3. Overview of optical detectors

(This section is mainly revision of material covered in the A1Y Observational course, so we will proceed fairly rapidly).

We will summarise the basic characteristics of:

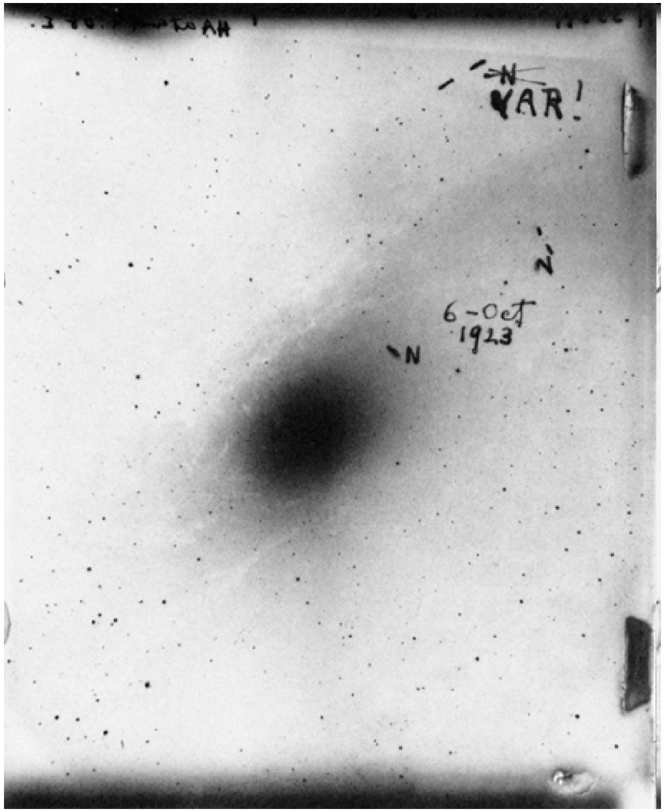
- photographic plates
- photomultipliers
- image Intensifiers
- charged coupled devices (CCDs)

This list is roughly chronological: i.e. photographic plates were the earliest detector technology to be developed; CCDs are the most recent.

3.1 Photographic plates

From the late 19th century until the late 20th century photographic plates were the usual optical detectors.

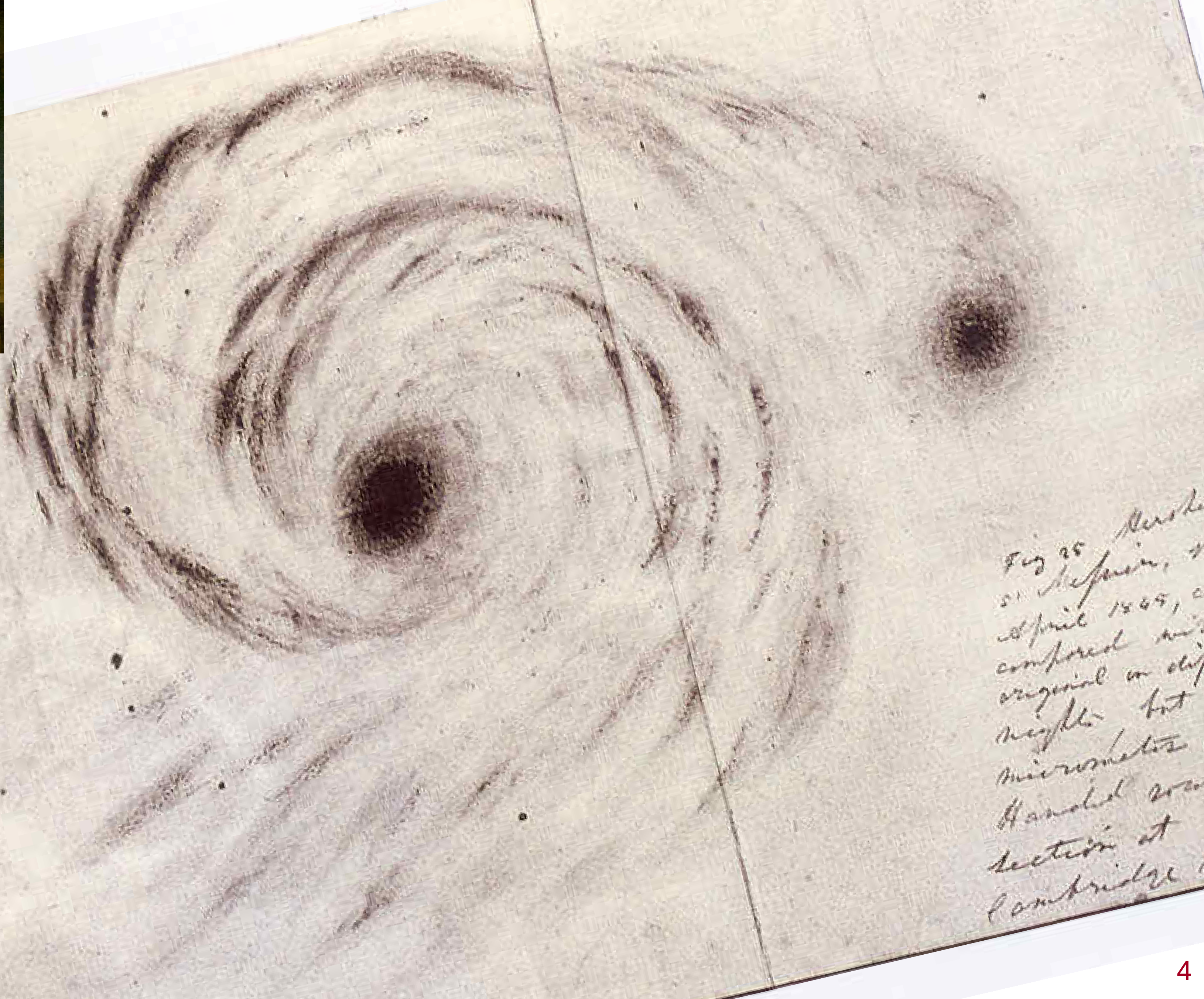
(prior to that astronomers had to be good artists!)



Hale Observatory

The Great Telescope (Birr Castle, Ireland, 1.8m)

William Parsons, Earl of Rosse



Whirlpool Galaxy (M51)

3.1 Photographic plates

From the late 19th century until the late 20th century photographic plates were the usual optical detectors.

(prior to that astronomers had to be good artists!)

A photographic plate is a thin emulsion of silver bromide crystals. The photographic process consists of:

1) exposure to radiation

This results in the chemical separation of Ag and Br

2) development

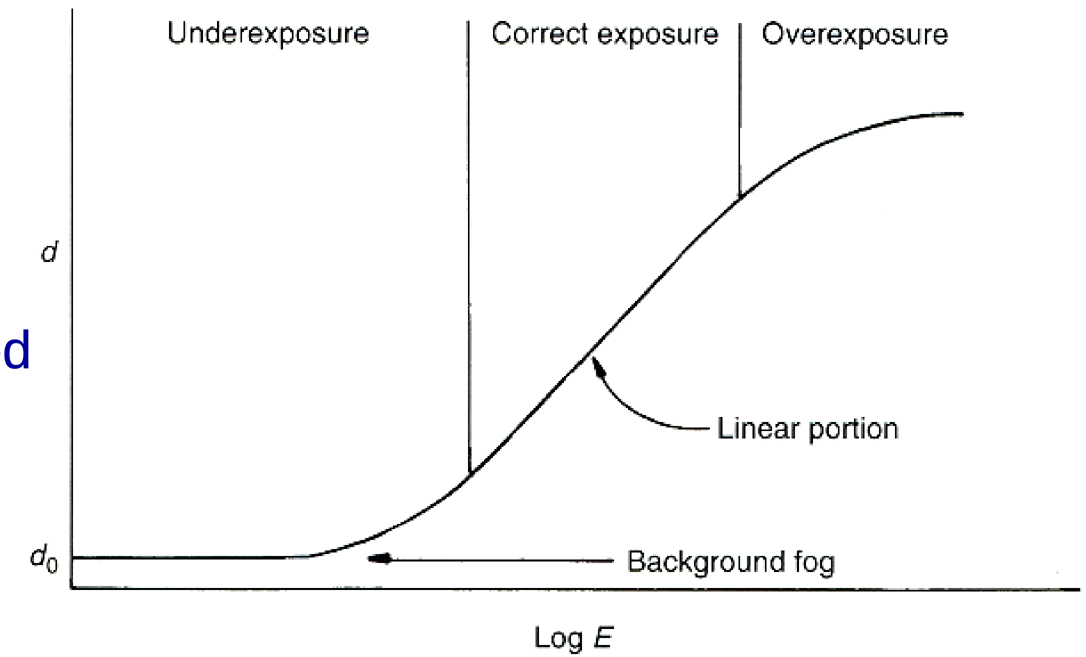
This enhances the separation process

3) fixing

This washes out the Br, leaving Ag grains, which make up the image.

3.1 Photographic plates

Characteristic curve of a photographic emulsion



- The exposure, *E*, is defined as the illumination, *J*, multiplied by the exposure time, *t*.

- The image strength is measured by the density, *d*, of Ag grains.

- For an underexposed image, *d* tends to a constant low background value (‘fog’).

- Over a short range of exposures the density increases linearly with the log of the exposure.

- For larger values of the exposure, the image saturates and the density no longer increases - no further information recorded.

48-inch Samuel Oschin Telescope -- a Schmidt telescope, for wide-field photographic surveys, including the Palomar Sky Survey.

Edwin Hubble is looking through a 10-inch refractor used for guiding.

3.1 Photographic plates

Weaknesses of photography:

- Low quantum efficiency (fraction of incident photons which produce a response) of ~ 0.001
- Non-linear response: the strength of image not proportional to number of photons
- Wavelength sensitivity is biased towards **blue** colours

Strengths of photography:

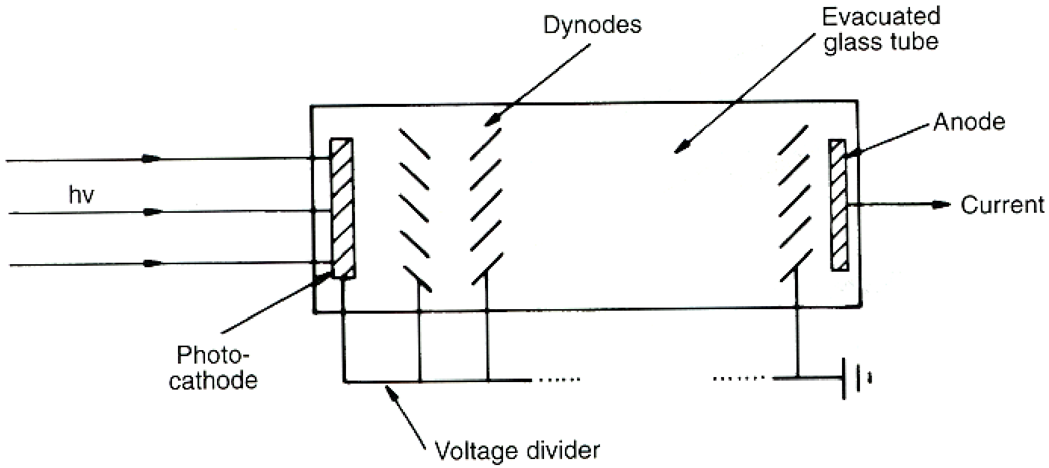
- Large area -- e.g. Schmidt camera plates (40 cm x 40 cm)
- Small 'pixel' (i.e. silver grain) size: ~ 10 μm

$\Rightarrow$ Schmidt plates have about 40000 x 40000 pixels.

But electronic detectors are catching up fast!

3.2 Photomultiplier tube

- Incident photon strikes a photocathode, held at a potential of ~ 1kV relative to the anode at the other end of a vacuum tube.



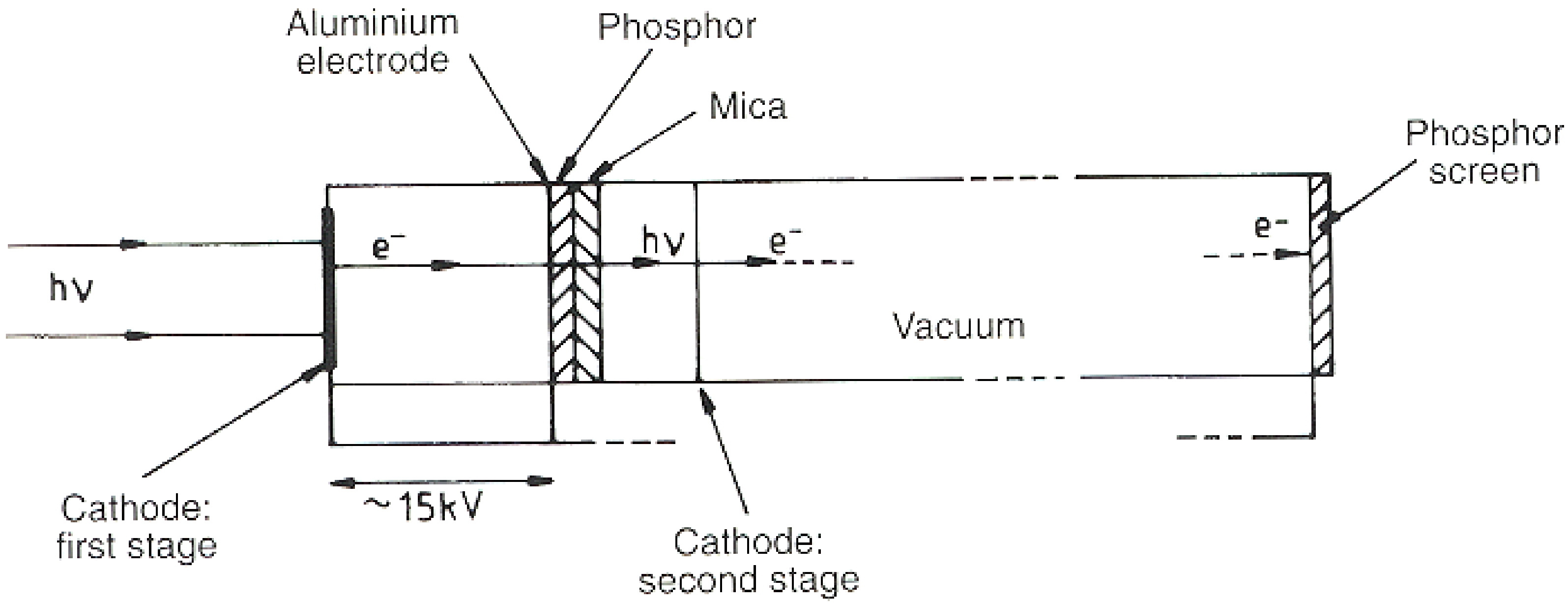
- The cathode and anode are separated by a series of dynodes at successively more positive potentials.
- Electrons emitted from cathode are accelerated towards first dynode, where they each have enough energy to release several more electrons.
- This is repeated at all dynodes and a cascade of electrons reaches the anode.
- Each initial electron produces a output pulse of up to 10^6 electrons.

Typical quantum efficiency ~ 10% but little directional information

$\Rightarrow$ poor imaging capability (just one pixel!).

Photomultiplier tube

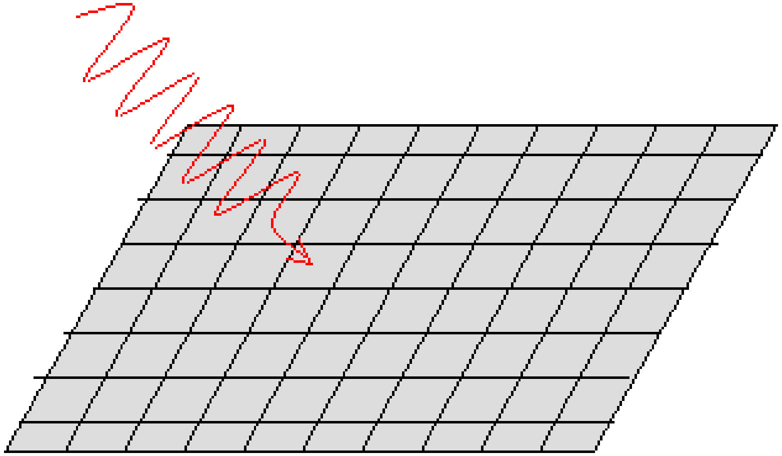
3.3 Image Intensifier



- Photoelectrons emitted from the first cathode are accelerated down the evacuated tube by a voltage difference of ~ 15 kV and strike a phosphor screen $\Rightarrow$ image
- The photons emitted from the phosphor strike a second cathode, and the process repeats – with the intensity of the image on the phosphor increasing at each stage. (The mica layer absorbs electrons not stopped in the phosphor).

Typical quantum efficiency is 20 – 30%

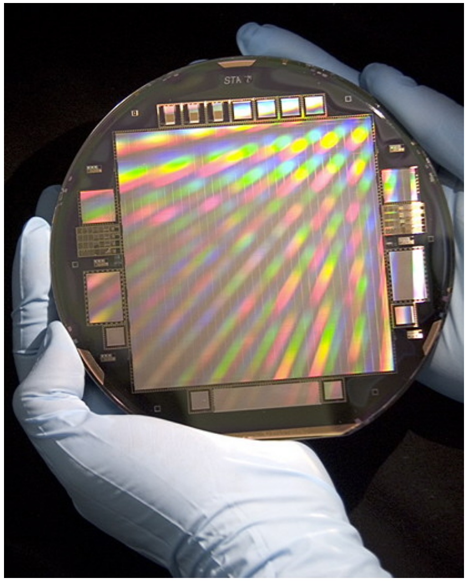
3.4 Charge Coupled Device (CCD)

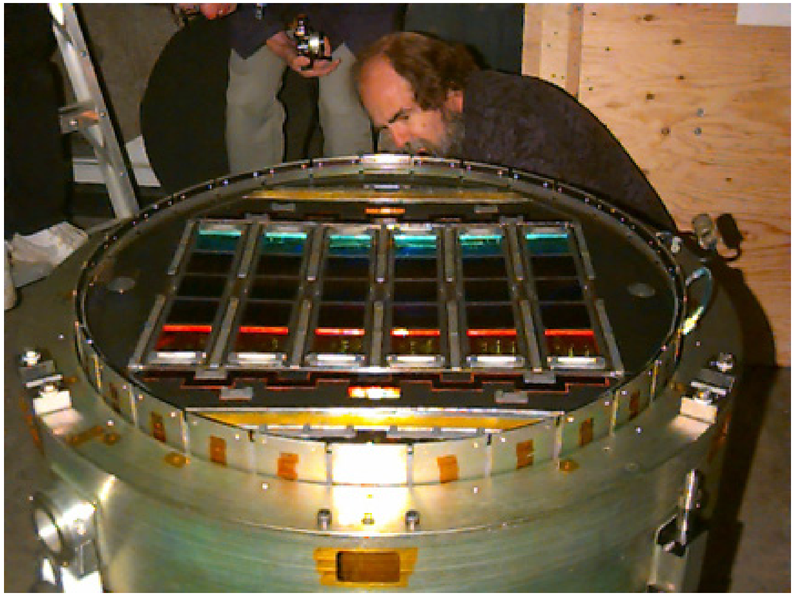


A CCD is a semiconductor array of light-sensitive pixels – typically about 10 μm across.

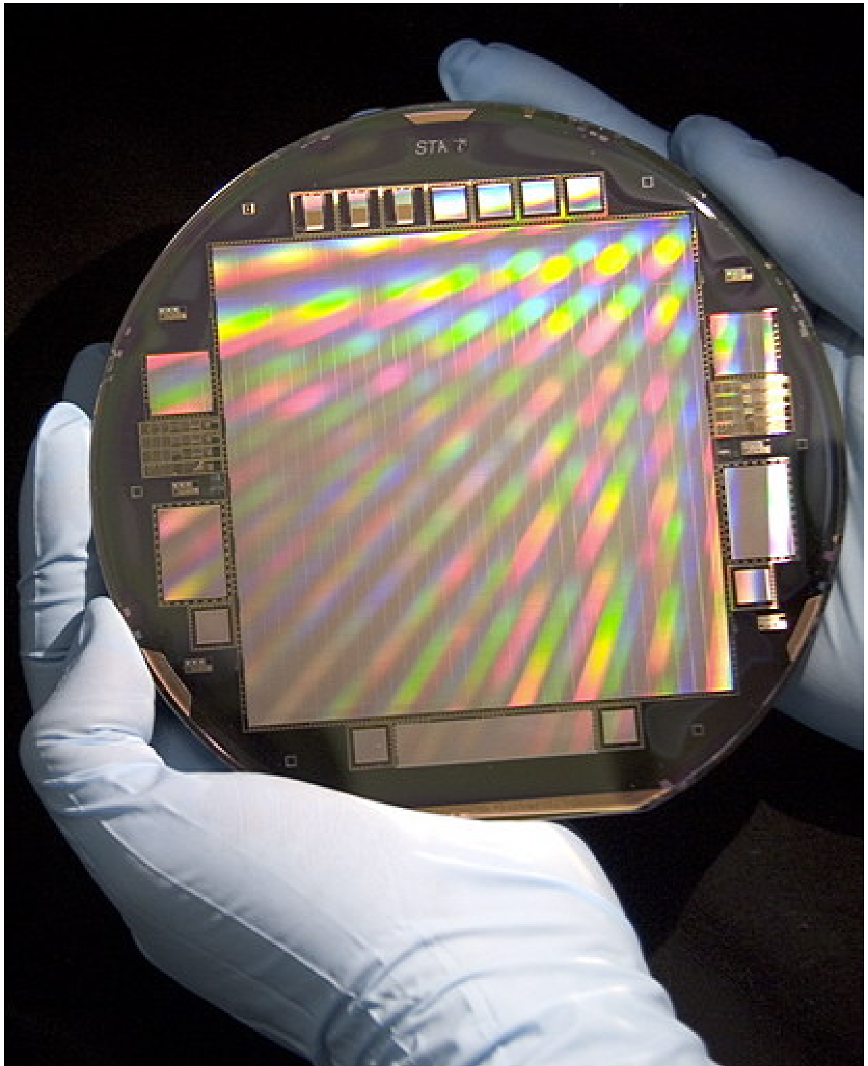
Arrays of 10^7 pixels are standard.

'State of the art' – mosaics of CCDs, approaching 10^9 pixels in total.





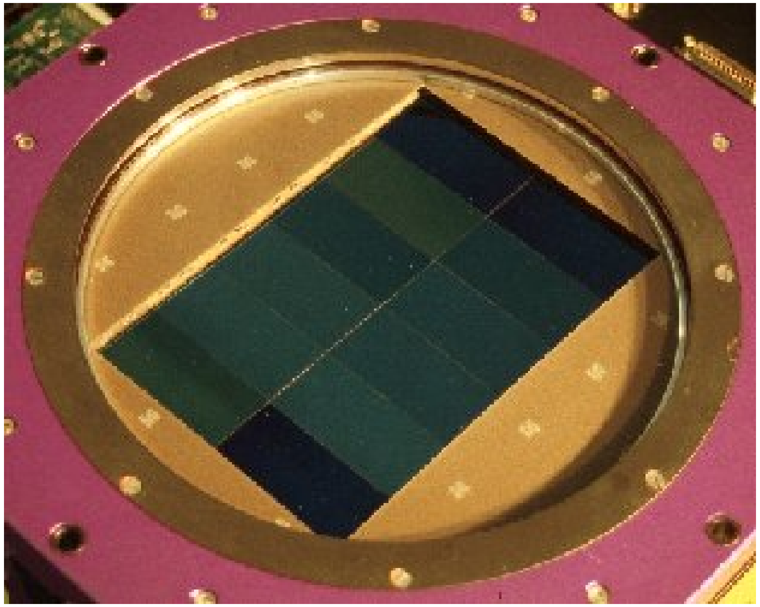
A big astronomical CCD: the STA1600A (Semiconductor Technology)



- 10580 x 10560 ~ 111.5 megapixels
- 95.22 mm x 95.22 mm active area
- 9 μm pixel width
- ~16 s readout time (at 1 MHz)
- linearity ~1%
- SNR = 78 dB at 1 MHz, 65 dB at 25 MHz
- >90% quantum efficiency in r
- readout noise <4 e^- at 1 MHz
- readout noise 18 e^- at 10 MHz
- -100 ^{o}C cryo-cooled
- dark current 1 e^-/pix/hr
- 16-bit quantization
- full well capacity of 80,000 e^-
- back-illuminated (thinned)

Canada-France Hawaii Telescope, Mauna Kea

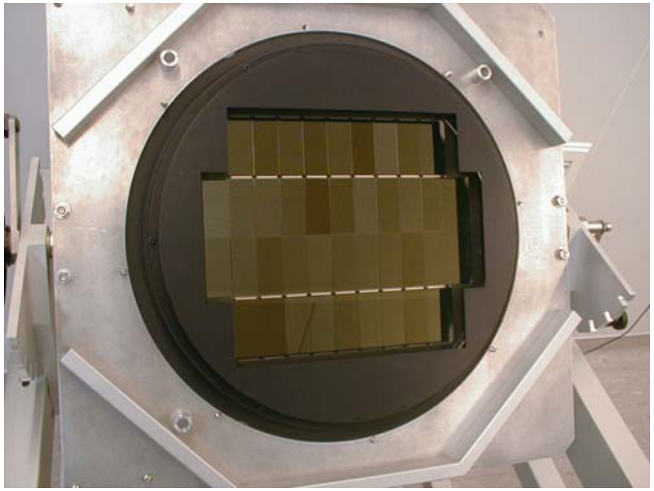
CFH12K
camera



mosaic of 12 CCDs, each 12288 x 8192
~ 100 million pixels


Coelum
Astronomia
NGC5194 The Whirlpool Galaxy (NGC 5194) NGC 5195 by
CFH
© CFHT

Canada-France Hawaii Telescope, Mauna Kea

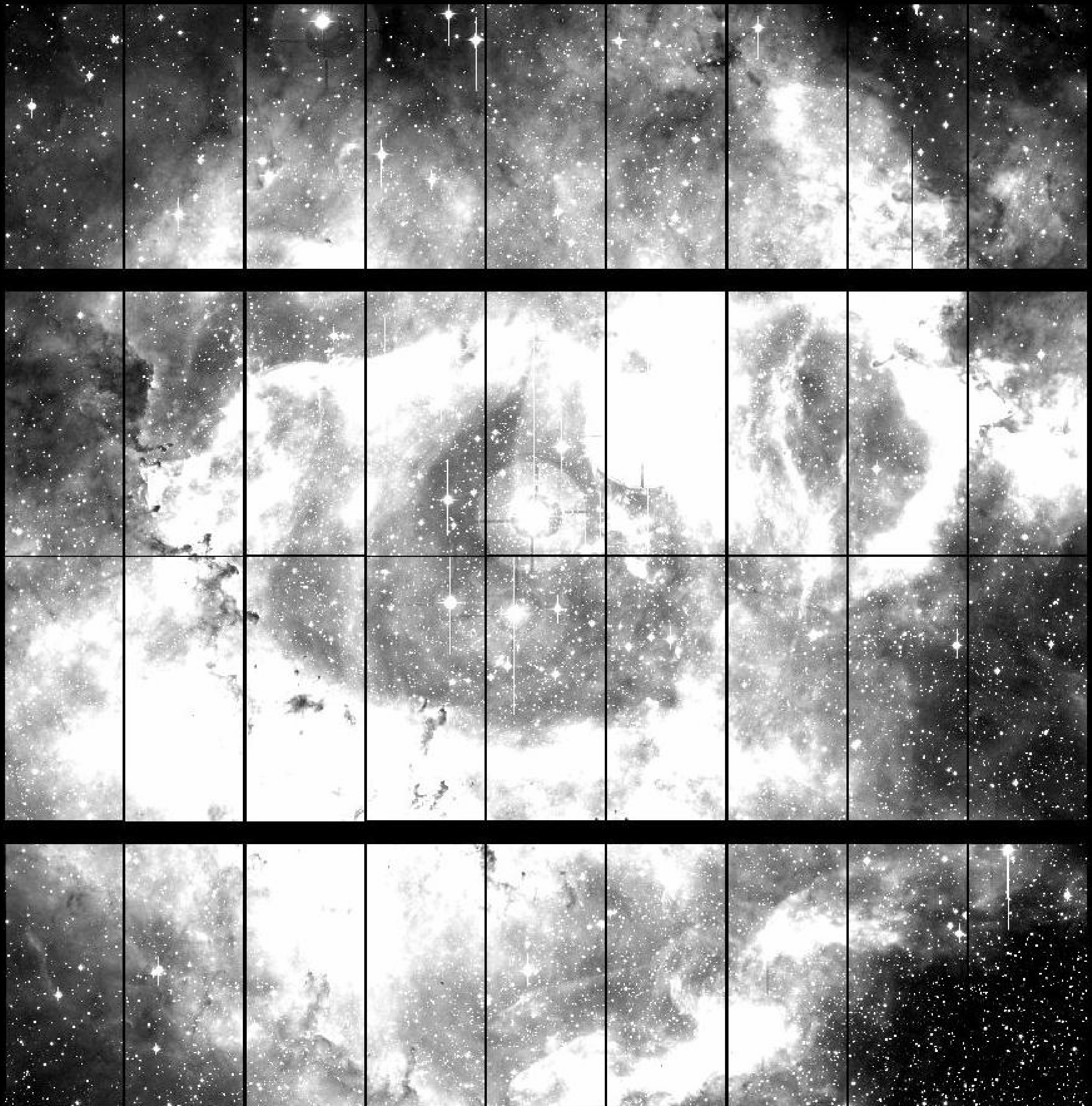


MEGACAM:

40 x 2048 x 4612 pixel CCDs

Focal Plane = 313mm x 261mm

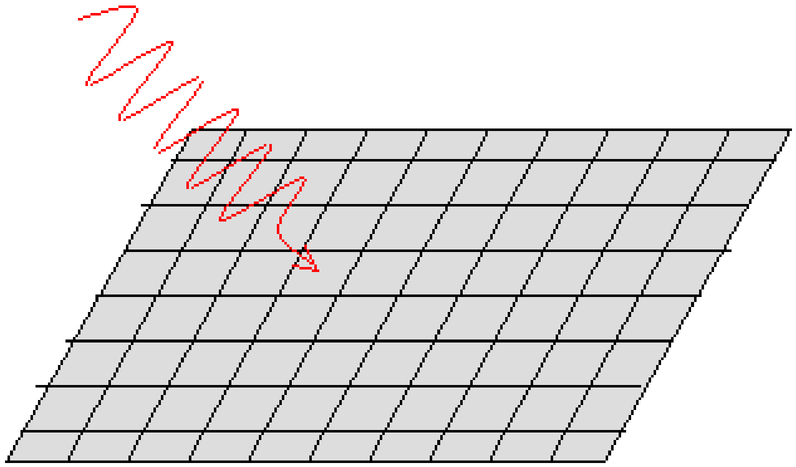
~ 370 million pixels



Rosette Nebula

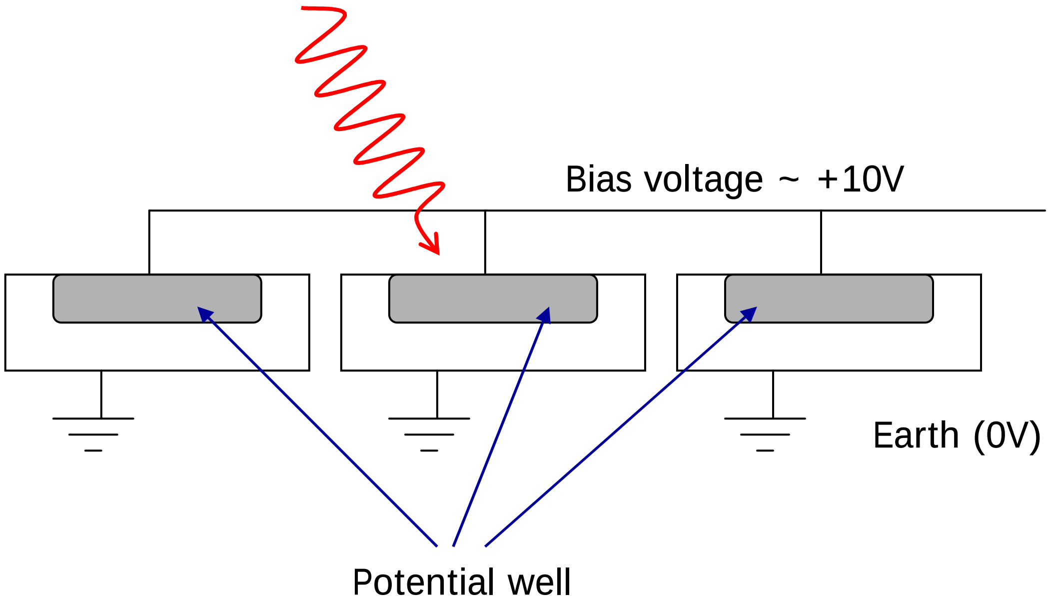
Rosette Nebula

3.4 Charge Coupled Device (CCD)



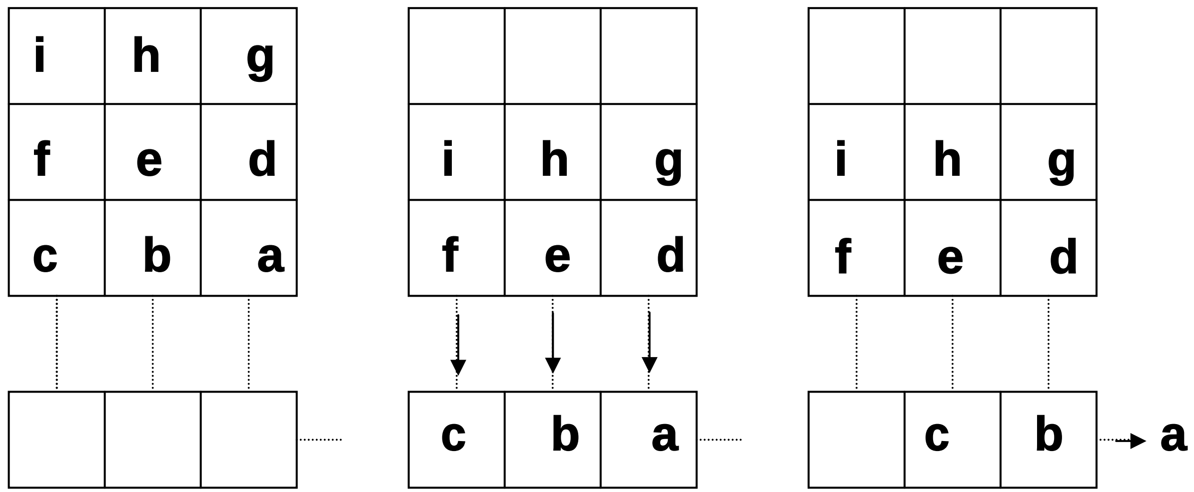
A CCD is a semiconductor array of light-sensitive pixels – typically about 20 μm across.
Arrays of 10^7 pixels standard.

'State of the art' – mosaics of CCDs, approaching 10^9 pixels in total.



- Electron released when photon strikes semiconductor.
- Bias voltage draws electron into potential well; stored there during exposure.

3.4 Charge Coupled Device (CCD)



• The stored charge is read out by manipulating the bias voltages. The contents of potential wells are moved across the chip line by line to a line register, then read out pixel by pixel.

• Readout rate up to 10^8 pixels per second.

Readout noise: very low, ~10 times less than for photomultipliers, and can be nearly zero.

Quantum efficiency: 50 – 70% (90% at 600 – 700 nm)

3.4 Charge Coupled Device (CCD)

- The number of electrons that a pixel (potential well) can store is called the pixel capacity (a few tens of thousands of electrons)

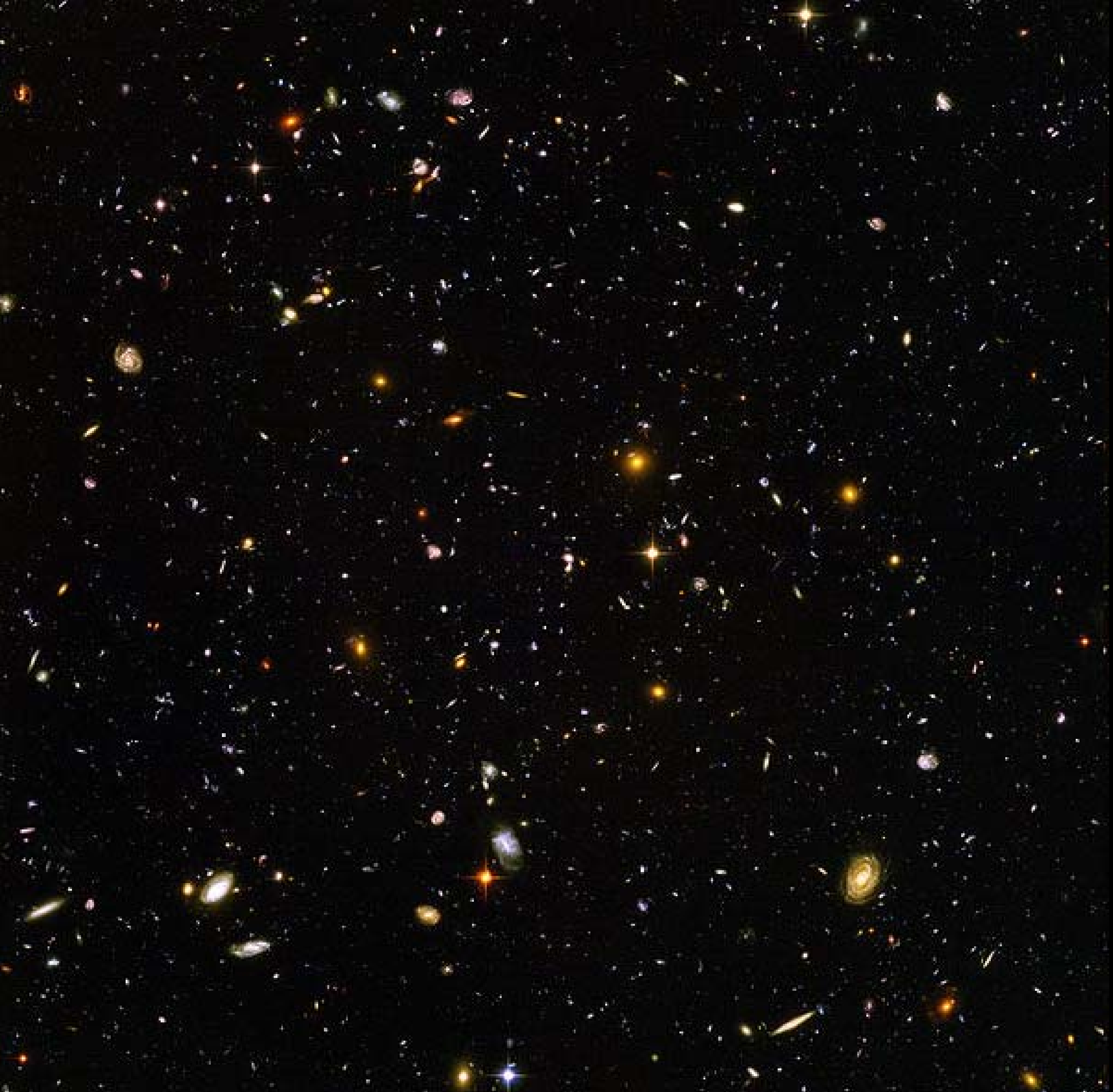
- For long exposures, the number of electrons produced may exceed the pixel capacity. The pixel then saturates and electrons spill over into neighbouring pixels (analogous to the saturation of a photograph)

- However, until saturation the pixel response is linear: the number of electrons stored is proportional to number of incident photons.

So CCDs have a large dynamic range = range over which detector response is linear.

$$\frac{\text{brightest object before saturation}}{\text{faintest object detectable}} \approx 10^6$$

or 60 dB



Hubble
Ultra
Deep
Field

800x1200 s
exposures

3.4 Charge Coupled Device (CCD)

Improving CCD performance

There are several sources of systematic error which need to be eliminated from CCD observations:

a) Bias

This is the signal from the CCD due to residual charge in the CCD and readout noise rather than photons.

This can be measured by taking a bias frame: an exposure of zero seconds followed by readout of the CCD chip.

3.4 Charge Coupled Device (CCD)

b) Dark (thermal) current

This is the signal from electrons produced in the absence of light, due to thermal emission in the CCD. The signal will vary from pixel to pixel, but grows with time.

The dark current can be reduced by cooling the CCD.

This can be measured by taking a dark frame: an exposure of the same length of time and at the same temperature as the real observation, but in total darkness.

3.4 Charge Coupled Device (CCD)

c) Response factor

The signal read out from each pixel differs from the 'true' signal that would be read out from a uniform detector due to variations in sensitivity across the CCD.

For a pixel at position (x, y), we can model this distortion by a response factor, $r(x, y)$

We can estimate $r(x, y)$ from a flat field observation: an exposure for a uniform light source (e.g. uniform sky at twilight), for which the 'true' signal should be uniform.

We need a new flat field for every observing session, since CCD irregularities (e.g. from dust) are constantly varying.

3.4 Charge Coupled Device (CCD)

Improving CCD performance

We can summarise the relation between these systematic effects via the following expressions:

$$\mathrm{I}(x,y,t,T) = \mathrm{I}_{\mathrm{true}}(x,y,t,T) \times r(x,y) + b(x,y) + d(x,y,t,T) \quad (3.1)$$

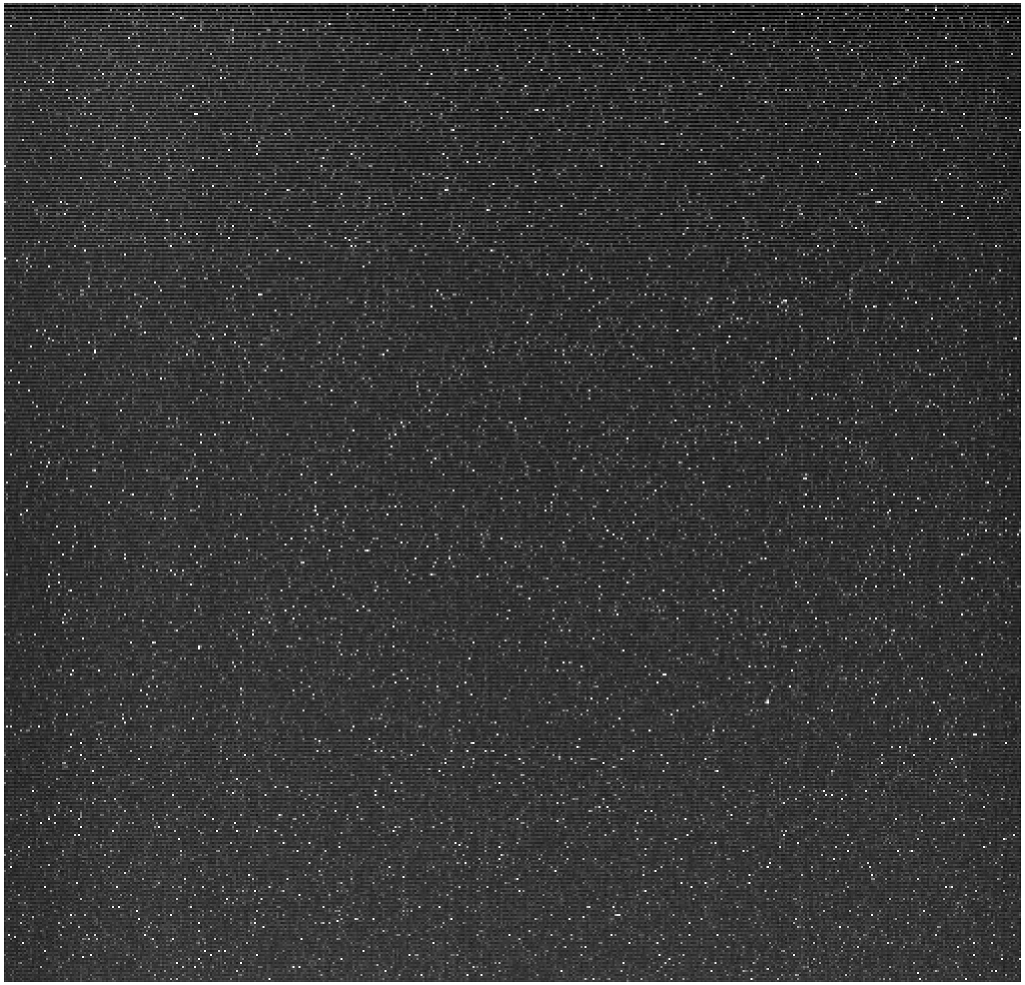
- $\mathrm{I}(x,y,t,T)$: signal measured from pixel (x,y) for an exposure of time t at temperature T
- $\mathrm{I}_{\mathrm{true}}(x,y,t,T)$: 'true' signal that would have been measured with a uniform detector
- $b(x,y)$: bias signal for pixel (x,y)
- $d(x,y,t,T)$: dark current signal from pixel (x,y), for an exposure time t at temperature T

$$r(x,y) \propto \left[\mathrm{I}_{\mathrm{flat}}(x,y,t,T) - b(x,y) - d(x,y,t,T)\right] \quad (3.2)$$

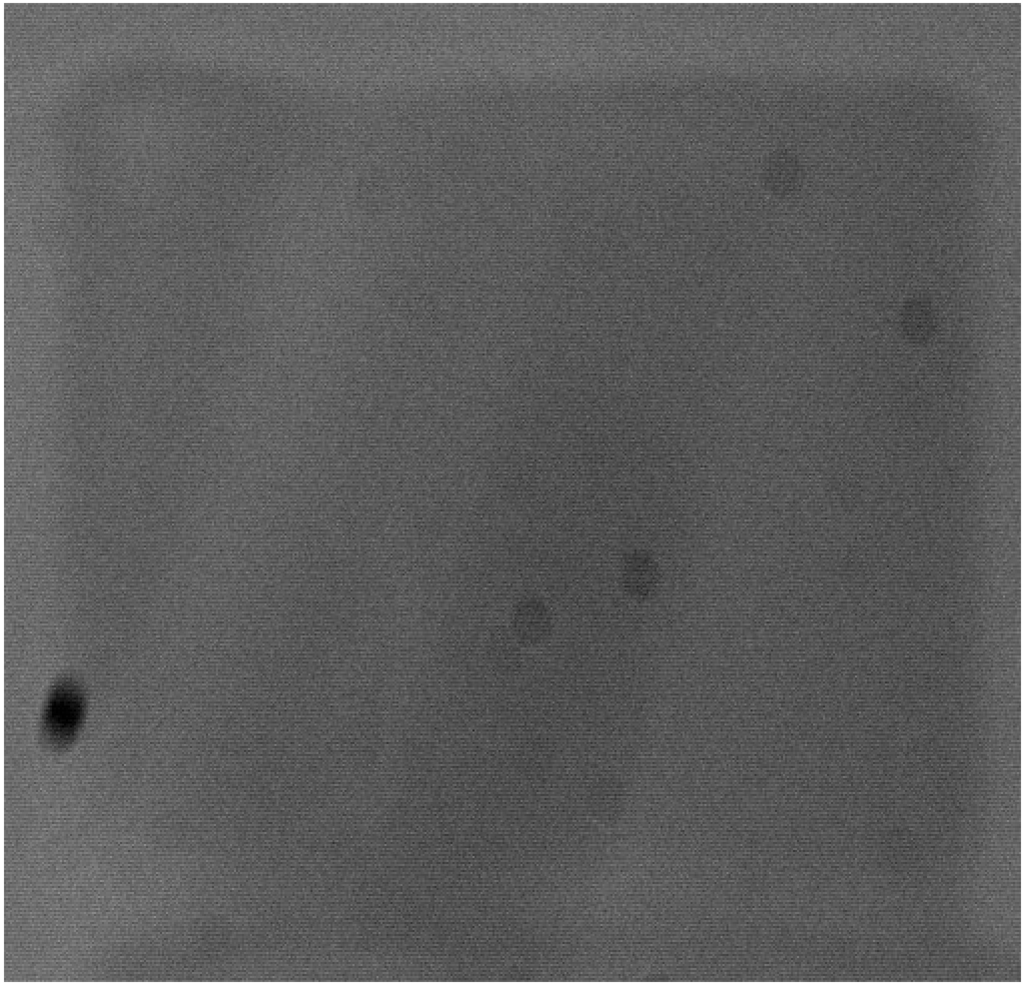
- $\mathrm{I}_{\mathrm{flat}}(x,y,t,T)$: signal measured during **flat field** observation

Raw image

Dark frame



Flat field



Calibrated image

H. Raab