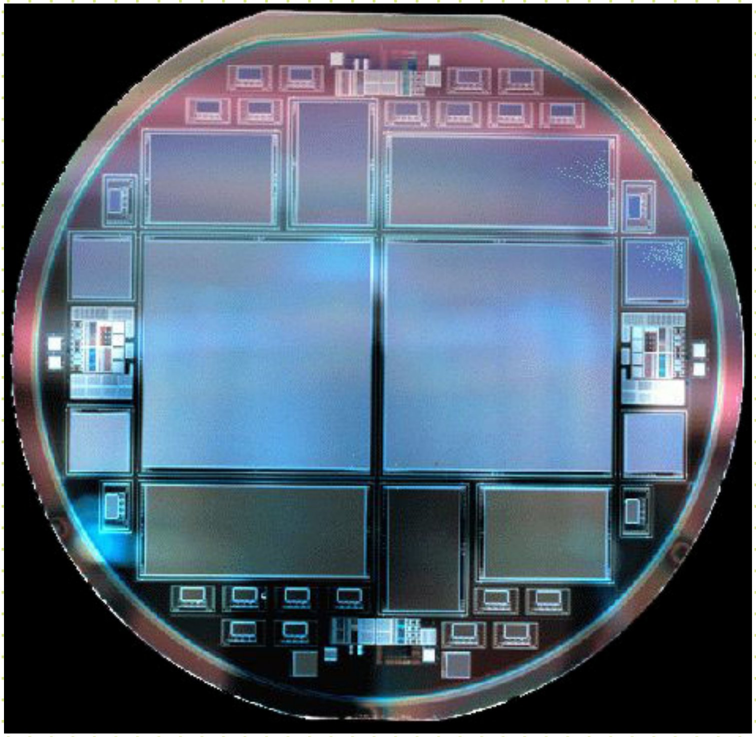
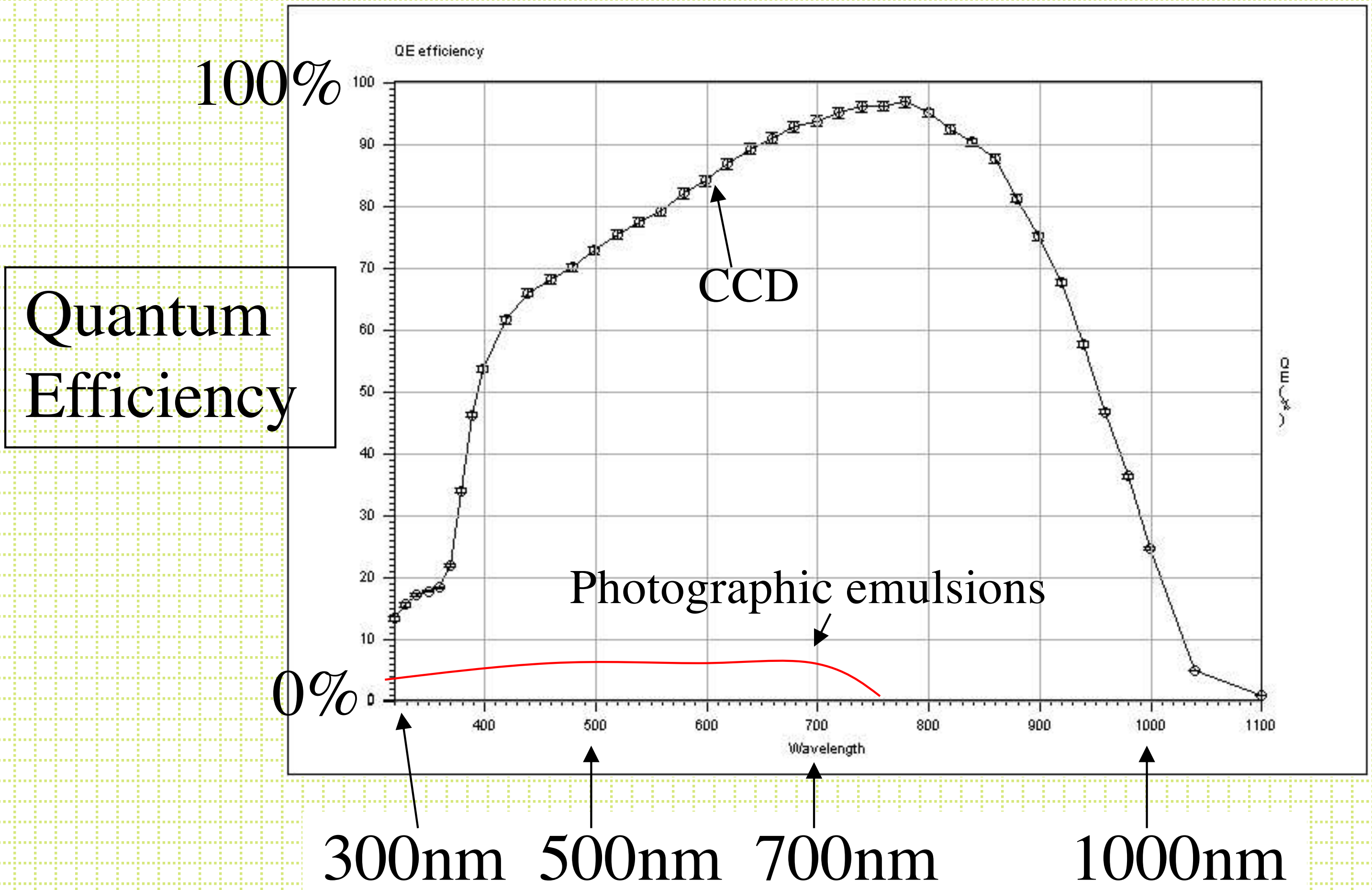
Digital Detectors

- By far the most common detector for wavelengths 300nm<λ<1000nm is the CCD.



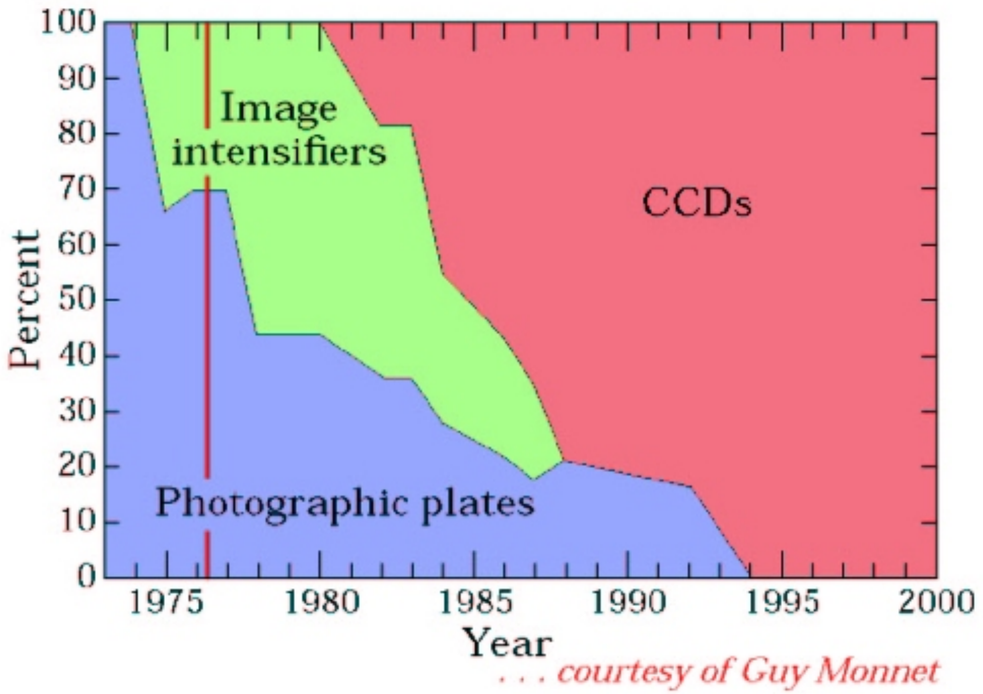
CCDs

1. Quantum efficiency is more than an order of magnitude better than photographic plates.



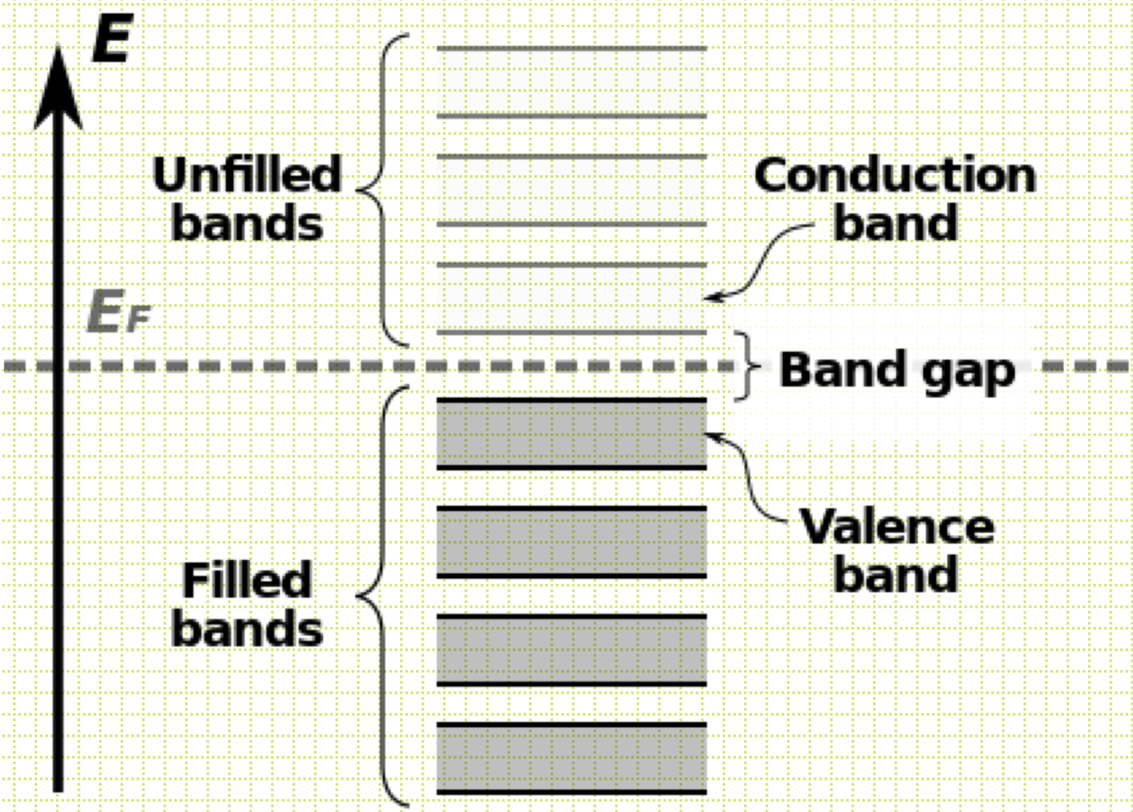
These are silicon fab-line devices and complicated to produce

Invented 1969 Boyle and Smith at AT&T Bell Labs



CCDs remain physically small compared to photographic plates, but they took over rapidly anyway.

CCDs: How do they work?



Photon with energy greater than the band gap can be absorbed and bump an e- into the conduction band

λ_{max}= 1.24 μm/E_{gap}(eV)

For Si:

E_{gap}=1.11eV

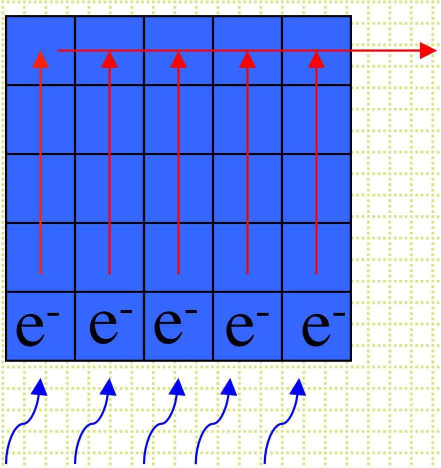
λ_{max}=1.12μm

To catch Infrared photons, need a material with a smaller band gap

CCDs: How do they work?

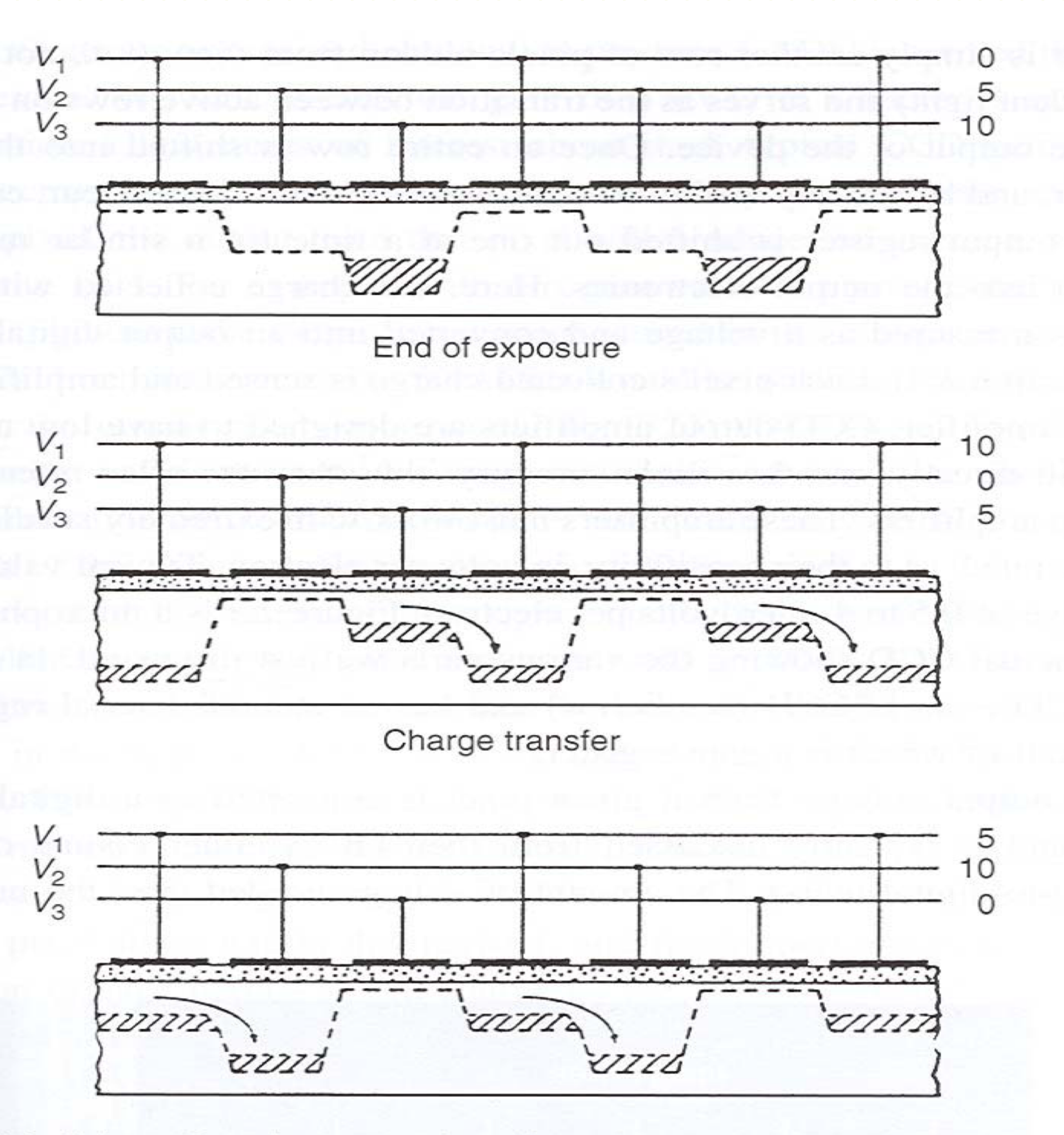
- Silicon semiconductors with ``gate’’ structure to produce little potential corrals.

Photons → Electrons bumped into conduction band → Read out and amplify current → A/D convert to DN



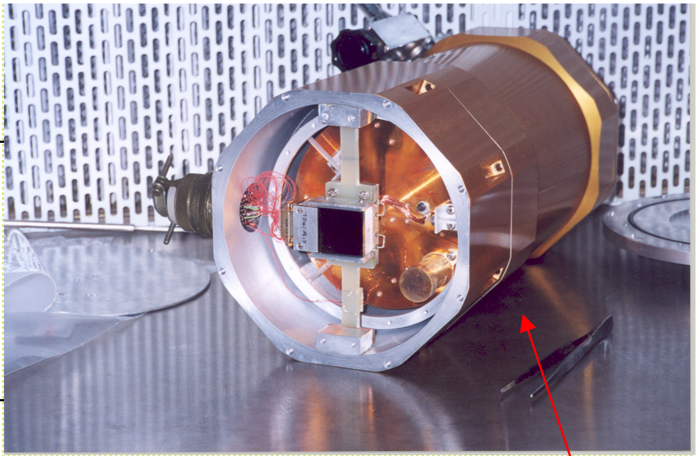
`clock’ parallel and serial registers

``CTE’’ > 0.99999



- Example three-phase readout to create bucket brigade and move accumulated charge into readout amplifier

CCD operation



- At room temperature, electrons in high-energy tail of the silicon spontaneously pop up into the conduction band: "dark current". Cooling the detectors reduced the dark current although at about -120C the quantum efficiency starts to decrease.
- Therefore, CCDs usually are put into dewars with liquid nitrogen cold baths and heaters and the temperature is actively controlled to ~1C.
- Readout speed is typically adjustable--faster readout gives higher readout noise per pixel.

CCDs cont.

- The potential corrals that define the pixels of the CCD start to flatten as e^- collect. This leads first to saturation, then to e^- spilling out along columns.
- The "inverse gain" is the number of e^- per final "count" post the A/D converter.
- One *very* important possibility for CCDs is to tune the response to be linear.

- ``Counts'' = ADU = DN

Analogue-to-digital unit

Digital Number

- DN is not the fundamental unit, the # of detected electrons is. The ``Gain'' is set by the electronics.
- Most A/D converters use 16 bits.

  DN from: 0 to $(2^{16} - 1) = 65535$

for unsigned, long integers

- Signed integers are dumb: -32735 to +32735

  $+/-(2^{15} - 1)$

Binary arithmetic

Each bit can be 0 or 1

Register: 16 15 14 13 12……………1

2^{15} 2^{14} ……………………………2^{0}

so 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 1

is $2^4+2^2+2^0$

= 16+4+1=21

What gain do you want?

Example: LRIS-R had a SITe 24μ-pixel CCD with pixel ``wells'' that hold ~350,000 e-

- 16-bit unsigned integer A/D saturates at 65535DN
- Would efficiently maximize dynamic range by matching these saturation levels:

$$\frac{350{,}000}{65{,}535} = 5.3\,\frac{e-}{DN}$$

- Note, this undersamples the readout noise and leads to "digitization" noise.

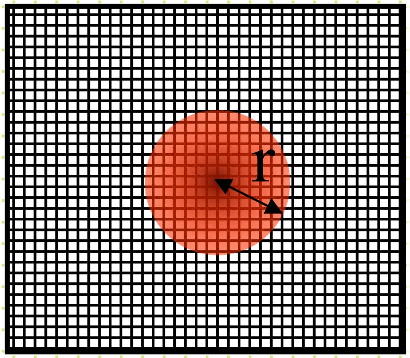
Signal-to-Noise (S/N)

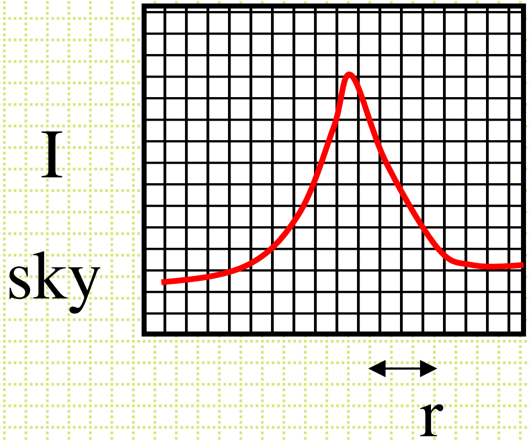
- Signal=R_*• t

time

detected e-/second

- Consider the case where we count all the detected e- in a circular aperture with radius r.





- Noise Sources:

$$\sqrt{R_* \cdot t} \quad \Rightarrow \text{ shot noise from source}$$

$$\sqrt{R_{sky} \cdot t \cdot \pi r^2} \quad \Rightarrow \text{ shot noise from sky in aperture}$$

$$\sqrt{RN^2 \cdot \pi r^2} \quad \Rightarrow \text{ readout noise in aperture}$$

$$\sqrt{\left[RN^2 + (0.5 \times \text{gain})^2\right]} \cdot \sqrt{\pi r^2} \quad \Rightarrow \text{ more general RN}$$

$$\sqrt{\text{Dark} \cdot t \cdot \pi r^2} \quad \Rightarrow \text{ shot noise in dark current in aperture}$$

$R_* = \text{e}^-/\text{sec}$ from the source

$R_{sky} = \text{e}^-/\text{sec/pixel}$ from the sky

$RN =$ read noise (as if RN^2 e^- had been detected)

Dark $= \text{e}^-/\text{second/pixel}$

- Note that each arriving photon is independent of previous or subsequent photons so the noise is "statistical" or "shot" or "Poisson". For Poisson distribution the standard deviation is:

$$\sigma=\sqrt{N}$$

- Need to apply this to detected e–, not counts

S/N for object measured in aperture with radius r: n_{pix}=# of pixels in the aperture= πr^2

Noise from the dark current in aperture

Signal ⟷

$$\frac{R_* t}{\left[R_* \cdot t + R_{\text{sky}} \cdot t \cdot n_{\text{pix}} + \left(RN + \frac{\text{gain}}{2}\right)^2 \cdot n_{pix} + \text{Dark} \cdot t \cdot n_{\text{pix}}\right]^{\frac{1}{2}}}$$

Noise ⟷

$$\sqrt{(R_* \cdot t)^2}$$

Readnoise in aperture

Noise from sky *e*- in aperture

All the noise terms added in quadrature
Note: always calculate in *e*-

S/N Calculations

- So, what do you do with this?
  - Demonstrate feasibility
  - Justify observing time requests
  - Get your observations right

Side Issue: S/N $\Leftrightarrow$ δmag

$$
\begin{aligned}
m \pm \delta(m) &= c_o - 2.5\log(S \pm N) \\
&= c_o - 2.5\log\left[S\left(1 \pm \tfrac{N}{S}\right)\right] \\
&= \underbrace{c_o - 2.5\log(S)}_{\text{m}} \underbrace{- 2.5\log(1 \pm \tfrac{N}{S})}_{\delta\text{m}}
\end{aligned}
$$

$$
\begin{aligned}
\delta(m) &\approx 2.5\log(1 + \tfrac{1}{S/N}) \\
&= \frac{2.5}{2.3}\left[\tfrac{N}{S} - \tfrac{1}{2}(\tfrac{N}{S})^2 + \tfrac{1}{3}(\tfrac{N}{S})^3 - \ldots\right] \\
&\approx 1.087(\tfrac{N}{S})
\end{aligned}
$$

Note:in log +/- not symmetric

Fractional error

This is the basis of people referring to +/- 0.02mag error as "2%"

S/N $\Longleftrightarrow$ δmag

S/N	δmag
2	0.44
10	0.10
100	0.01

How do you get values for some of these parameters?

- Dark Current: CCD@-120˚C < 2*e*-/pix/hour

  HgCdTe: ~30*e*-/pix/hour
- RN: CCD: 2 - 6 *e*-/pix

  HgCdTe: 3 - 10 *e*-/pix
- R_*: for a given source brightness, this can be calculated for any telescope and total system efficiency.
- In practice: *Go to the facility WWW site for everything!*
- Example: MOSFIRE

Source Count Rates

Example: LRIS on Keck 1

for a B=V=R=I=20mag object @ airmass=1

B	1470 e-/sec
V	1521 e-/sec
R	1890 e-/sec
I	1367 e-/sec

To calculate R_* for a source of arbitrary brightness only requires this table and a bit of magnitude math.

Source Count Rates

$$m_1 = c_o - 2.5\log(I_1)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$m_2 = c_o - 2.5\log(I_2)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$m_1 - m_2 = -2.5\left[\log(I_1) - \log(I_2)\right]\ldots\ldots\ldots(1)-(2)$$

$$m_1 - m_2 = -2.5\log\left(\frac{I_1}{I_2}\right)$$

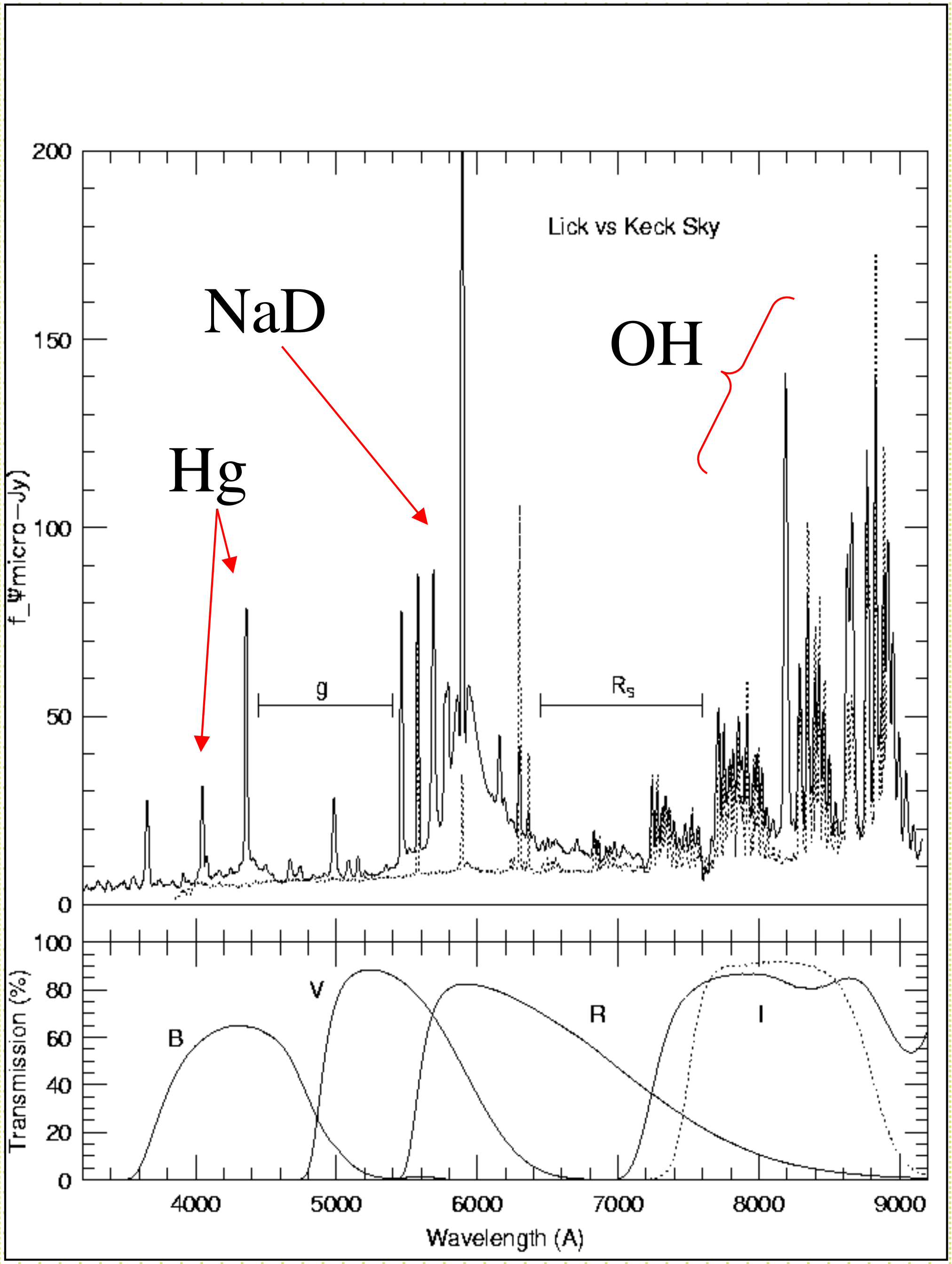
$$\frac{I_1}{I_2} = 10^{-\left(\frac{m_1 - m_2}{2.5}\right)}$$

Let I_2 be the intensity for the fiducial m=20 object

$$I_1 = R_*(m_1) = I_{20} \cdot 10^{-\left(\frac{m_1 - 20}{2.5}\right)}$$

So, plug in magnitude of target to get estimates source rate of detected e-

R_{sky}



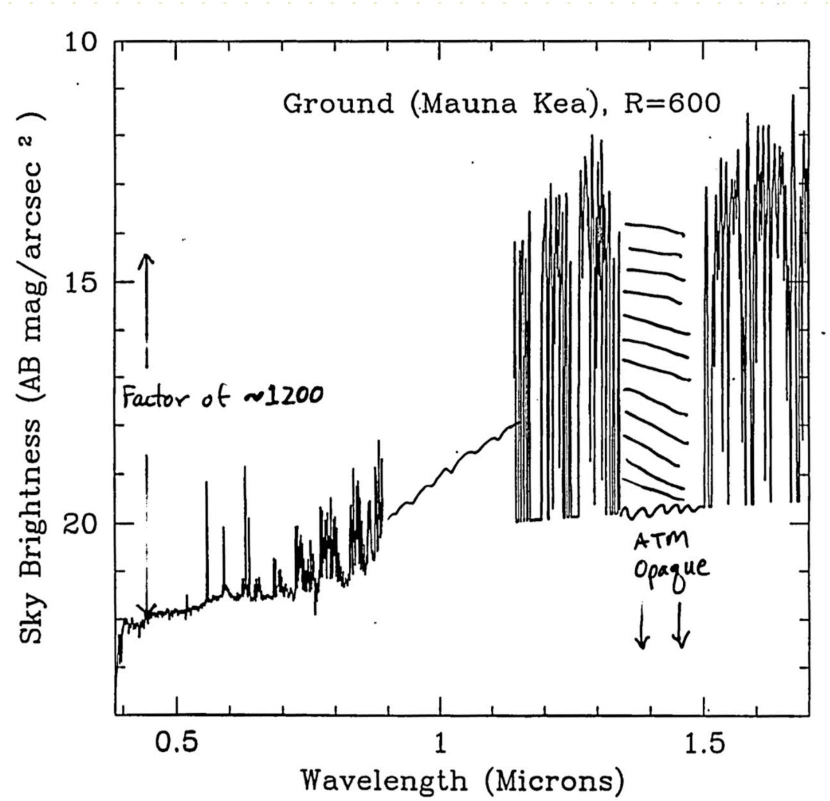
Signal from the sky background is present in every pixel of the aperture. Because each instrument generally has a different pixel scale, the sky brightness is usually tabulated for a site in units of mag/arcsecond^2.

(mag/□″)

Lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

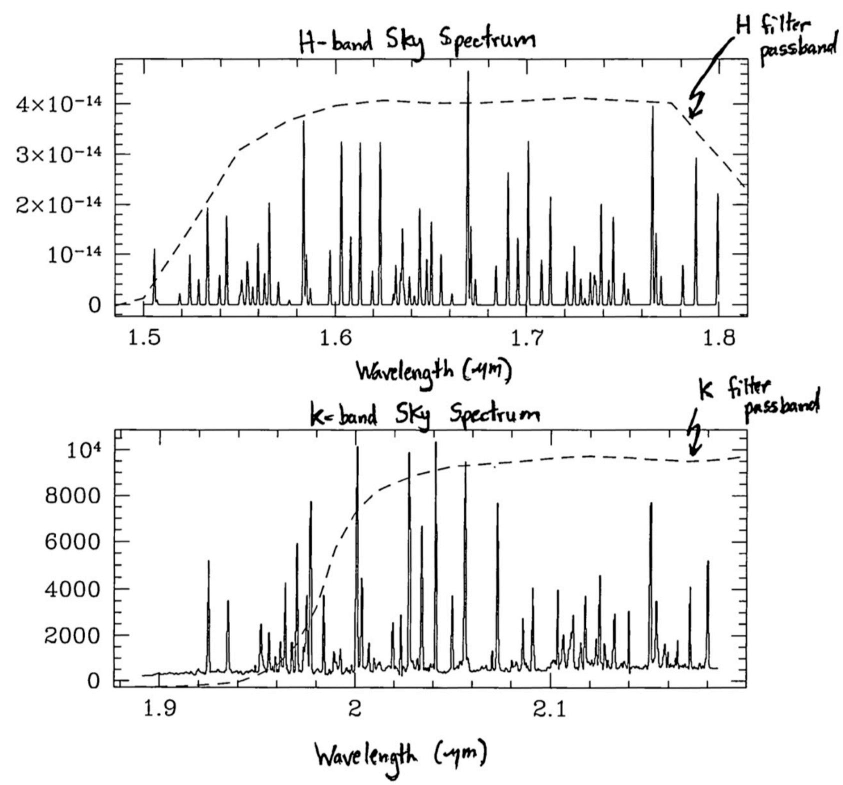
Sky: Optical – near IR

- The sky brightness in the blue is (mostly) Rayleigh scattered light from the Sun
- Moving redward of 550nm, sky brightness increasingly due to atmospheric emission (mostly OH) although there is still scattered sunlight



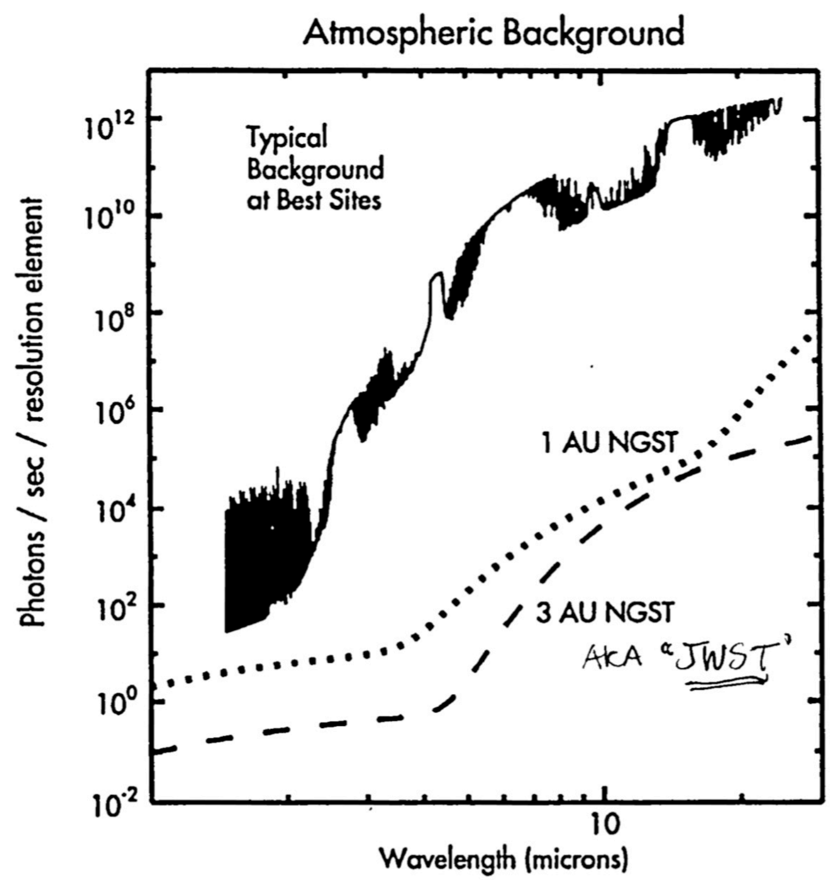
H- and K-band sky

- Much higher than optical, particularly integrated in a broad filter
- At $\lambda/\Delta\lambda > 3000$ can resolve the OH emission and it can be quite dark between lines
- There is additionally some blackbody emission from the earth's atmosphere and telescope/instruments



"thermal" wavelengths

- Become dominated by the black-body emission of the facility and atmosphere
- JWST has an eight order of magnitude advantage…



Scale $\Rightarrow$ "/pix (LRIS-R: 0.218"/pix)

Area of 1 pixel = $(\text{Scale})^2$ (LRIS–R: 0.0475"^{2}

this is the ratio of flux/pix to flux/"

In magnitudes:

$$I_{pix} = I_{''} \text{Scale}^2$$

$I \Rightarrow$ Intensity (e^-/sec)

$$-2.5\log(I_{pix}) = -2.5[\log(I_{''}) + \log(\text{Scale}^2)]$$

$$m_{pix} = m_{''} - 2.5\log(\text{Scale}^2)$$

(for LRIS-R: add 3.303mag)

and

$$R_{sky}(m_{pix}) = R(m = 20) \times 10^{(0.4 - m_{pix})}$$

To calculate sky in counts per pixel per time

Example, LRIS in the R-band:

$$R_{sky} = 1890 \times 10^{0.4(20-24.21)} = 39.1 \ e^- / \text{pix} / \text{sec}$$

$$\sqrt{R}_{sky} = 6.35 e^- / \text{pix} / \text{sec} \approx \text{RN in just 1 second}$$

S/N - some limiting cases. Let's assume CCD with Dark=0, well sampled read noise.

$$\frac{R_* t}{\left[R_* \cdot t + R_{\text{sky}} \cdot t \cdot n_{\text{pix}} + (RN)^2 \cdot n_{pix}\right]^{\frac{1}{2}}}$$

Bright Sources: $(R_* t)^{1/2}$ dominates noise term

$$\mathrm{S/N} \approx \frac{\mathrm{R_* t}}{\sqrt{\mathrm{R_* t}}} = \sqrt{\mathrm{R_* t}} \propto \mathrm{t}^{\frac{1}{2}}$$

Sky Limited $(\sqrt{\mathrm{R_{sky} t}} > 3 \times \mathrm{RN})$: $\mathrm{S/N} \propto \dfrac{\mathrm{R_* t}}{\sqrt{\mathrm{n_{pix} R_{sky} t}}} \propto \sqrt{\mathrm{t}}$

Note: seeing comes in with n_{pix} term

What is ignored in this S/N eqn?

- Bias level/structure correction
- Flat-fielding errors
- Charge Transfer Efficiency (CTE) 0.99999/pixel transfer
- Non-linearity when approaching full well
- Scale changes in focal plane
- A zillion other potential problems