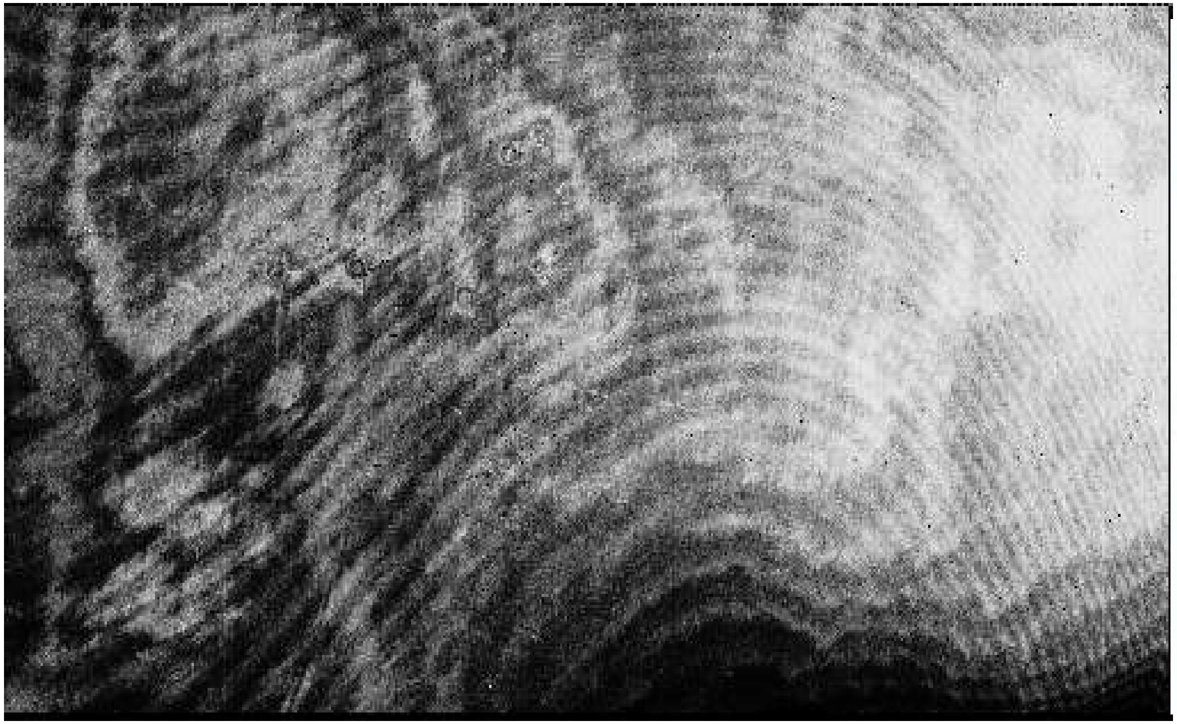


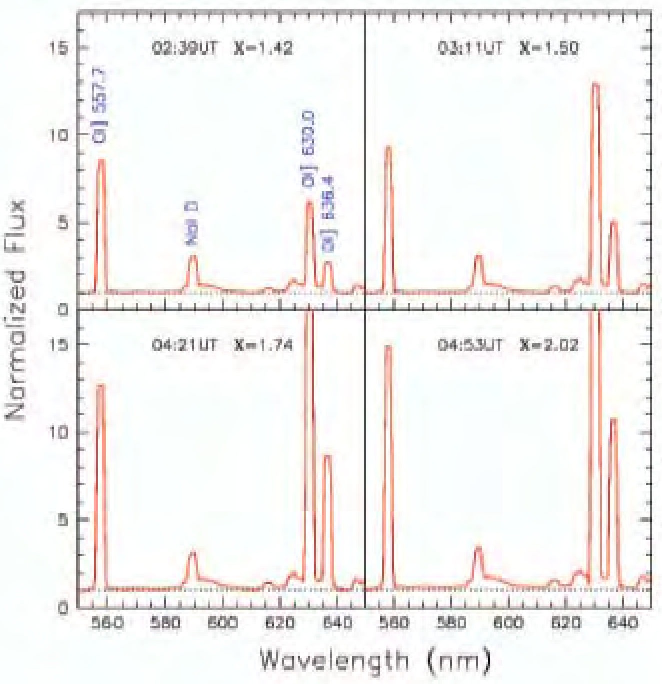
# Fringing in a CCD



# Fringing plus silicon growth rings

Fringing (additive systematic) and QE variations (multiplicative systematic) are corrected by separate sequential subtraction and division operations.





# Biases, Flat Fields and Dark Frames

These are three types of calibration exposures that must be taken with a scientific CCD camera, generally before and after each observing session. They are stored alongside the science images and combined with them during image processing. These calibration exposures allow us to compensate for imperfections in the CCD. As much care needs to be exercised in obtaining these images as for the actual scientific exposures. Applying low quality flat fields and bias frames to scientific data can degrade rather than improve its quality.

## Bias Frames

A bias frame is an exposure of zero duration taken with the camera shutter closed. It represents the zero point or base-line signal from the CCD. Rather than being completely flat and featureless the bias frame may contain some structure. Any bright image defects in the CCD will of course show up, there may be also slight gradients in the image caused by limitations in the signal processing electronics of the camera.
It is normal to take about 20 bias frames before a night's observing. These are then combined using an image processing algorithm that averages the images, pixel by pixel, rejecting any pixel values that are appreciably different from the other 19. This can happen if a pixel in one bias frame is affected by a cosmic ray event. It is unlikely that the same pixel in the other 19 frames would be similarly affected so the resultant 'master bias', should be uncontaminated by cosmic rays. Taking a number of biases and then averaging them also reduces the amount of noise in the bias images. Averaging 25 frames will reduce the amount of read noise (electronic noise from the CCD amplifier) in the image by a factor of 5.

# Biases, Flat Fields and Dark Frames

## Flat Fields

Some pixels in a CCD will be more sensitive than others. In addition there may be dust spots on the surface of either the chip, the window of the camera or the colored filters mounted in front of the camera. A star focused onto one part of a chip may therefore produce a lower signal than it might do elsewhere. These variations in sensitivity across the surface of the CCD must be calibrated out or they will add noise to the image. The way to do this is to take a ‘flat-field ‘ image : an image in which the CCD is evenly illuminated with light. Dividing the science image, pixel by pixel, by a flat field image will remove these sensitivity variations very effectively.

Since some of these variations are caused by shadowing from dust spots, it is important that the flat fields are taken shortly before or after the science exposures; the dust may move around! As with biases, it is normal to take many flat field frames and average them to produce a ‘Master’.

A flat field is taken by pointing the telescope at an extended, evenly illuminated source. The twilight sky or the inside of the telescope dome are the usual poor choices. An exposure time is chosen that gives pixel values about halfway to their saturation level i.e. a medium level exposure. But beware of non-linearity.

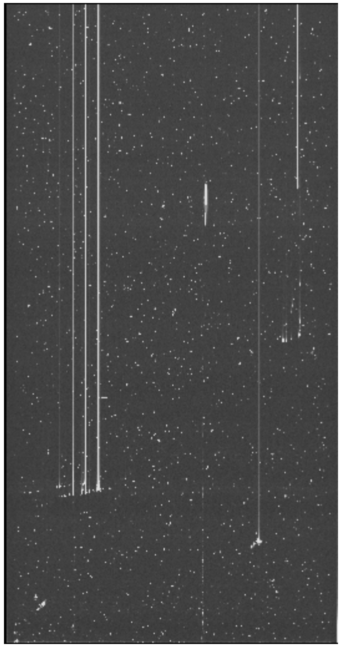
## Dark Frames.

Dark current is generally low or absent from professional CCD cameras since they are operated cold using liquid nitrogen as a coolant. Generally it is worth taking a few ‘dark frames’ at the beginning of the observing run. These are exposures with the same duration as the science frames but taken with the camera shutter closed. These are later subtracted from the science frames. Again, it is normal to take several dark frames and combine them to form a Master, using a technique that rejects cosmic ray features.

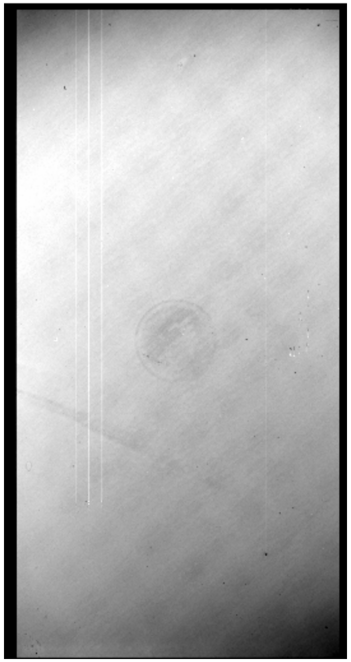
# Biases, Flat Fields and Dark Frames

A dark frame and a flat field from the same CCD are shown below. The dark frame shows a number of bright defects on the chip. The flat field shows a criss-cross patterning on the chip created during manufacture and a slight loss of sensitivity in two corners of the image. Some dust spots are also visible.

Dark Frame

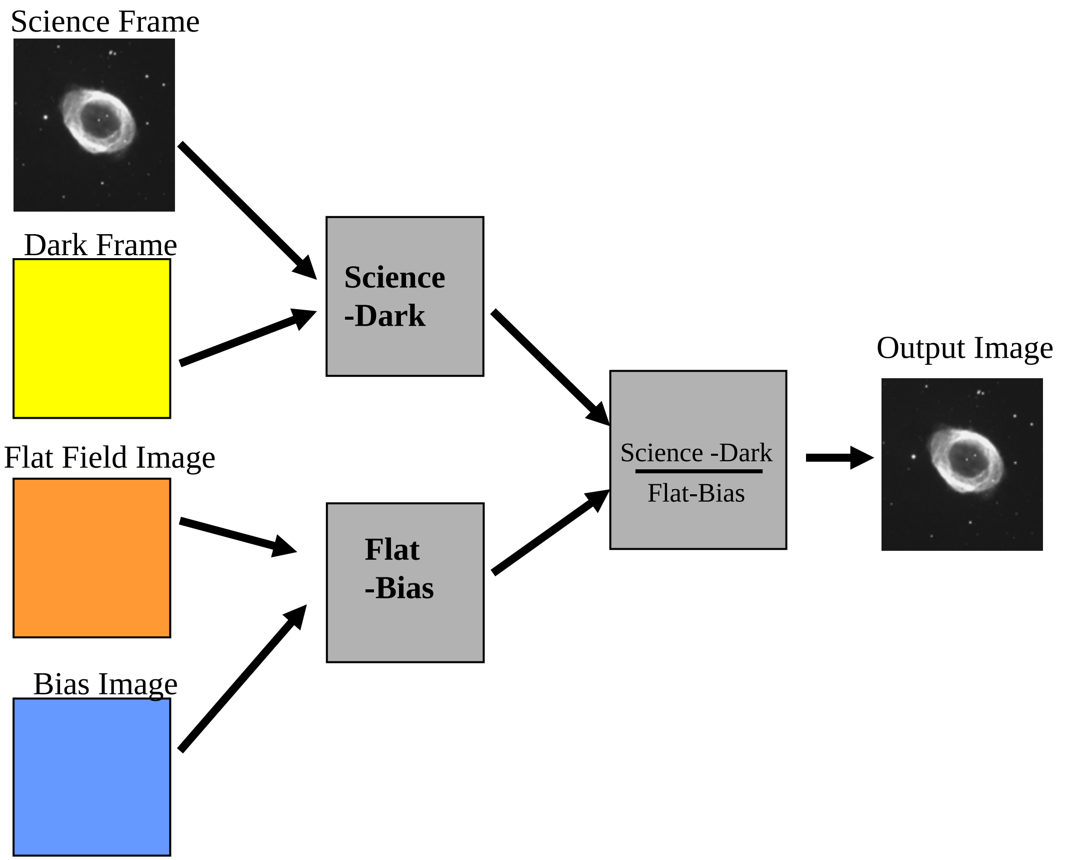


Flat Field



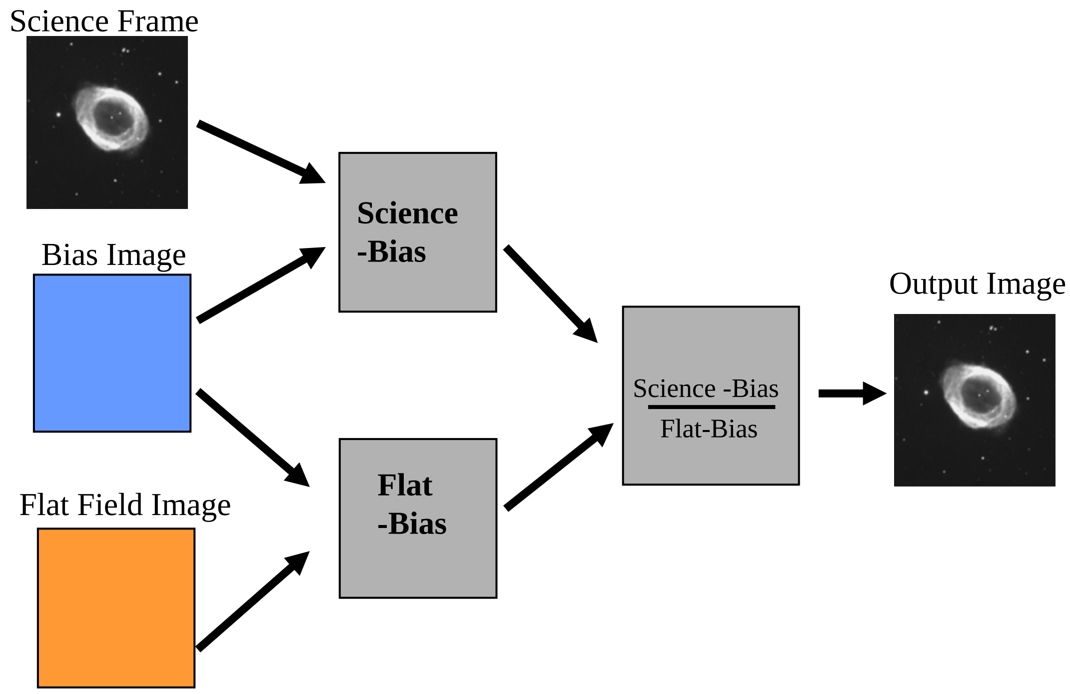
# Biases, Flat Fields and Dark Frames

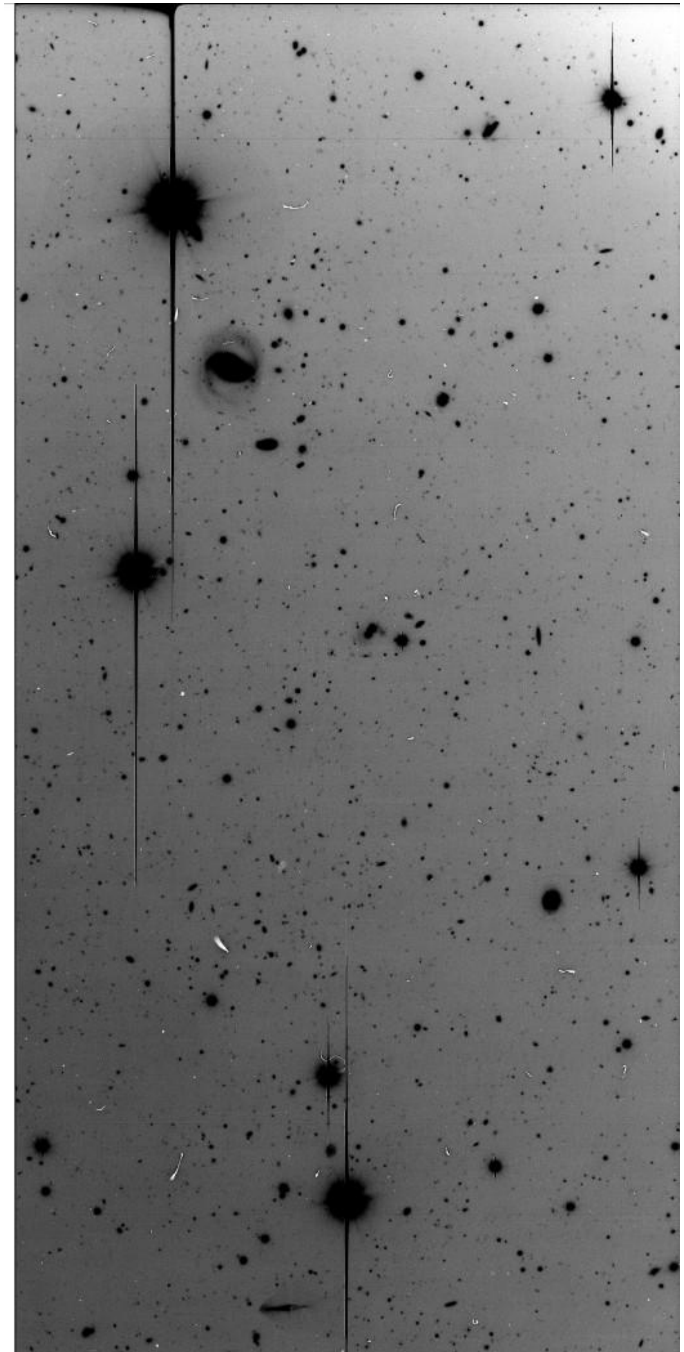
If there is significant dark current present, the various calibration and science frames are combined by the following series of subtractions and divisions :



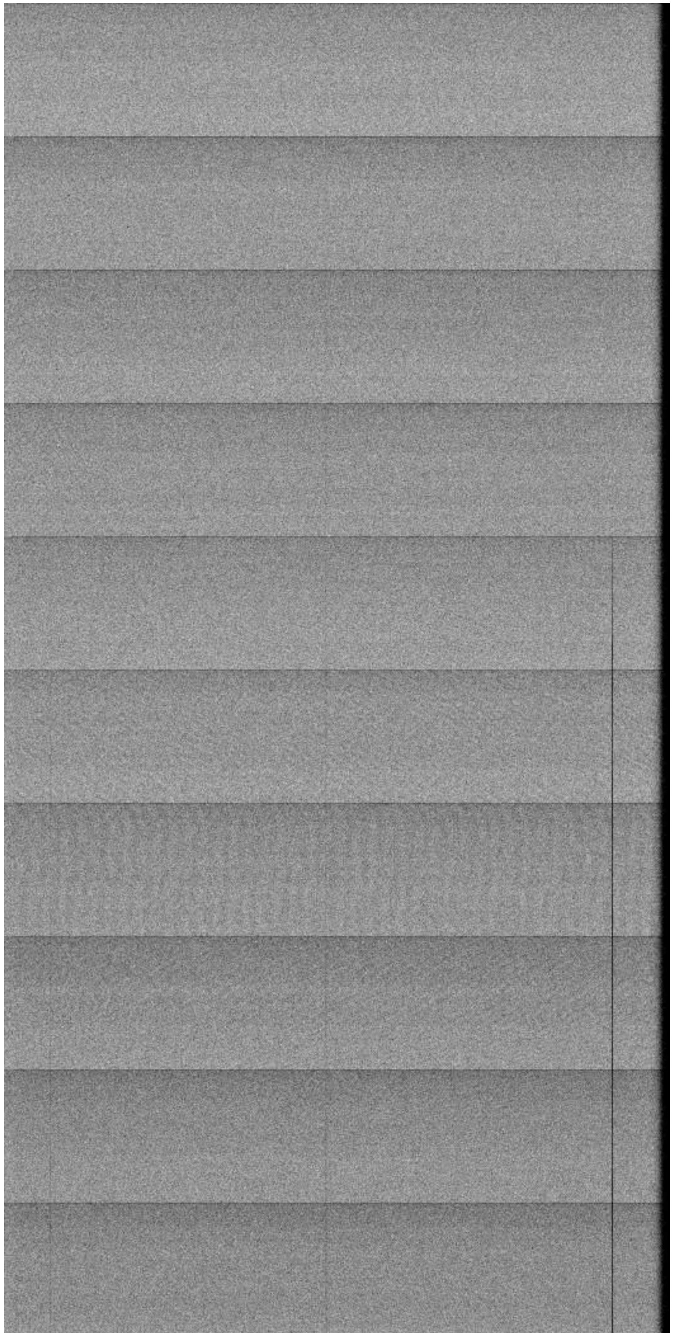
# Flat Fielding

In the absence of dark current, the process is slightly simpler :

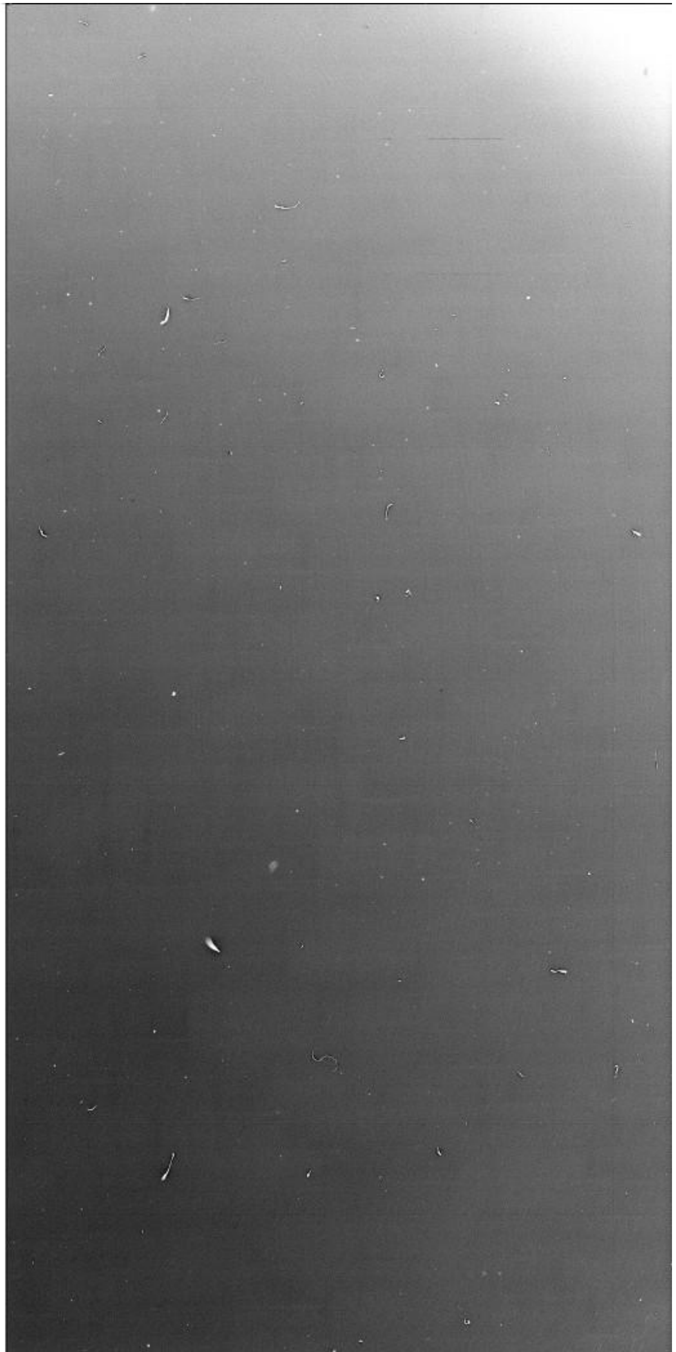




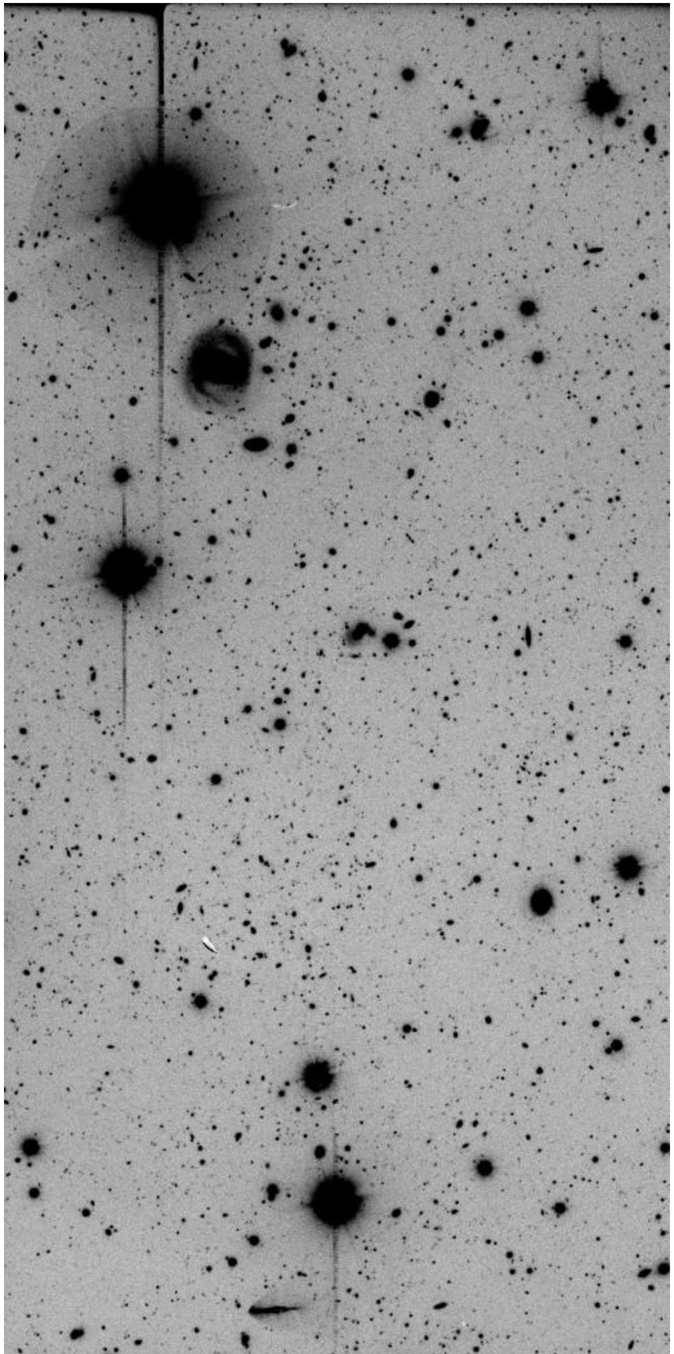
Raw



Bias



Raw Dome Flat



Dome Flat corrected

# Pixel Size and Binning

## Nyquist Sampling

It is important to match the size of a CCD pixel to the focal length of the telescope. Atmospheric seeing places a limit on the sharpness of an astronomical image for telescope apertures above 15cm. Below this aperture, the images will be limited by diffraction effects in the optics. In excellent seeing conditions, a large telescope can produce stellar images with a diameter of 0.4 arc-seconds. In order to record all the information present in such an image, two pixels must fit across the stellar image; the pixels must subtend at most 0.2 arc-seconds on the sky. This is the ‘Nyquist criteria’. If the pixels are larger than 0.2 arc-seconds the Nyquist criteria is not met, the image is under-sampled and information is lost. The Nyquist criteria also applies to the digitization of audio waveforms. The audio bandwidth extends up to 50KHz , so the Analog to Digital Conversion rate needs to exceed 100KHz for full reproduction of the waveform. Exceeding the Nyquist criteria leads to ‘over-sampling’.This has the disadvantage of wasting silicon area; with improved matching of detector and optics a larger area of sky could be imaged.

Under-sampling an image can produce aliasing effects.

# Pixel Size and Telescope

## Matching the Pixels to the telescope

**Example**

The Blanco Telescope, with a 4m diameter primary mirror and a focal ratio of 2.7 is to be used for prime focus imaging. What is the optimum pixel size assuming that the best seeing at the telescope site is 0.7 arc-seconds ?

First we calculate the 'plate-scale' in arc-seconds per millimeter at the focal plane of the telescope.

$$\text{Plate Scale (arc-seconds per mm)} = \frac{206265}{\text{Aperture in mm } \mathbf{X} \text{ f-number}} = 19.1 \text{ arc-sec per mm}$$

(here the factor 206265 is the number of arc-seconds in a Radian )

Next we calculate the linear size at the telescope focal plane of a stellar image (in best seeing conditions)

Linear size of stellar image = 0.7 arcsec / Plate Scale = 0.7/ 19.1 = 37 microns.

To satisfy the Nyquist criteria, the maximum pixel size is therefore 18 microns. In practice, the nearest pixel size available is 15 microns which leads to a small degree of over-sampling.

# Controlling the CCD Clocks

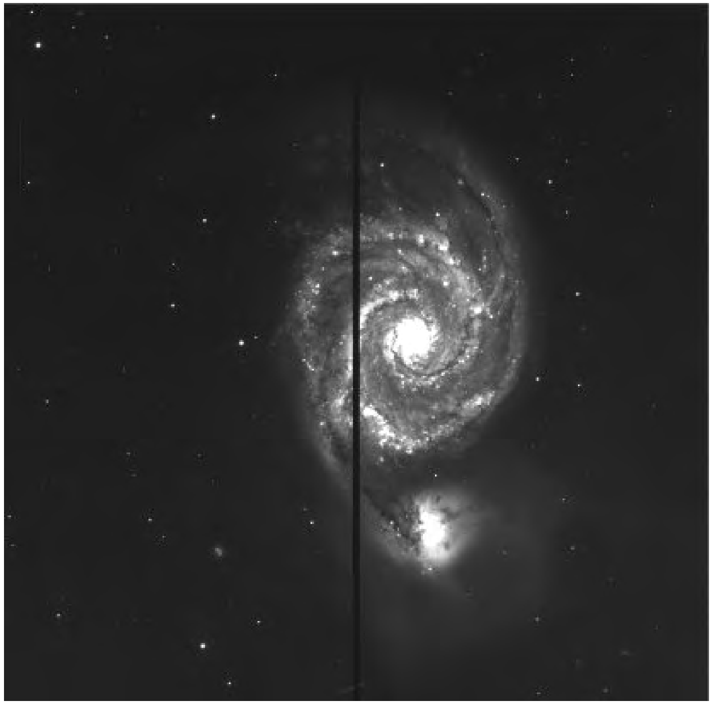
Computers are required firstly to coordinate the sequence of clock signals that need to be sent to a CCD and its signal processing electronics during the readout phase, but also for data collection and the subsequent processing of the images.

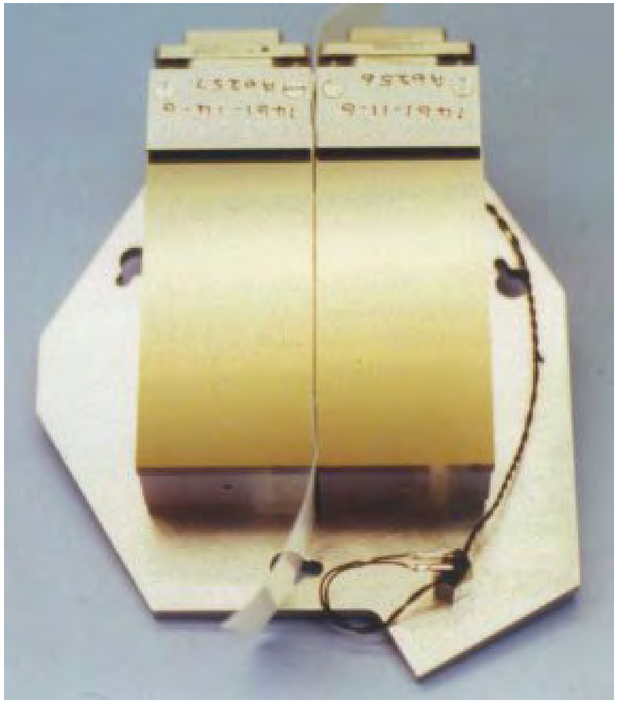
## The CCD Controller

In this first application, the computer is an embedded system running in a ‘CCD controller’. This controller will typically contain a low noise analog section for amplification and filtering of the CCD video waveform, an analog to digital converter, a high speed processor for clock waveform generation and a fibre optic transceiver for receipt of commands and transmission of pixel data.
An astronomical system might require clock signals to be generated with time resolutions of a few tens of nanoseconds. This is typically done using Digital Signal Processing (DSP) chips running at 50Mhz. Clock sequences are generated in software and output from the DSP by way of on-chip parallel ports. The most basic CCD design requires a minimum of 7 clock signals. Perhaps 5 more are required to coordinate the operation of the signal processing electronics. DSPs also contain several on-chip serial ports which can be used to transmit pixel data at very high rates. DSPs come with a small on-chip memory for the storage of waveform generation tables and software. Less time critical code , such as routines to initialise the camera and interpret commands can be stored in a few KB of external RAM. The computer running in the CCD controller is thus fast and of relatively simple design. A poorly performing processor here could result in slow read out times and poor use of telescope resources. Remember that when a CCD is reading out the telescope shutter is closed and no observations are possible.

# Mosaic Cameras

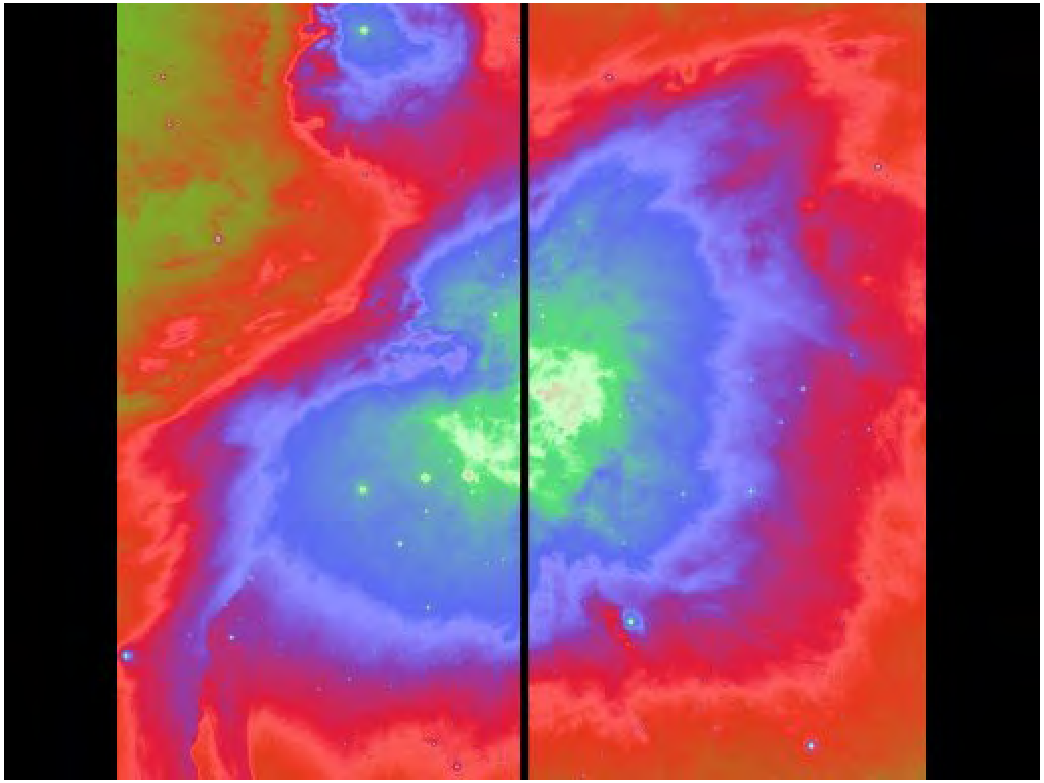
The pictures below show the galaxy M51 and the CCD mosaic that produced the image. Two EEV42-80 CCDs are screwed down onto a very flat Invar plate with a 50 micron gap between them. Light falling down this gap is obviously lost and causes the black strip down the centre of the image. This loss is not of great concern to astronomers, since it represents only 1% of the total data in the image.





# Mosaic Cameras

Another image from this camera is shown below. The object is M42 in Orion. This false color image covers an area of sky measuring 16’ x 16’.

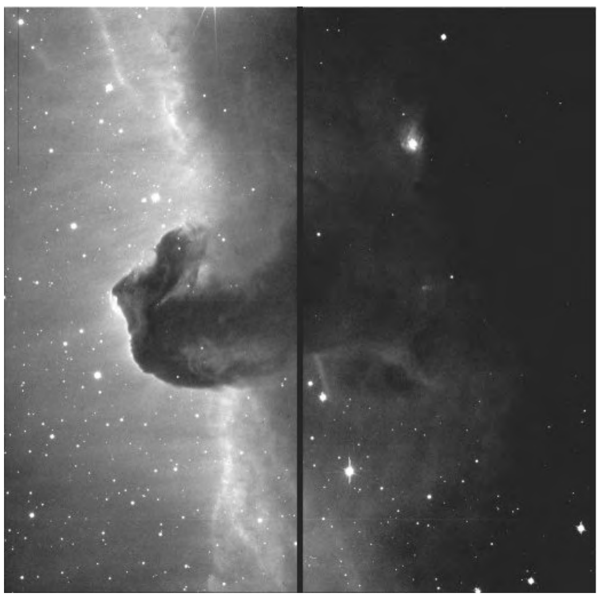


# Mosaic Cameras

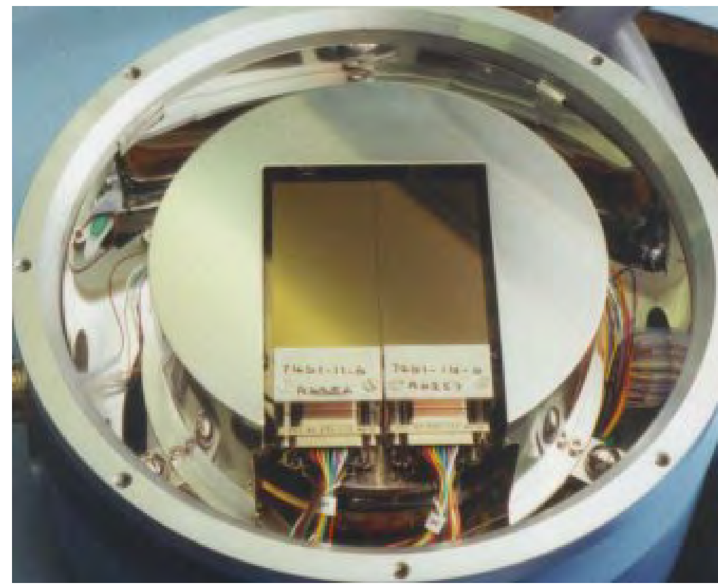
A further image is shown below, of the galaxy M33 in Triangulum. Images from this camera are enormous; each of the two chips measures 2048 x 4100 pixels. The original images occupy 32MB each.

# Mosaic Cameras

The Horsehead Nebula in Orion.

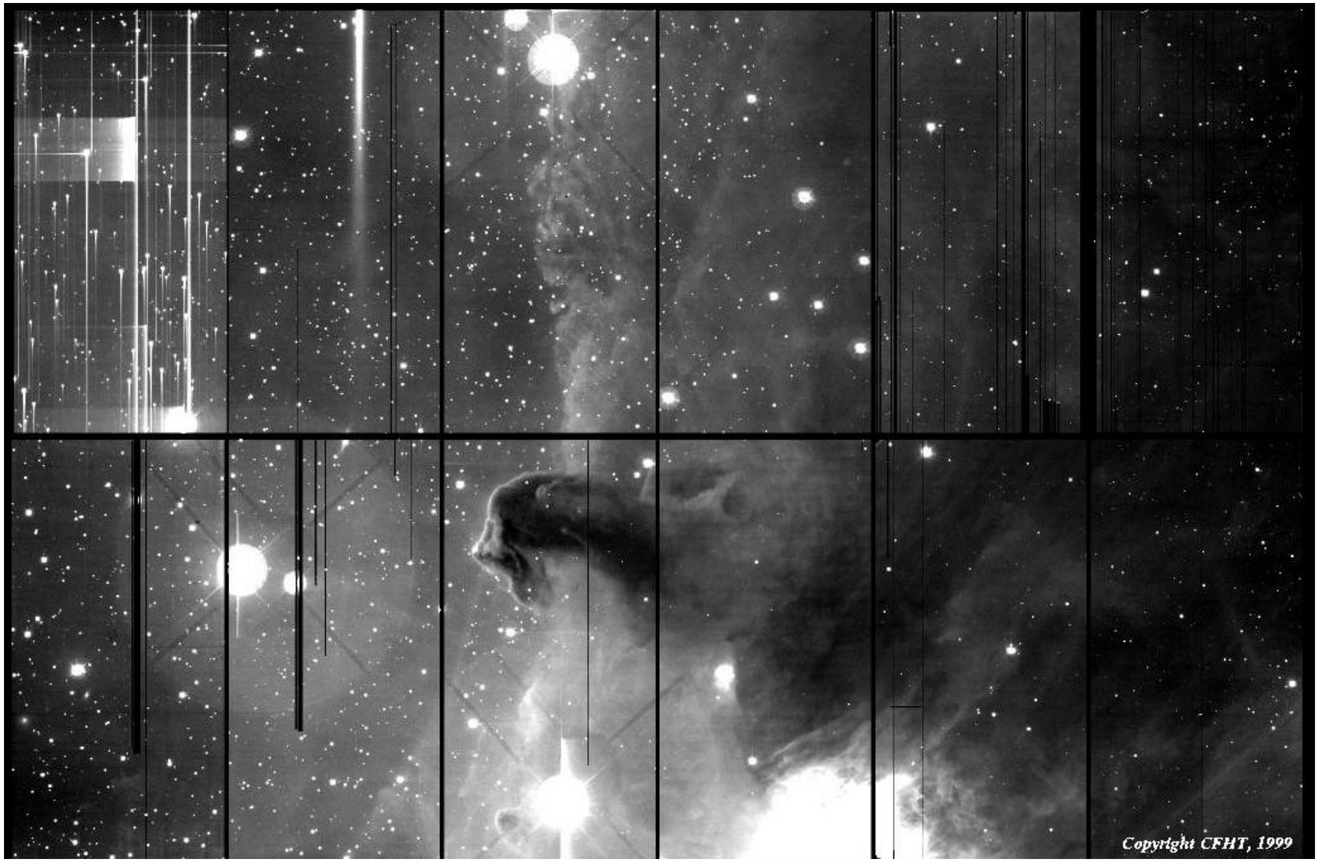


The mosaic mounted in its camera.



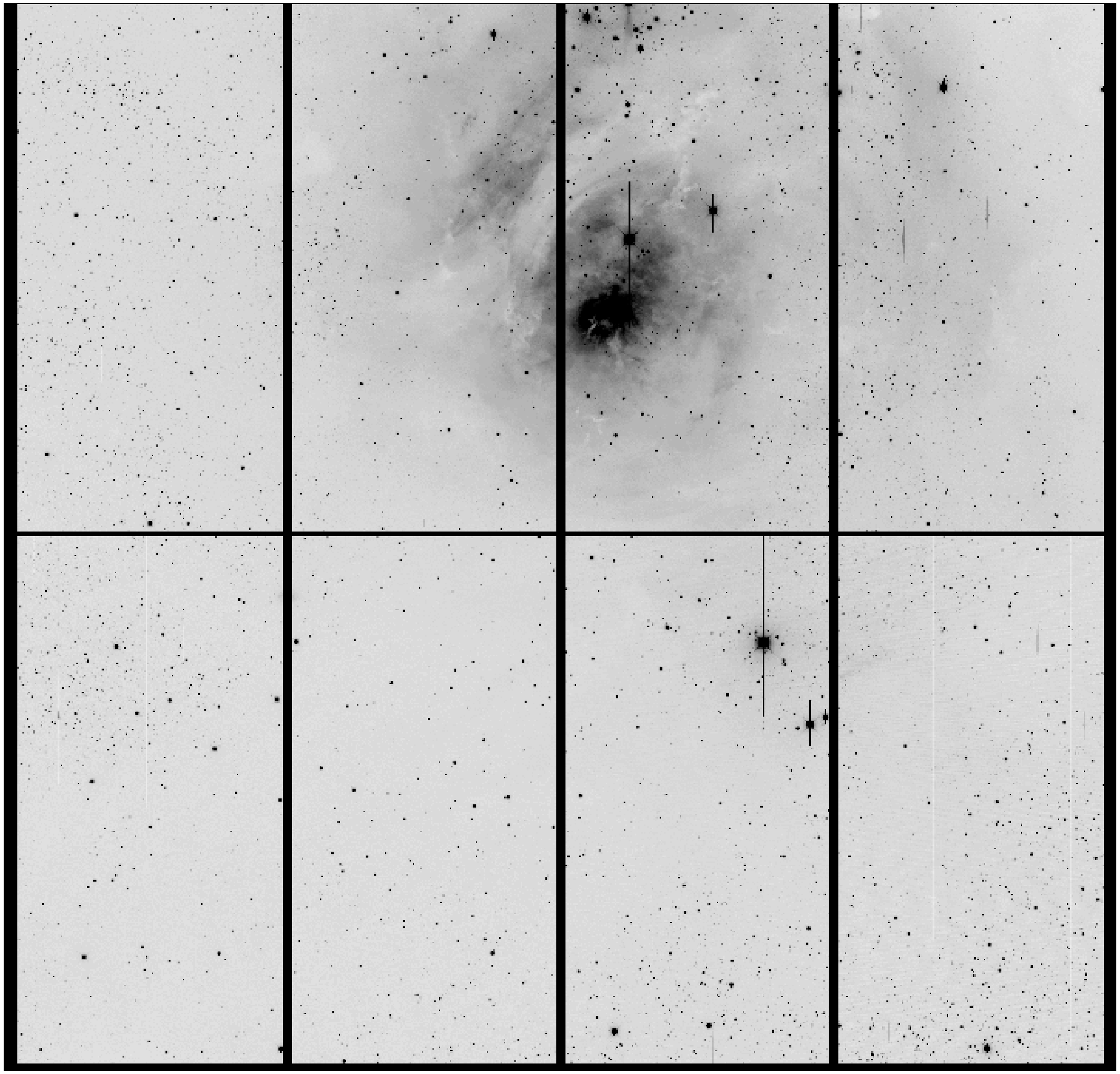
# Mosaic Cameras 6.

This mosaic of 12 CCDs is in operation at the CFHT in Hawaii. Here is an example of what it can produce. The chips are of fairly low cosmetic quality.



# Mosaic Cameras

This mosaic of 8 science CCDs was built for the NOAO 4-meter telescopes.



# Camera Construction Techniques

The main body of the camera is a 3mm thick aluminium pressure vessel able to support an internal vacuum. Most of the internal volume is occupied by a 2.5 liter copper can that holds liquid nitrogen (LN2). The internal surfaces of the pressure vessel and the external surfaces of the copper can are covered in aluminized mylar film to improve the thermal isolation. As the LN2 boils off , the gas exits through the same tube that is used for the initial fill

The CCD is mounted onto a copper cold block that is stood-off from the removable end plate by thermally insulating pillars. A flexible copper braid connects this block to the LN2 can. The thickness of the braid is adjusted so that the equilibrium temperature of the CCD is about 10 degrees below the optimum operating temperature. The mounting block also contains a heater resistor and a Platinum resistance thermometer that are used to servo the CCD temperature. Without using a heater resistor close to the chip for thermal regulation , the operating temperature and the CCD characteristics also, will vary with the ambient temperature.

The removable end plate seals with a synthetic rubber ‘o’ ring. In its center is a fused silica window big enough for the CCD and thick enough to withstand atmospheric pressure. The CCD is positioned a short distance behind the window and radiatively cools the window. To prevent condensation it is necessary to blow dry  air across the outside.

# Camera Construction Techniques

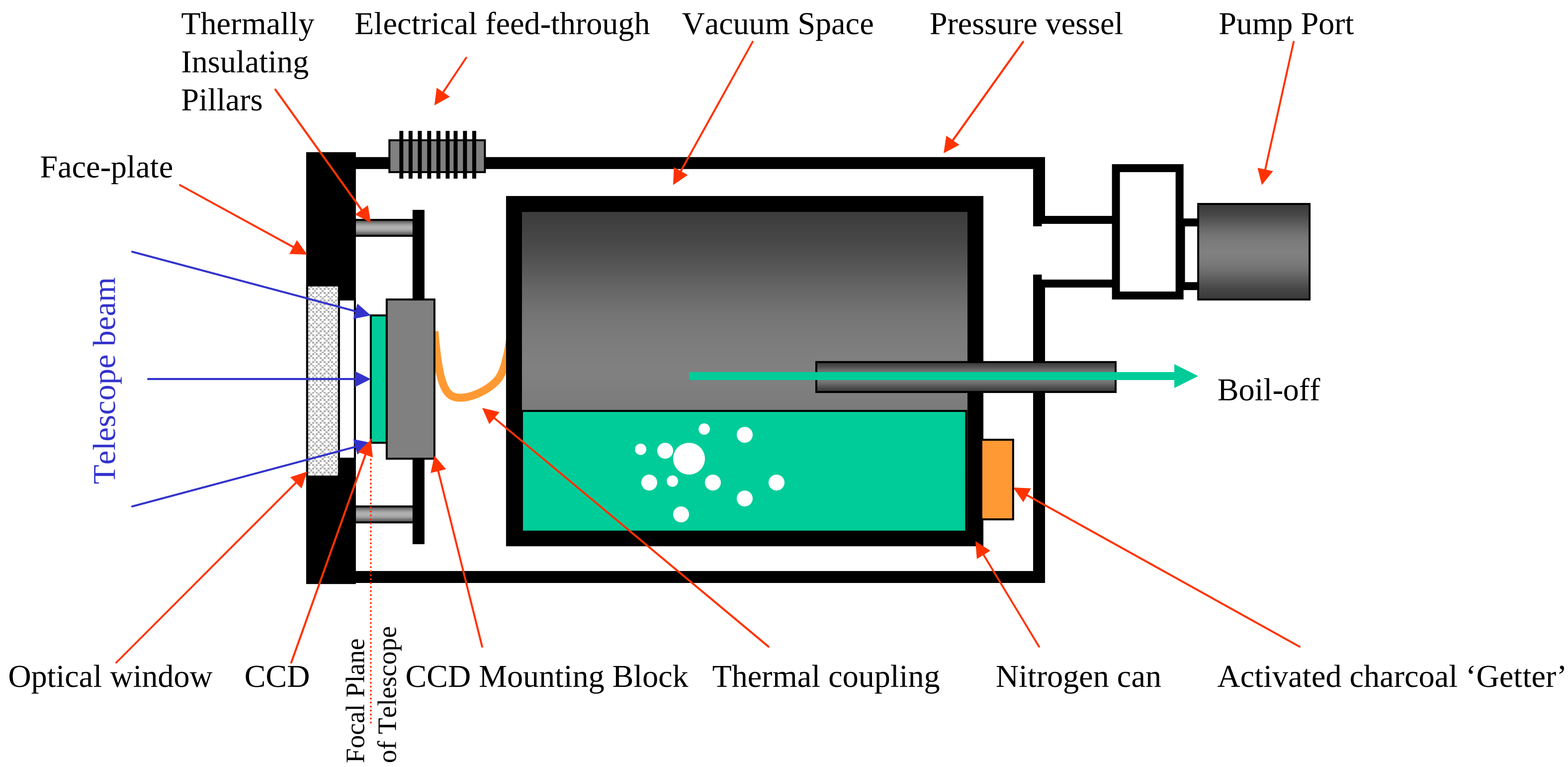
The basic structure of the camera is that of a Thermos flask. Its function is to protect the CCD in a cold clean vacuum. The thermal design is very important, so as to maximize the hold time and the time between LN2 fills. Maintenance of a good vacuum is also very important, firstly to improve the thermal isolation of the cold components but also to prevent contamination of the CCD surface. A cold CCD is very prone to contamination from volatile substances such as certain types of plastic. These out-gas into the vacuum spaces of the camera and then condense on the coldest surfaces. This is generally the LN2 can. On the back of the can is a small container filled with activated charcoal known as a 'Getter'. This acts as a sponge for any residual gases in the camera vacuum. The getter contains a heater to drive off the absorbed gases when the camera is being pumped.

This camera is vacuum pumped for several hours before it is cooled down. The pressure at the end of the pumping period is about $10^{-4}$ mBar. When the LN2 is introduced, the pressure will fall to about $10^{-6}$mBar as the residual gases condense out on the LN2 can.

When used in an orientation that allows this camera to be fully loaded with LN2, the boil off or 'hold time' is about 20 hours. The thermal energy absorbed by 1g of LN2 turning to vapor is 208J, the density of LN2 is 0.8g/cc. From this we can calculate that the heat load on the LN2 can, from radiation and conduction is about 6W.

# Camera Construction Techniques

A cutaway diagram of a typical camera is shown below.



# Camera Construction Techniques

The camera with the face-plate removed is shown below