Ay 20 - Lecture 3: Astronomical Instruments and Measurements

- What can be measured and how
- Magnitudes, fluxes, and photometric systems
- Imaging and photometry
- Spectroscopy
- Other stuff: time series, polarimetry …

What Properties of Electromagnetic Radiation Can We Measure?

- Specific flux = Intensity (in ergs or photons) per unit area (or solid angle), time, wavelength (or frequency), e.g., $f_{\lambda} = 10^{-15}$ erg/cm^2/s/Å - a good spectroscopic unit
- It is usually integrated over some finite bandpass (as in photometry) or a spectral resolution element or a line
- It can be distributed on the sky (surface photometry, e.g., galaxies), or changing in time (variable sources)
- You can also measure the polarization parameters (photometry ➙ polarimetry, spectroscopy ➙ spectro-polarimetry); common in radio astronomy

Photon Energies

Electromagnetic radiation of frequency ν, wavelength λ, in free space obeys:

$$\lambda\nu = c \quad \longleftarrow \text{speed of light}$$

In c.g.s. units: $h = 6.626 \times 10^{-27}$ erg s

$c = 3.0 \times 10^{10}$ cm s^{-1}

Individual photons have energy:

$$E = h\nu \qquad h = \text{Planck's constant}$$

Common to measure energies in electron volts, where:

$$1\ \text{eV} = 1.6 \times 10^{-12}\ \text{erg} = 1.6 \times 10^{-19}\ \text{J}$$

(From P. Armitage)

The Concept of Signal-to-Noise (S/N)
or: How good is that measurement?

- **S/N = signal/error** (If the noise is Gaussian, we speak of 3-σ, 5-σ, … detections. This translates into a probability that the detection is spurious.)
- For a counting process (e.g., photons), error = $\sqrt{n}$, and thus S/N = $n / \sqrt{n} = \sqrt{n}$ ("Poissonian noise"). This is the *minimum possible error;* there may be other sources of error (e.g., from the detector itself)
- If a source is seen against some back(fore)ground, then

$$\sigma^2_{\text{total}} = \sigma^2_{\text{signal}} + \sigma^2_{\text{background}} + \sigma^2_{\text{other}}$$

Measuring Flux = Energy/(unit time)/(unit area)

Real detectors are sensitive over a finite range of λ (or ν). Fluxes are always measured over some finite bandpass.

Total energy flux:

$$F = \int F_\nu(\nu) d\nu$$

Integral of f_ν over all frequencies

Units: erg s^{-1} cm^{-2} Hz^{-1}

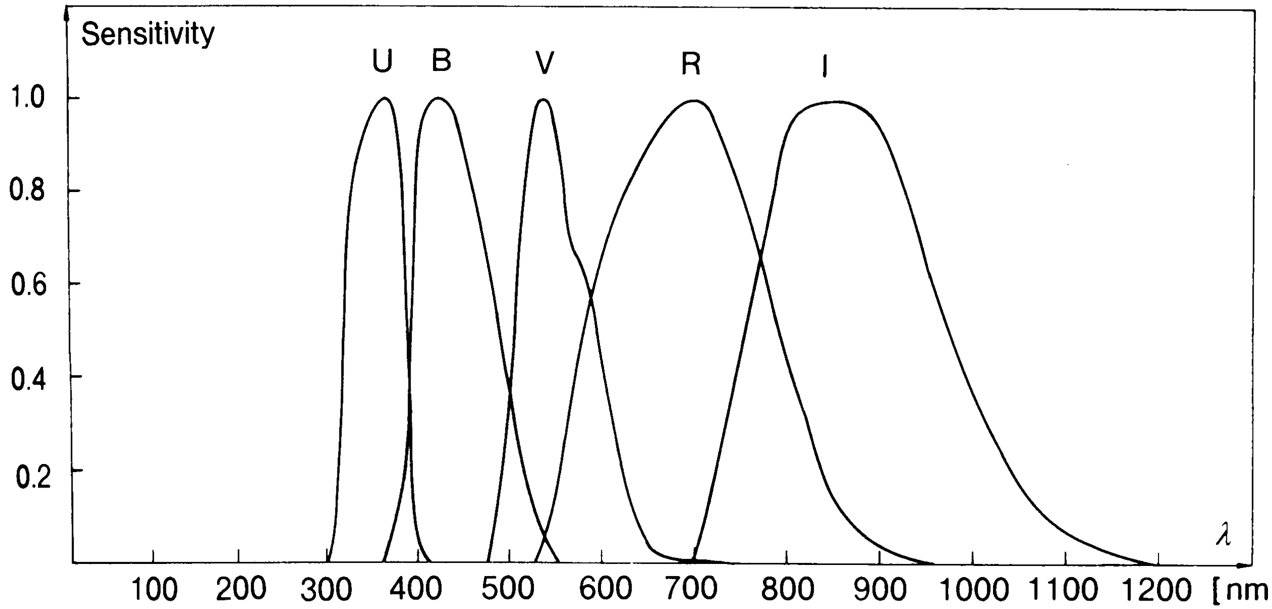
A standard unit for specific flux (initially in radio, but now more common):

$$1 \text{ Jansky (Jy)} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$$

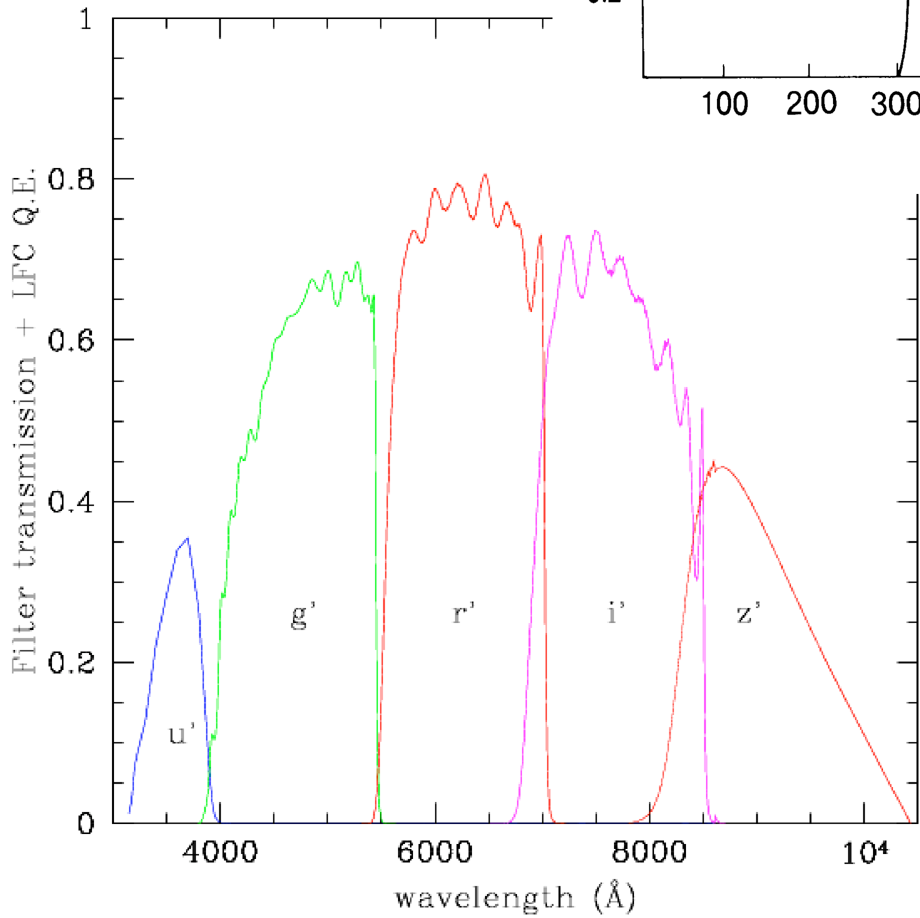
f_ν is often called the ***flux density*** - to get the ***power,*** one integrates it over the bandwith, and multiplies by the area

(From P. Armitage)

Johnson →



Gunn/SDSS
↓



Some Common Photometric Systems (in the visible)

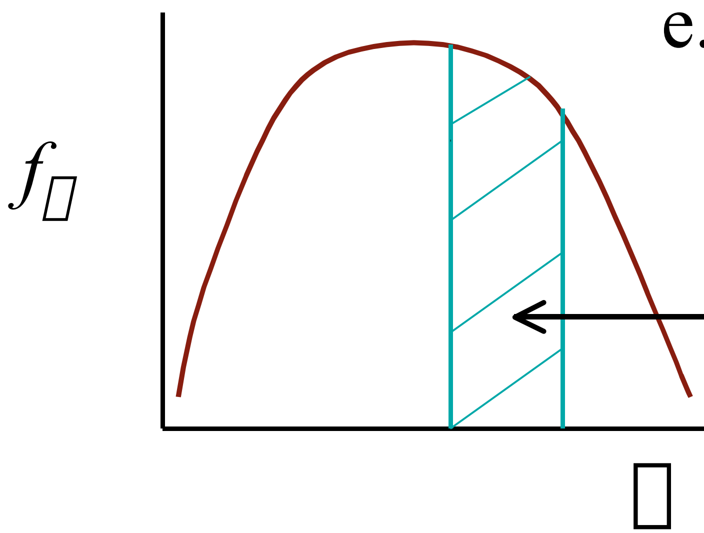
Fluxes and Magnitudes

For historical reasons, fluxes in the optical and IR are measured in magnitudes: $m = -2.5\log_{10} F + \text{constant}$

If F is the total flux, then m is the bolometric magnitude. Usually instead consider a finite bandpass, e.g., V band.

e.g. in the V band ($\lambda \sim$ 550 nm):

$$m_V = -2.5\log_{10} F + \text{constant}$$



flux integrated over the range of wavelengths for this band

(From P. Armitage)

Using Magnitudes

Consider two stars, one of which is a hundred times fainter than the other in some waveband (say *V*).

$$m_1 = -2.5\log F_1 + \text{constant}$$

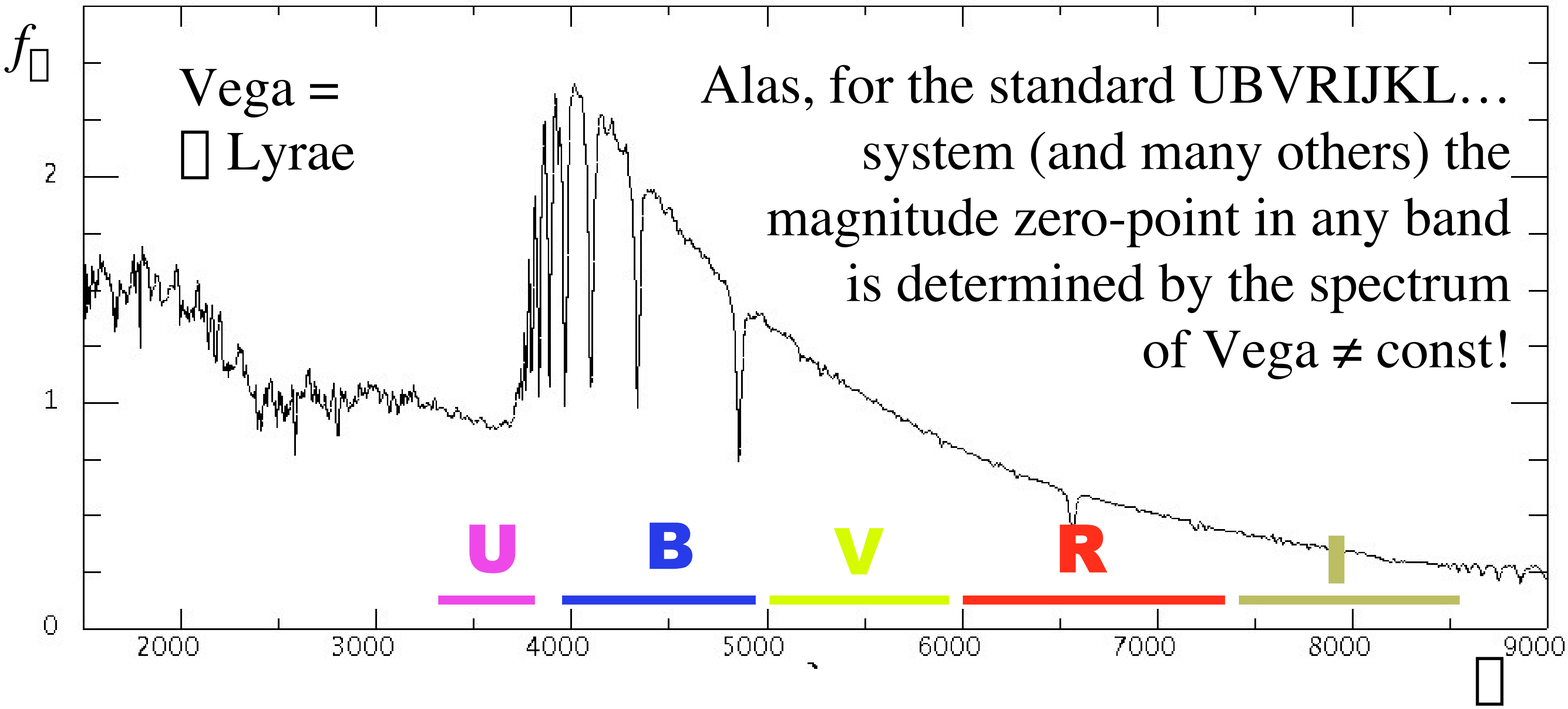
$$\begin{aligned} m_2 &= -2.5\log(0.01F_1) + \text{constant} \\ &= -2.5\log(0.01) - 2.5\log F_1 + \text{constant} \\ &= 5 - 2.5\log F_1 + \text{constant} \\ &= 5 + m_1 \end{aligned}$$

Source that is 100 times **fainter** in flux is five magnitudes fainter (**larger** number).

Faintest objects detectable with *HST* have magnitudes of ~ 28 in R/I bands. The sun has m_V = -26.75 mag

(From P. Armitage)

Magnitude Zero Points



Alas, for the standard UBVRIJKL… system (and many others) the magnitude zero-point in any band is determined by the spectrum of Vega ≠ const!

Vega calibration ($m = 0$): at $\lambda = 5556$:

$f_\lambda = 3.39 \times 10^{-9}$ erg/cm²/s/Å

$f_\nu = 3.50 \times 10^{-20}$ erg/cm²/s/Hz

$N_\lambda = 948$ photons/cm²/s/Å

A more logical system is AB_ν magnitudes:

$$AB_\nu = -2.5 \log f_\nu \text{ [cgs]} - 48.60$$

Magnitudes, A Formal Definition

$$m = -2.5\left[\log \int d\lambda R(\lambda) f_\lambda - \log \int d\lambda R(\lambda) f_\lambda(\alpha \text{ Lyr})\right]$$

e.g.,

$$U = -2.5 \log \int d\lambda R_U(\lambda) f_\lambda - 14.08 + c_U ,$$

$$B = -2.5 \log \int d\lambda R_B(\lambda) f_\lambda - 13.00 + c_B ,$$

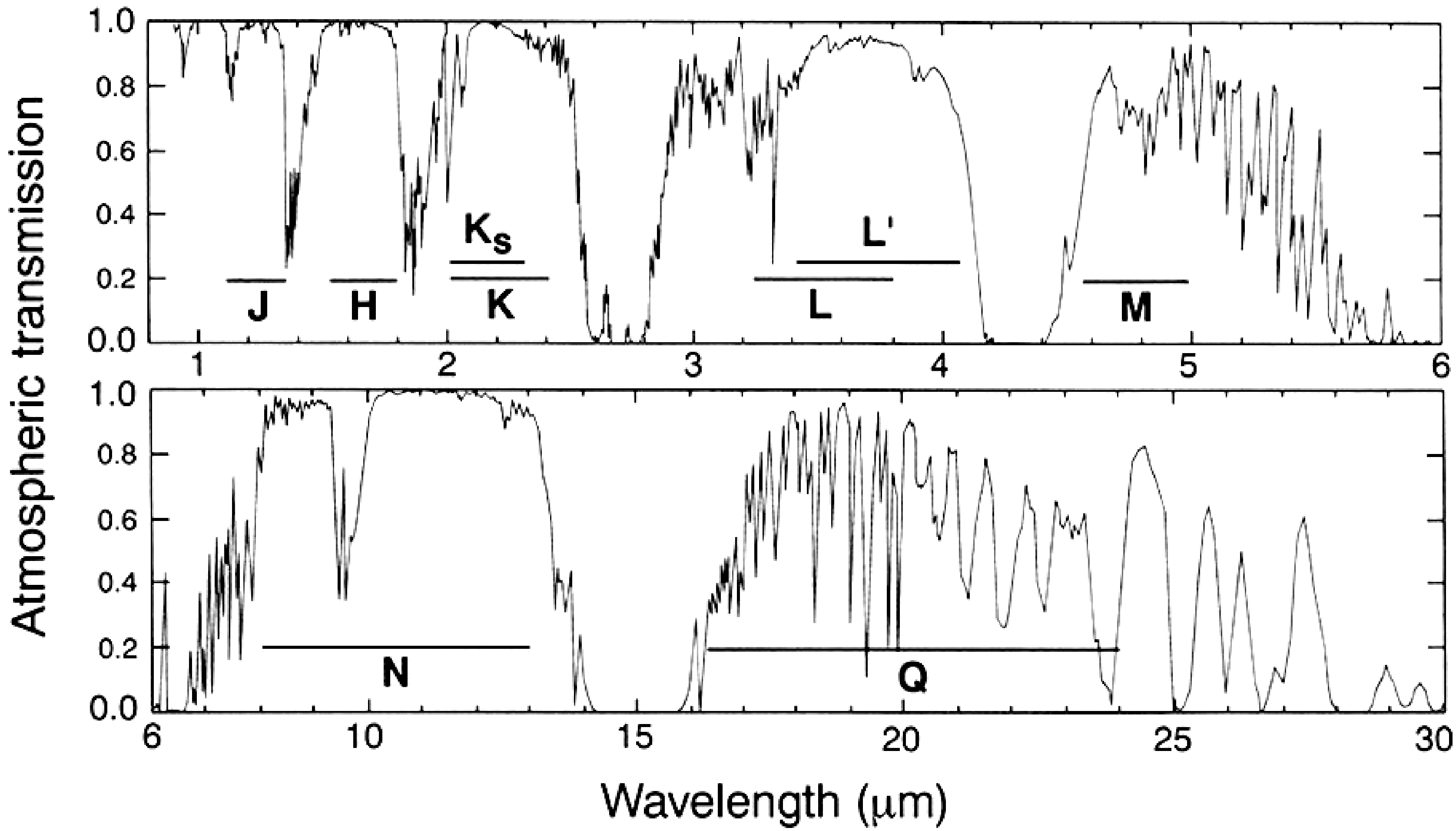
$$V = -2.5 \log \int d\lambda R_V(\lambda) f_\lambda - 13.76 + c_V ,$$

Because Vega (= □ Lyrae) is declared to be the zero-point! (at least for the UBV… system)

where the peak of the response function is normalized to unity, and c represents the magnitude of α Lyr; $c_U = 0.02$, $c_B = c_V = 0.03$ (Johnson and Morgan 1953).

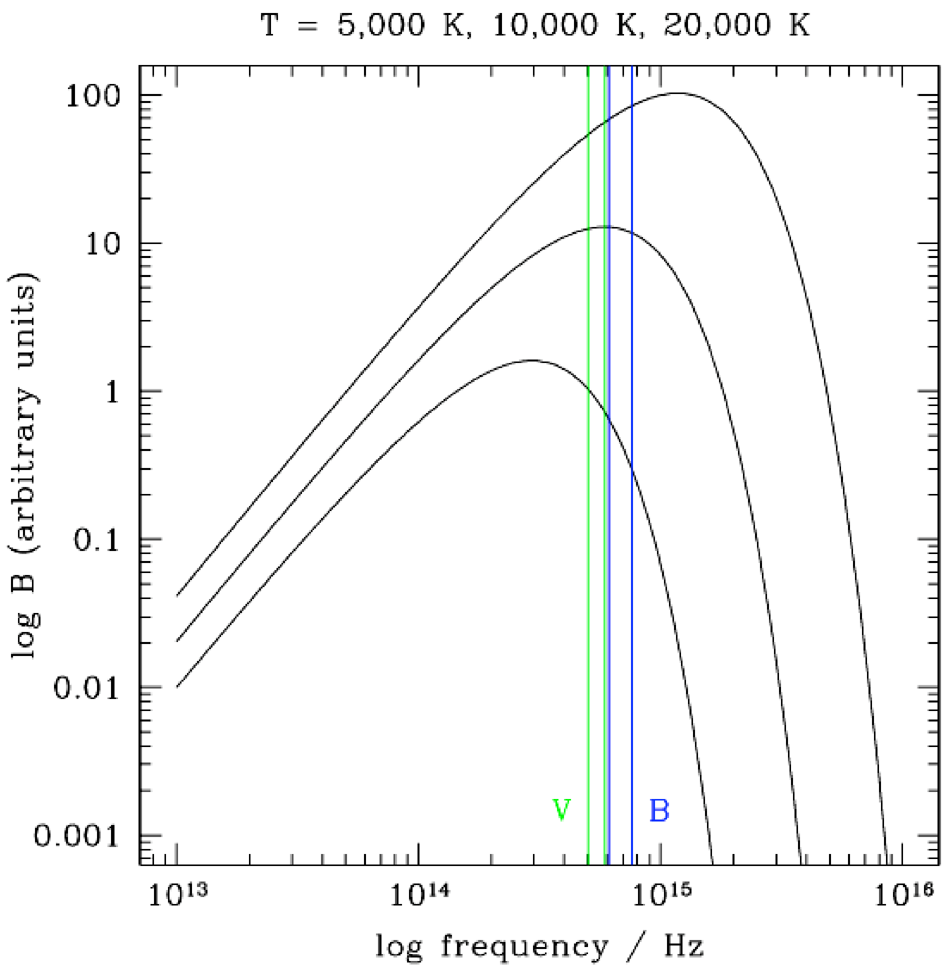
The Infrared Photometric Bands

… where the atmospheric transmission windows are



Colors From Magnitudes

The color of an object is defined as the difference in the magnitude in each of two bandpasses: e.g. the *(B-V)* color is: $B\text{-}V = m_B\text{-}m_V$



Stars radiate roughly as blackbodies, so the color reflects surface temperature.

Vega has T = 9500 K, by definition color is zero.

(From P. Armitage)

Apparent vs. Absolute Magnitudes

The absolute magnitude is defined as the apparent mag. a source would have if it were at a distance of 10 pc:

$$M = m + 5 - 5 \log d/\mathrm{pc}$$

It is a measure of the **luminosity** in some waveband.

For Sun: $M_{\odot B} = 5.47$, $M_{\odot V} = 4.82$, $M_{\odot bol} = 4.74$

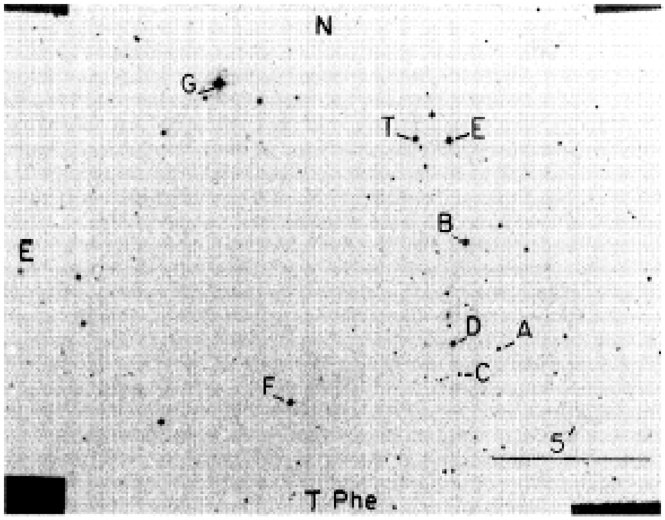
Difference between the apparent magnitude m and the absolute magnitude M (any band) is a ***measure of the distance*** to the source

$$\underbrace{m - M}_{\text{Distance modulus}} = 5\log_{10}\left(\frac{d}{10\ \mathrm{pc}}\right)$$

Distance modulus

(From P. Armitage)

Photometric Calibration: Standard Stars



Magnitudes of Vega (or other systems primary flux standards) are transferred to many other, secondary standards. They are observed along with your main science targets, and processed in the same way.

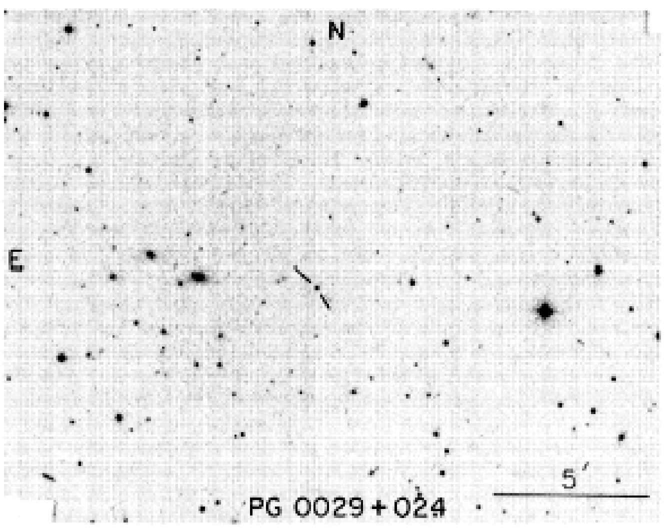


PLATE 21. (a) The field for the T Phe sequence. Star B is the eclipsing binary RW Phe. (b) The field of the star PG0029+024.

Star	α(2000)	δ(2000)	V	B-V	U-B	V-R	R-I	V-I	n	m	V
TPHE A	00:30:09	-46 31 22	14.651	0.793	0.380	0.435	0.405	0.841	29	12	0.0028
TPHE B	00:30:16	-46 27 55	12.334	0.405	0.156	0.262	0.271	0.535	29	17	0.0115
TPHE C	00:30:17	-46 32 34	14.376	-0.298	-1.217	-0.148	-0.211	-0.360	39	23	0.0022
TPHE D	00:30:18	-46 31 11	13.118	1.551	1.871	0.849	0.810	1.663	37	23	0.0033
TPHE E	00:30:19	-46 24 36	11.630	0.443	-0.103	0.276	0.283	0.564	34	8	0.0017
TPHE F	00:30:50	-46 33 33	12.474	0.855	0.532	0.492	0.435	0.926	5	3	0.0004
TPHE G	00:31:05	-46 22 43	10.442	1.546	1.915	0.934	1.085	2.025	5	3	0.0004
PG0029+024	00:31:50	+02 38 26	15.268	0.362	-0.184	0.251	0.337	0.593	5	2	0.0094
PG0039+049	00:42:05	+05 09 44	12.877	-0.019	-0.871	0.067	0.097	0.164	4	3	0.0020
92 309	00:53:14	+00 46 02	13.842	0.513	-0.024	0.326	0.326	0.652	2	1	0.0035
92 235	00:53:16	+00 36 18	10.595	1.638	1.984	0.894	0.911	1.806	5	2	0.0058
92 322	00:53:47	+00 47 33	12.676	0.528	-0.002	0.302	0.306	0.608	2	1	0.0007
92 245	00:54:16	+00 39 51	13.818	1.418	1.189	0.929	0.907	1.836	21	8	0.0028
92 248	00:54:31	+00 40 15	15.346	1.128	1.289	0.690	0.553	1.245	4	2	0.0255

Evolution of Astronomical Detectors

- **Historical evolution:** Eye → Photography → Photoelectic (single-channel) devices → Plate scanners → TV-type imagers → Semiconductor-based devices (CCDs, IR arrays, APDs, bolometers, …) → Energy-resolution arrays (STJ, ETS)
- Astronomical detectors today are applications of solid state physics
- **Detector characteristics:** Sensitivity as a f(□), size, number of pixels, noise characteristics, stability, cost
- **Types of noise:** Poissonian (quantum), thermal (dark current, readout), sensitivity pattern
- **Quantum efficiency:** QE = N(detected photons)/N(input photons)
- **Detective Quantum Efficiency:** DQE = $(S/N)_{out}/(S/N)_{in}$

Old Stuff: Photomultiplier Tubes

Typical QE ~ 5-10%
UV/B sensitive, poor in R/IR

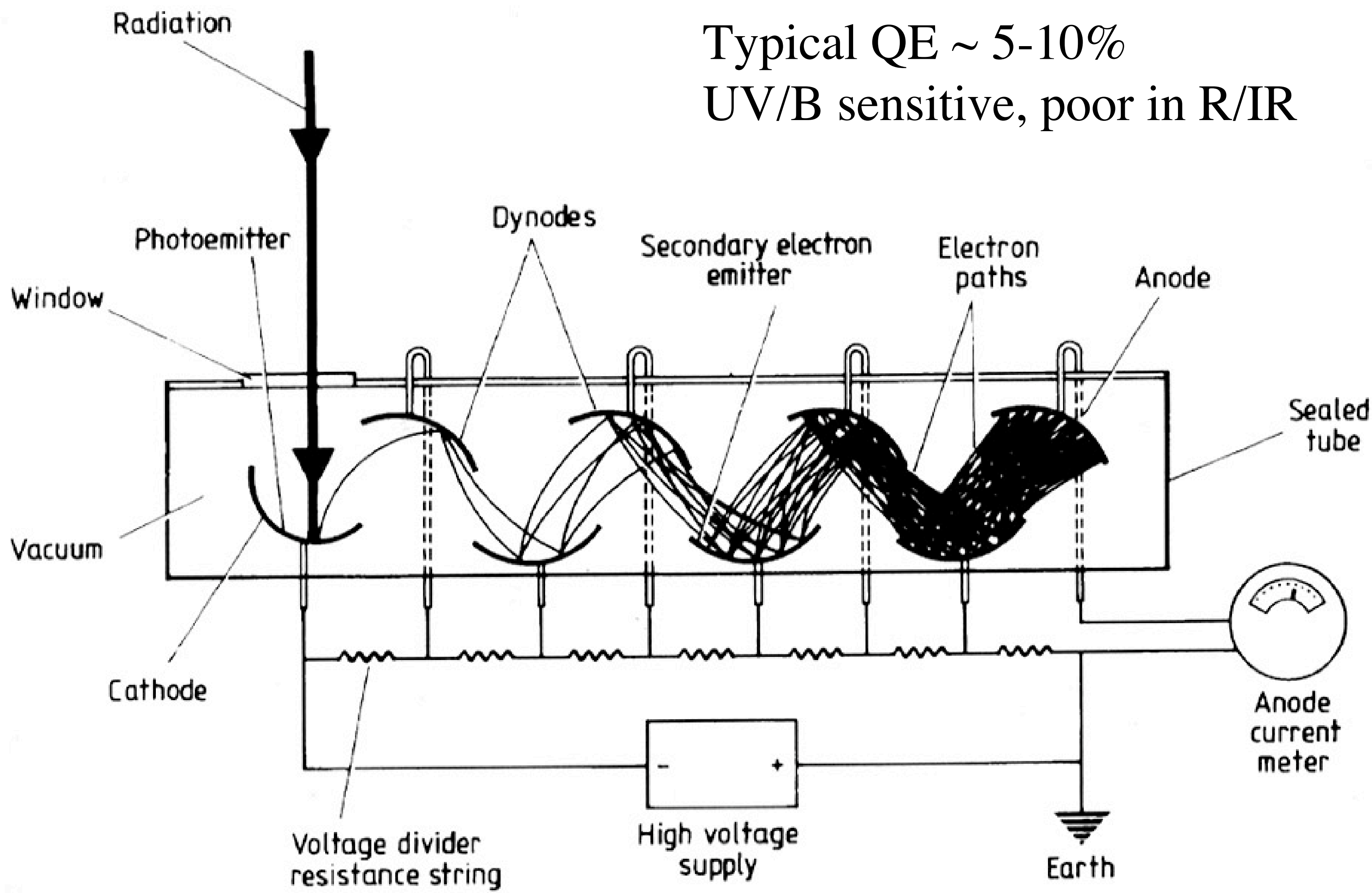


Figure 1.1.19. Schematic arrangement for a photomultiplier.

Microchannel Plates:

Effectively arrays of PMTs

Still used in UV (e.g., in *GALEX*)

Also for some night vision applications

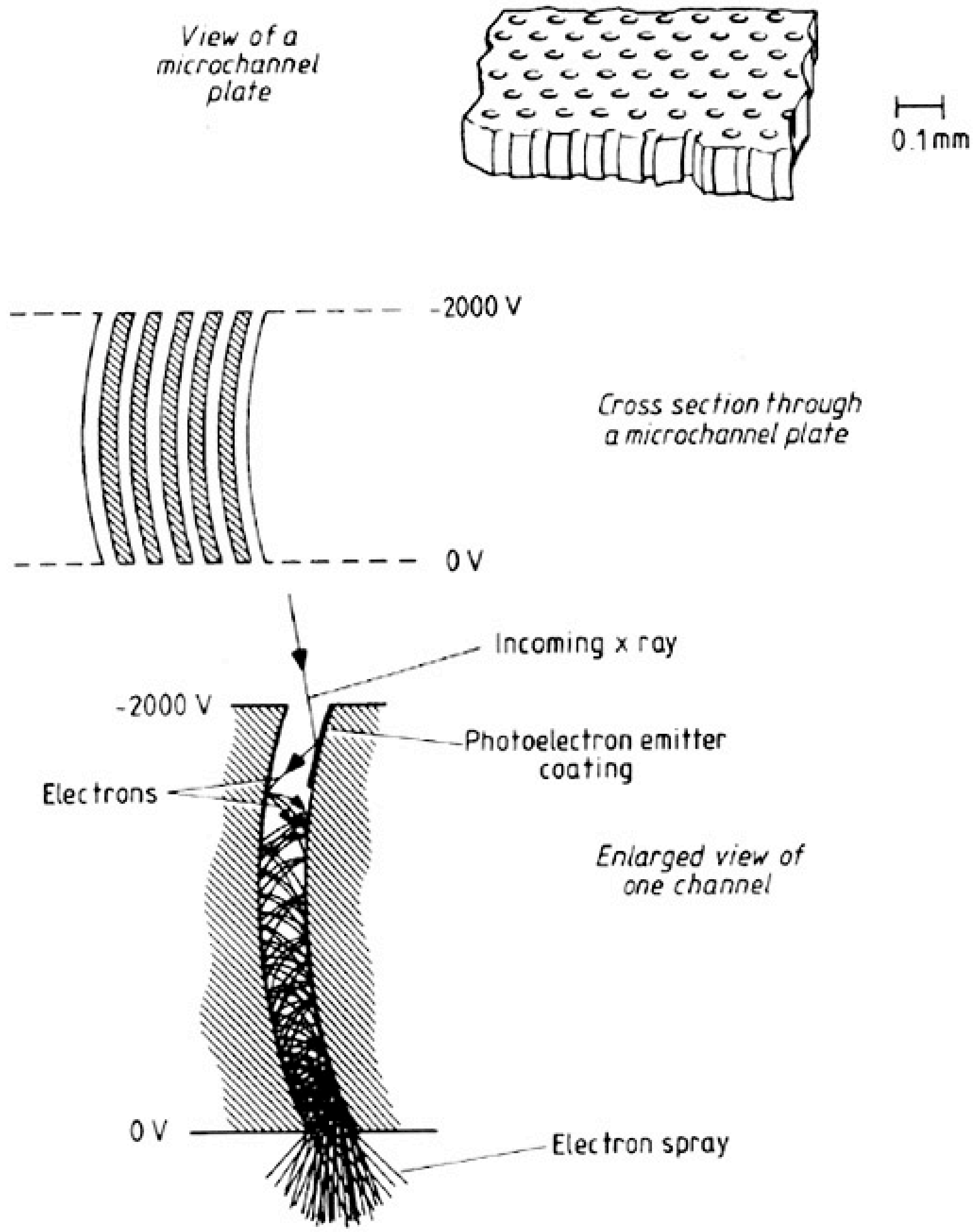


Figure 1.3.4. Schematic view of the operation of a microchannel plate.

Image Intensifiers

Still used for some night vision applications

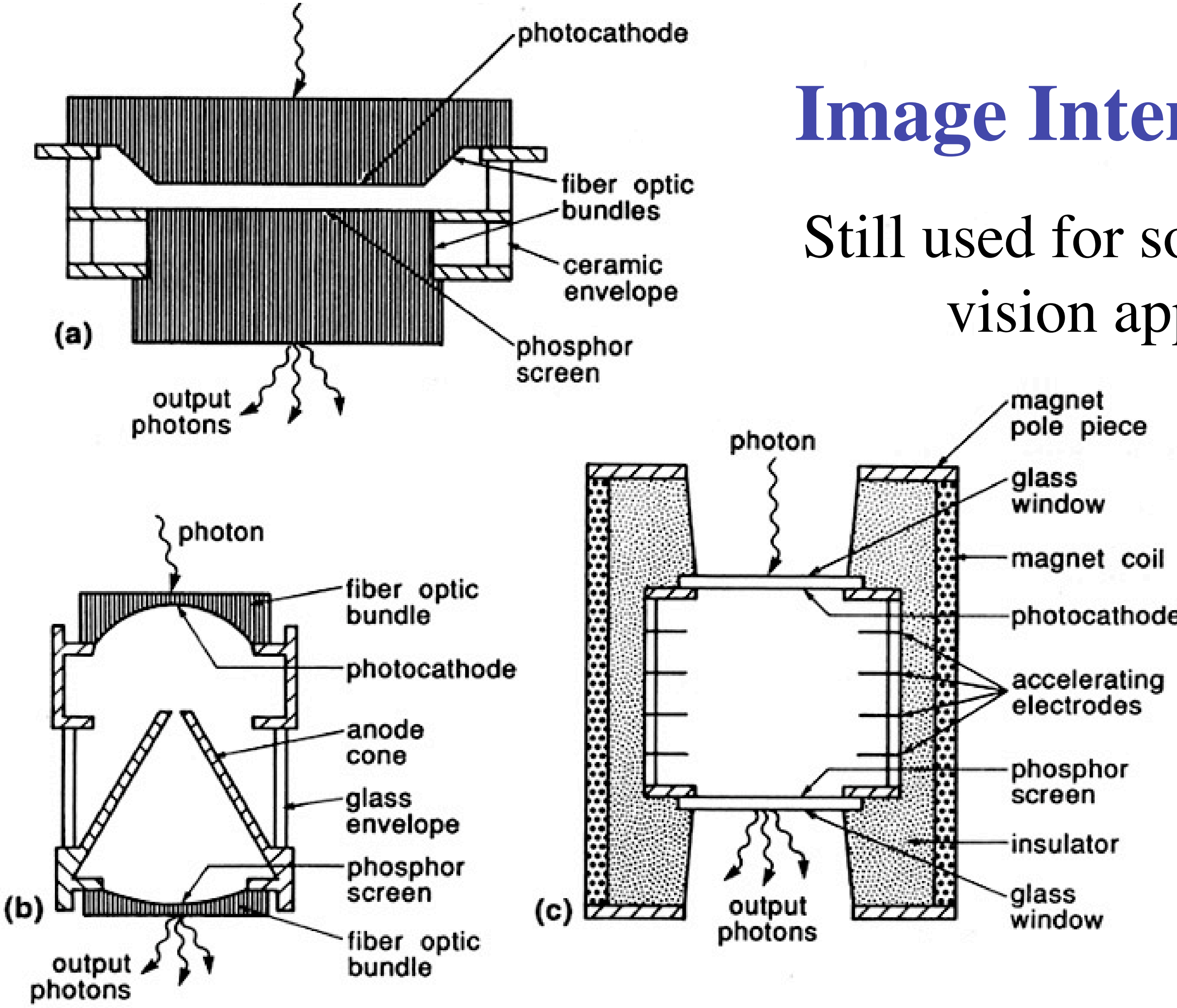
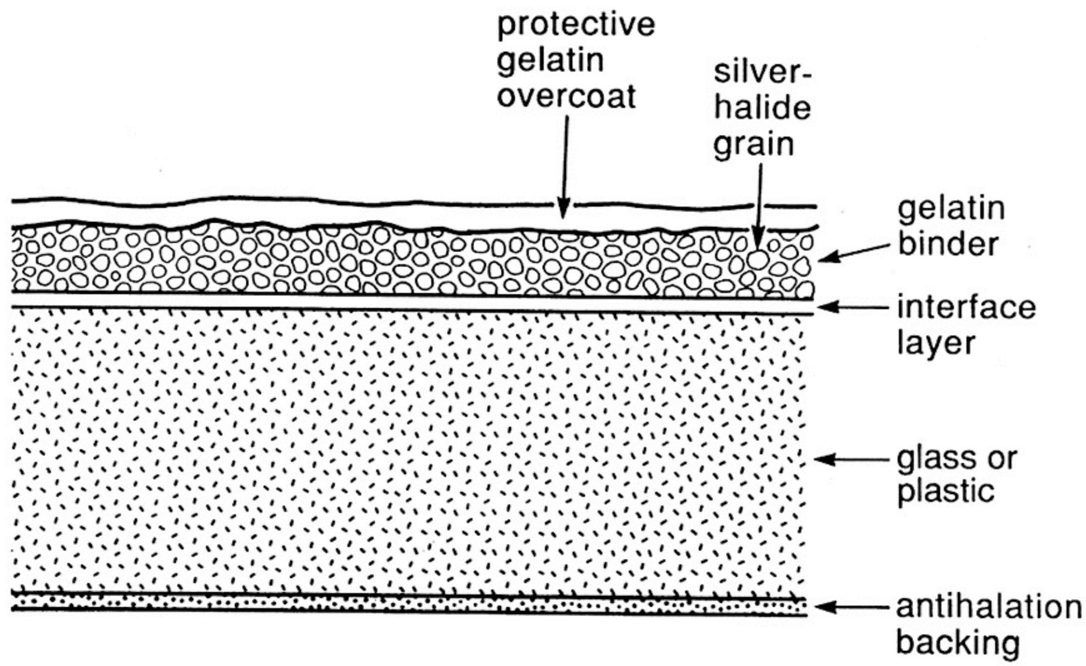


Figure 7.10. Cross-sectional diagrams of a variety of image intensifier types: (a) proximity focused; (b) electrostatically focused; and (c) magnetically focused. After Csorba (1985).

Classical Photography

Typical QE ~ 2-3%, but large formats available; can be digitized



Cross-section of a typical photographic plate.

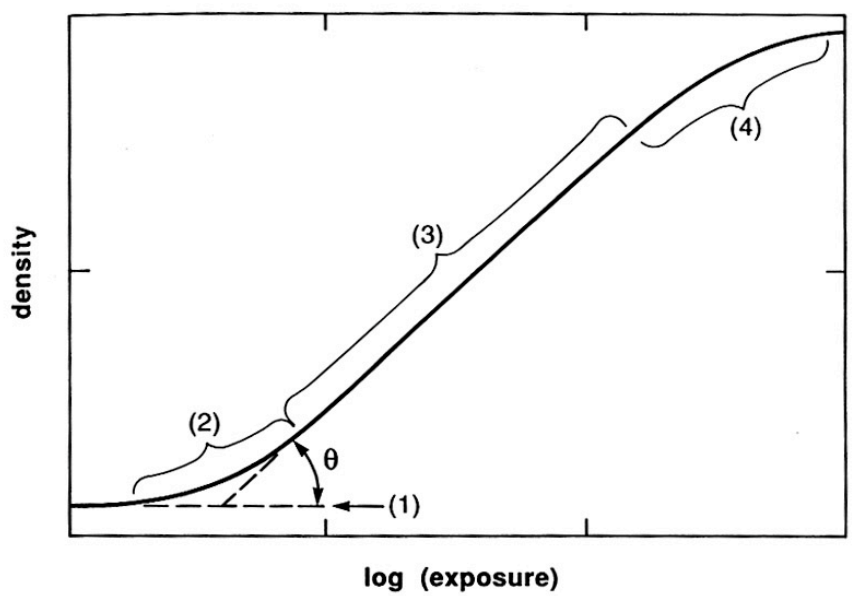


Figure 8.5. Characteristic curve. Zones of the curve include (1) level of gross fog; (2) toe; (3) straight-line portion; (4) shoulder. The contrast parameter γ (= $\tan\theta$) is discussed in Section 8.4.2.

A problem: non-linear response! (H-D curve)

Also: non-uniform

And messy …

Plate Digitization: Still used for sky surveys (DPOSS, DSS, etc.)

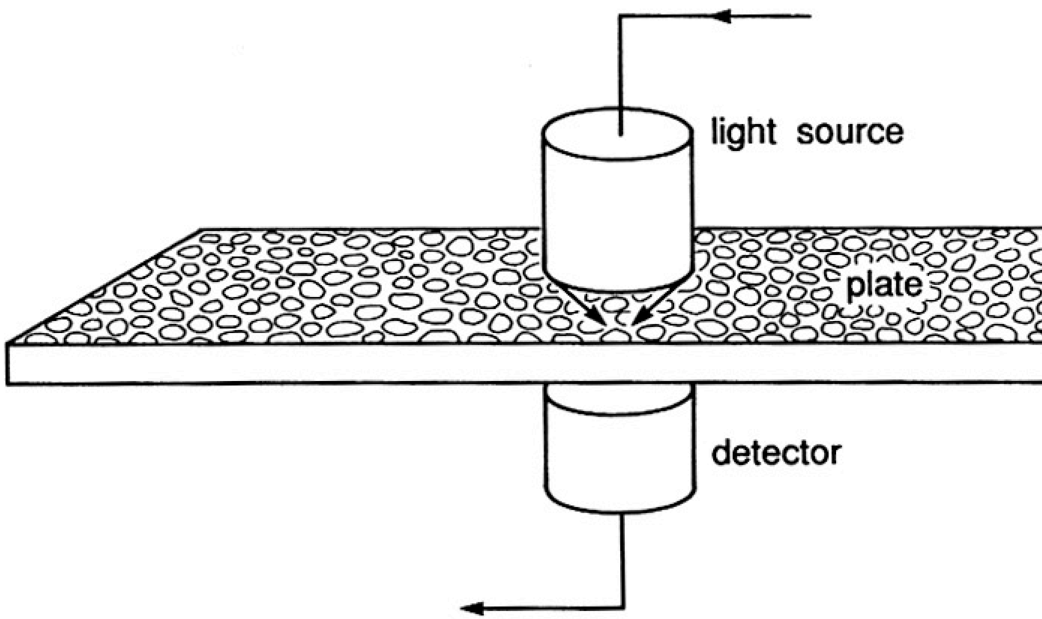


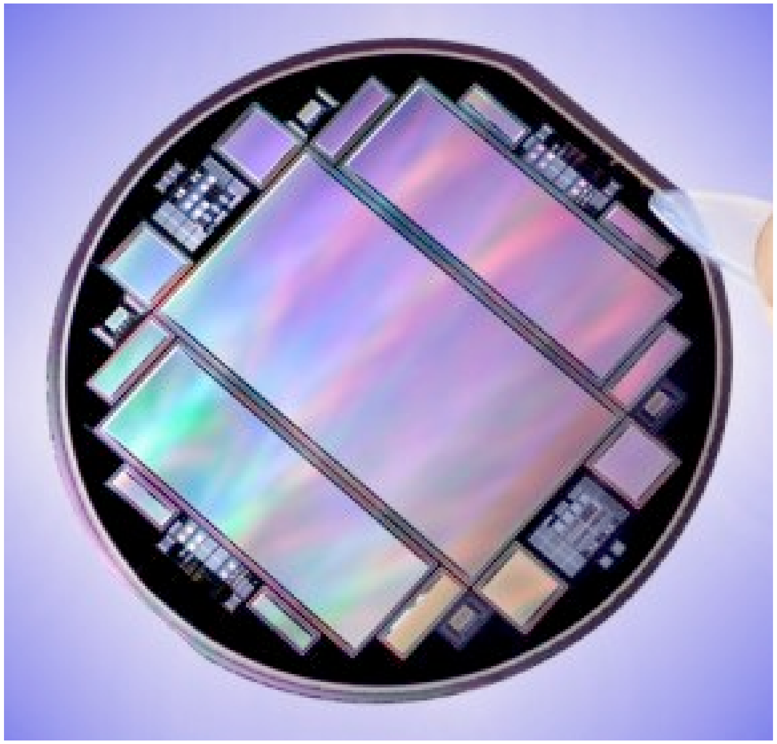
Figure 8.4. Electronic measurement of a photographic image.

Problems and challenges: Scattered light, calibration …
Limited to a pixel size of a few microns, due to the grains

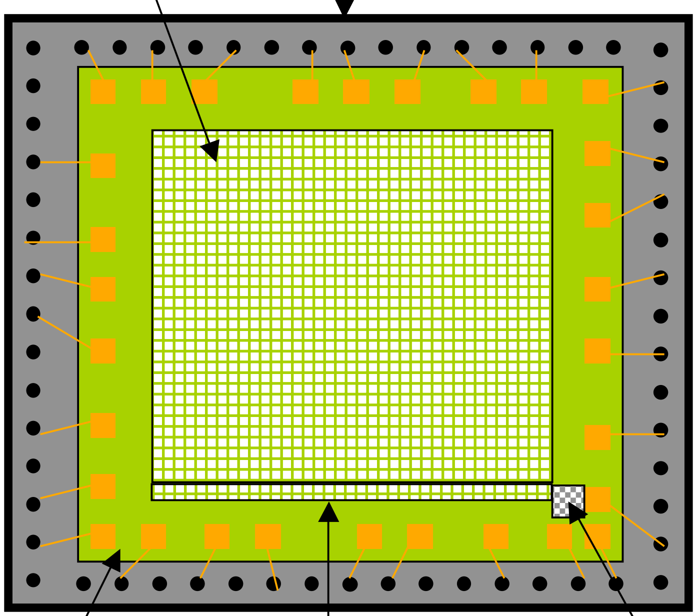
But Nowadays, Charge Coupled Devices (CCDs) Are The Detectors of Choice

(in visible, UV, and X-ray)

Nearly ideal detectors in many ways
Counting photons in a pixel array



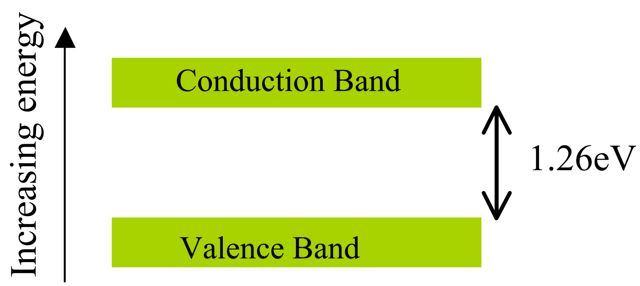
A whole bunch of CCDs on a wafer

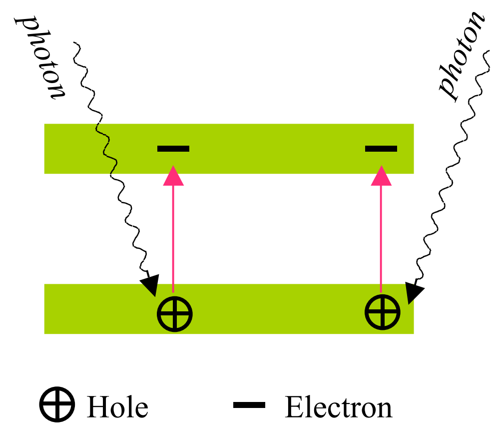


How Does A CCD Work?

Internal Photoelectric Effect in Doped Silicon

- Incoming photons generate electron-hole pairs
- That charge is collected in potential wells applied on the surface

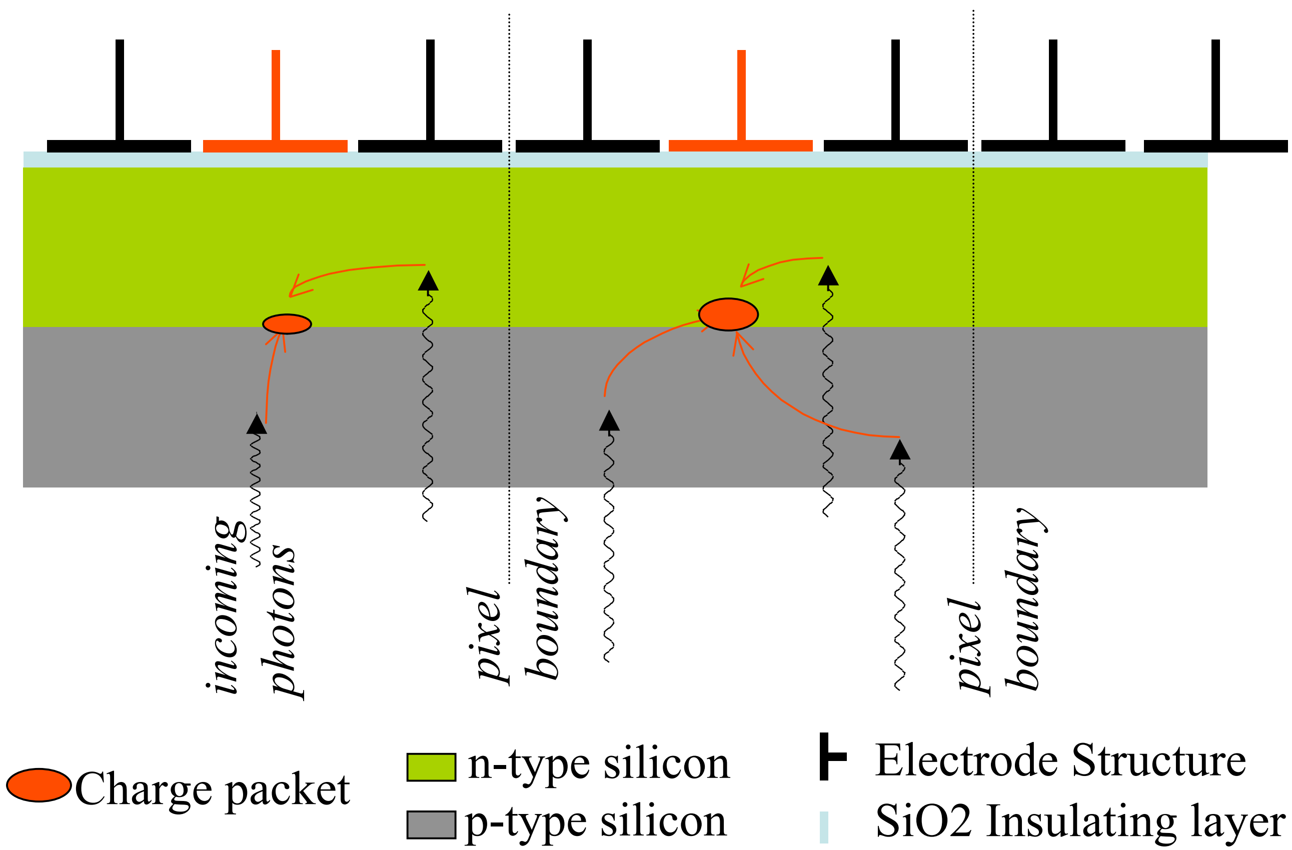




- Thermally generated electrons are indistinguishable from photo-generated electrons ➔ Dark Current ➔ keep the CCD cold!
- Silicon is transparent to photons with $E < 1.26eV$ ($\lambda \approx 1.05\ \mu m$) ➔ Red Cutoff! Need a different type of detector for IR …

How Does A CCD Work?

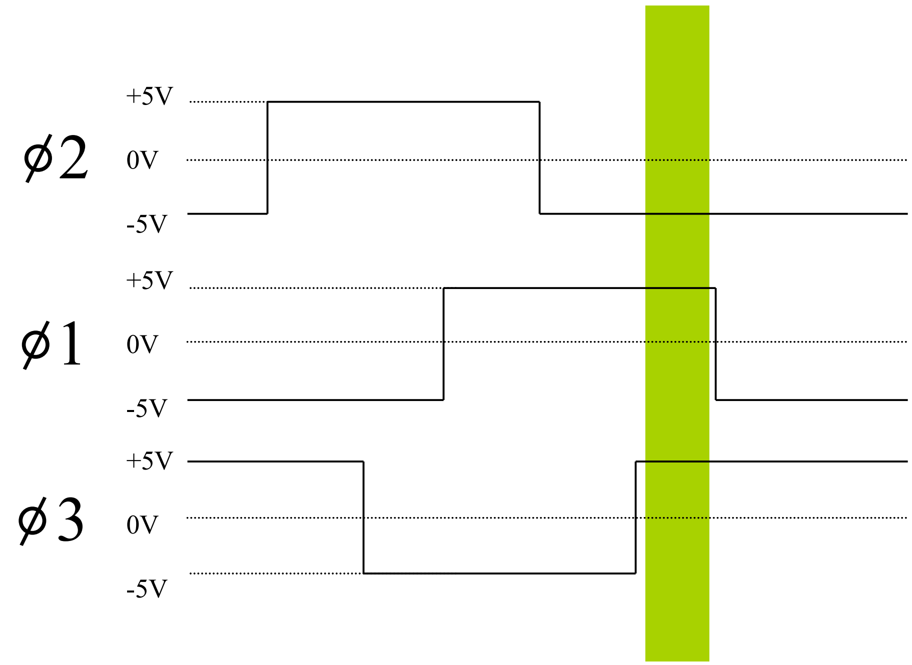
A grid of electrodes establishes a pixel grid pattern of electric potential wells, where photoelectrons are collected in “charge packets”

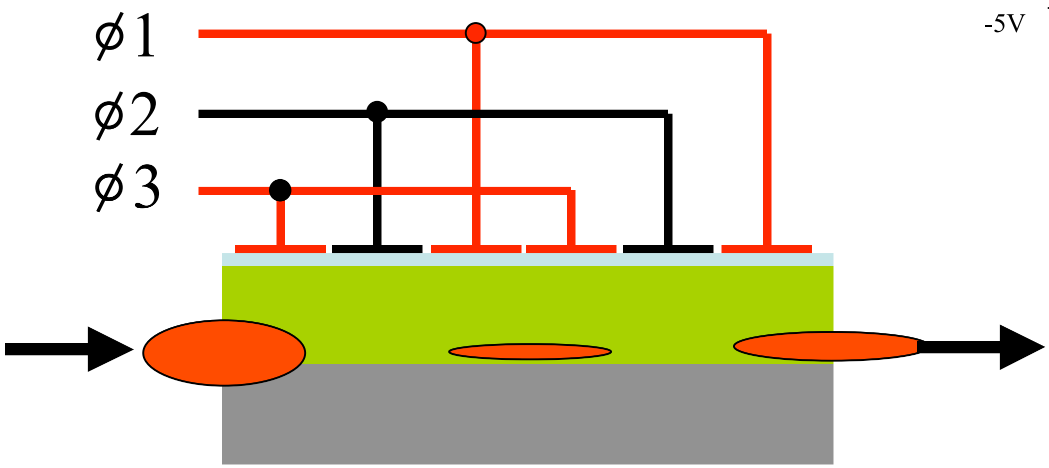


Typical well (pixel) capacity: a few $\times 10^5$ e^-. Beyond that, the charge “bleeds” along the electrodes.

Reading Out A CCD: Shift the electric potential pattern by clocking the voltages - pixel positions shift

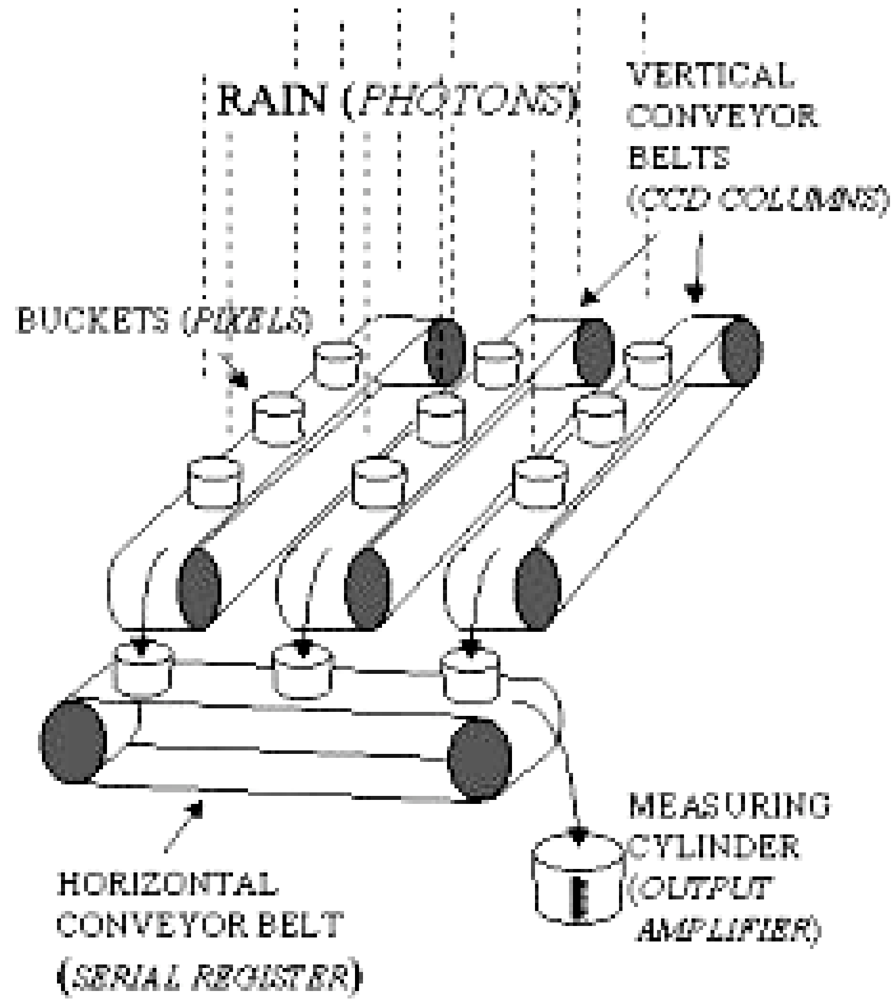
Charge packet from subsequent pixel enters from left as first pixel exits to the right.

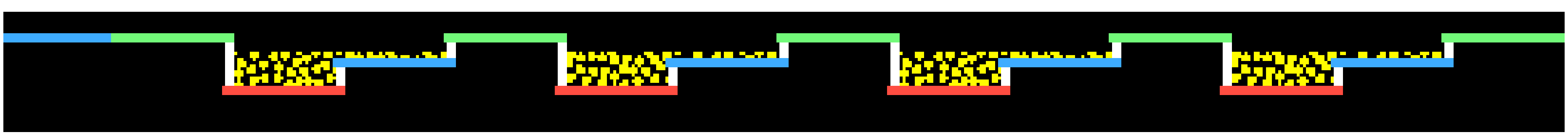




Pattern of collected electrons (= an image) moves with the voltage pattern, and is read out

Reading Out A CCD: The Buckets-on-a-Conveyor Metaphor

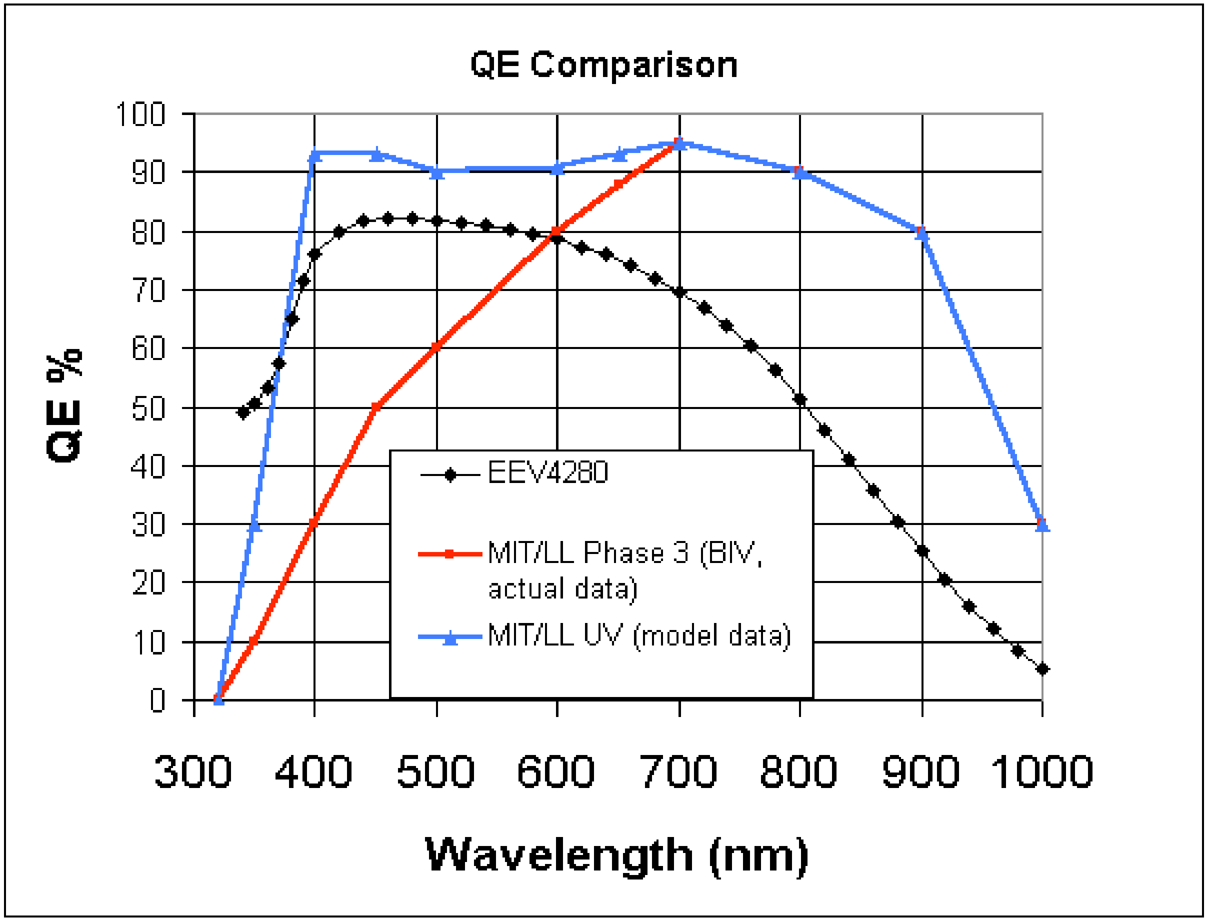




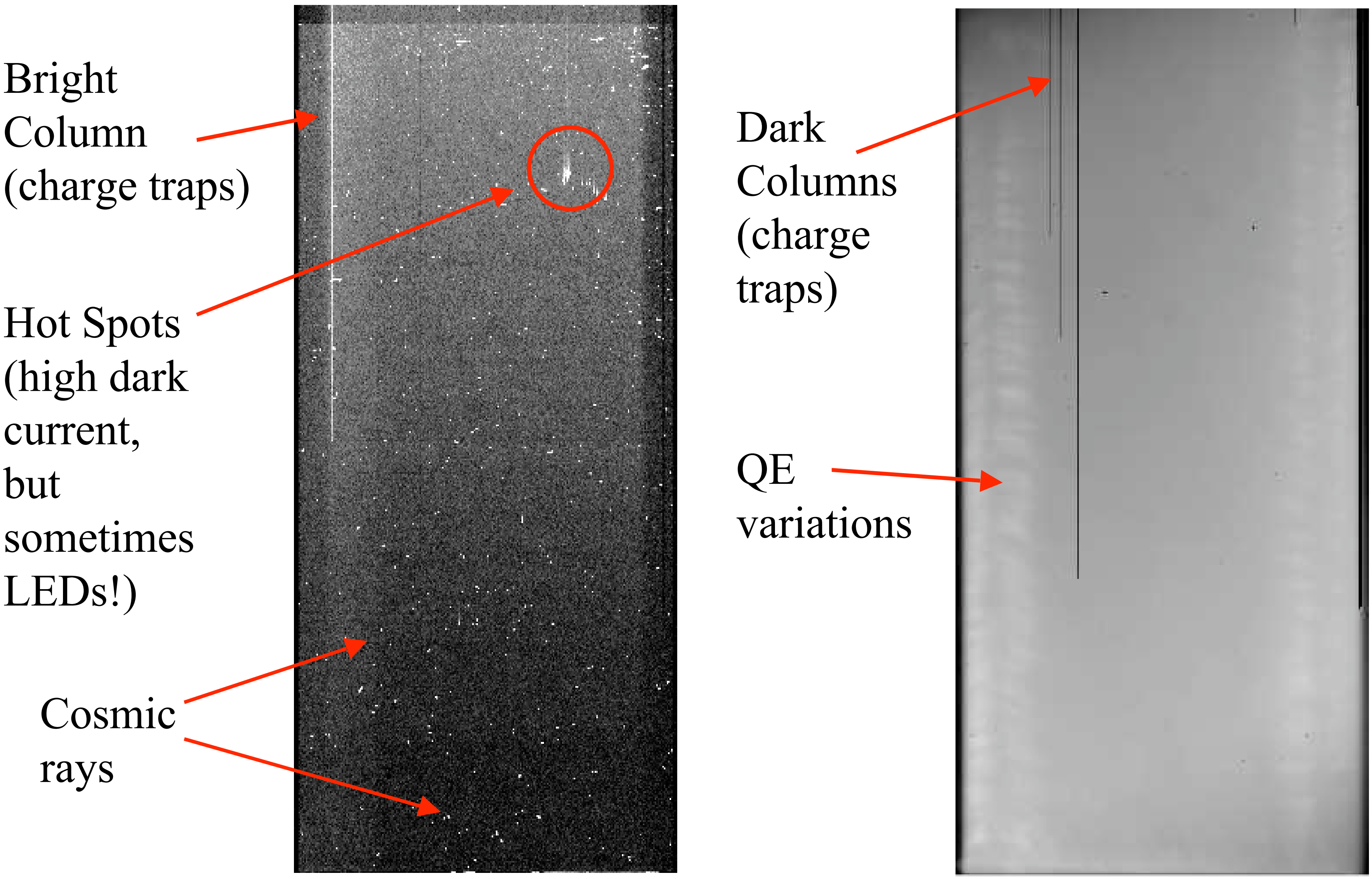
CCDs: The Quantum Efficiency

Nearly a unity through most of the visible

Usually lower in the blue/UV, due to the absorption of photons before they reach the p.e. layer - cured by doping, phosphor dyes, etc.



CCDs Are *Not* Perfect …



Noise Sources in a CCD Image

Readout Noise: Caused by electronic in the CCD output transistor and in the external circuitry; typically □$_{RON}$ ~ 2-3 e^-

Dark Current: Caused by thermally generated electrons in the CCD. Eliminated by cooling the CCD.

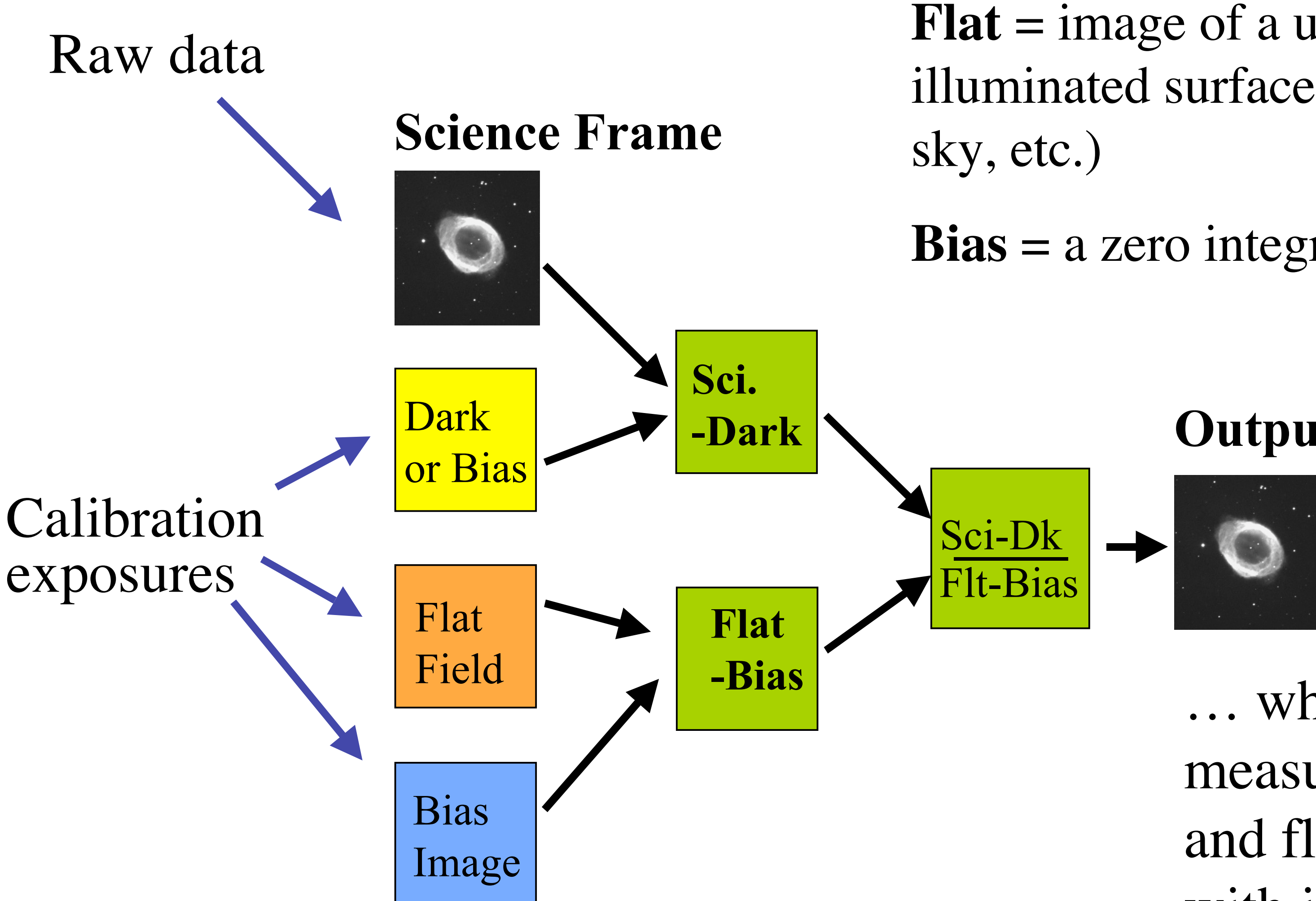
Photon Noise: Also called "Shot Noise". Photons arrive in an unpredictable fashion described by Poissonian statistics.

Pixel Response Nonuniformity: Also called "Pattern Noise". QE variations due to defects in the silicon and manufacturing. Removed by "Flatfielding"

Reducing A CCD Image

Flat = image of a uniformly illuminated surface (a dome, sky, etc.)

Bias = a zero integration image



… which you measure, analyse, and flux-calibrate with images of standard stars

IR (Hybrid) Arrays

Not like CCDs!

Each pixel is read out through its own transistor.

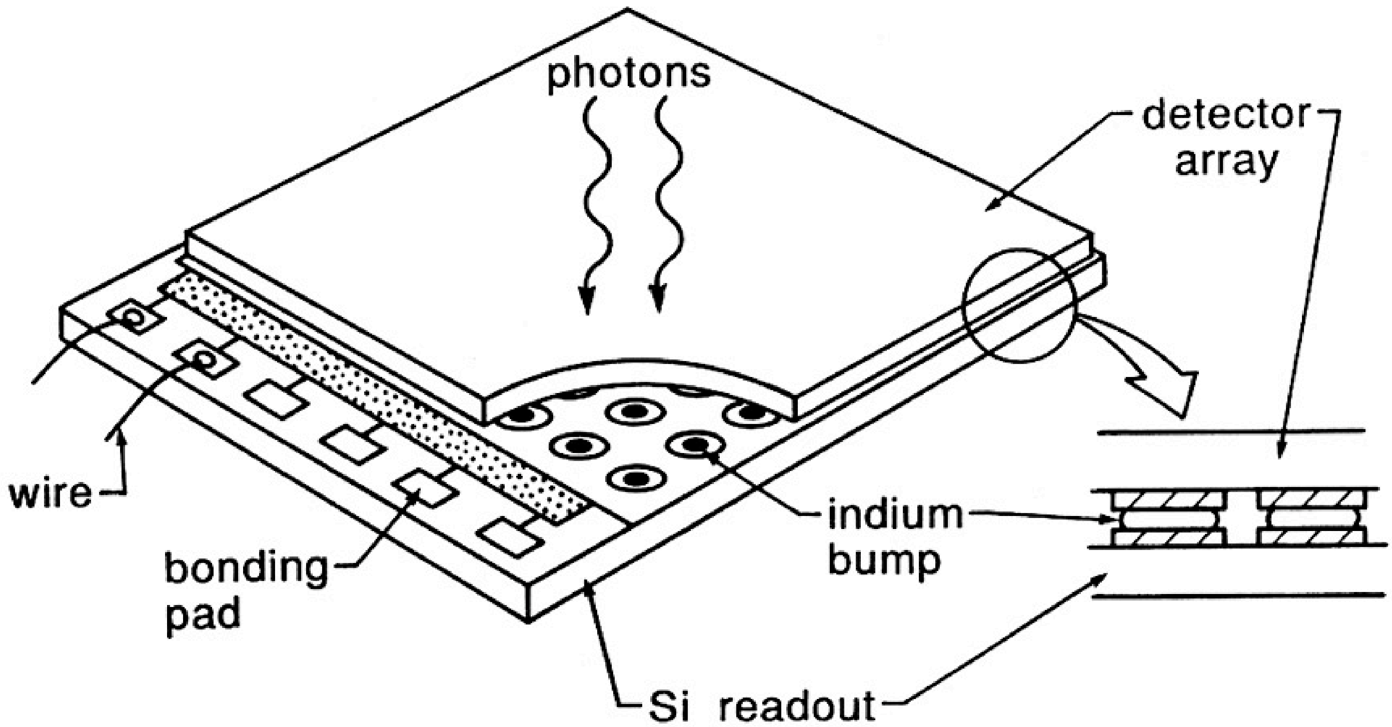
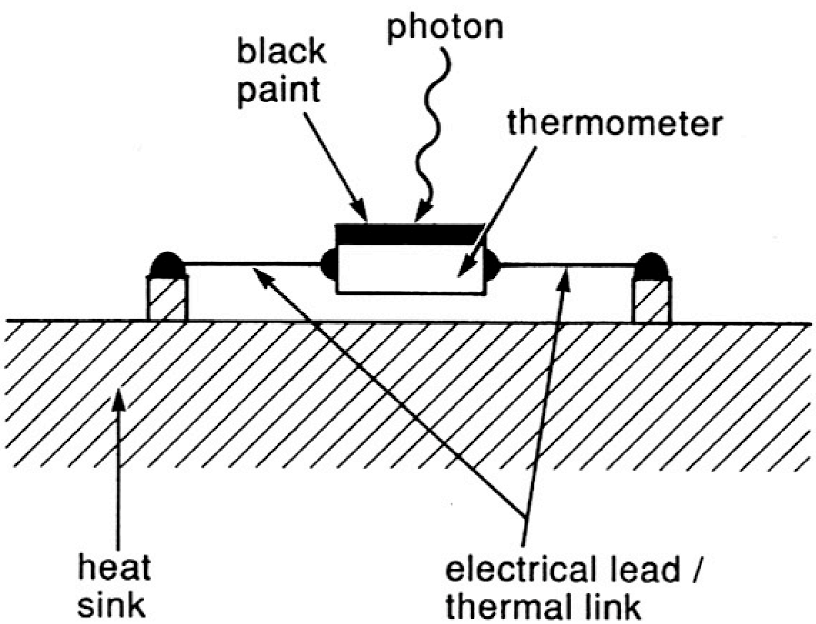


Figure 6.1. Infrared direct hybrid array.

Typical materials:
HgCdTe, InSb, PtSi, InGaAs

Bolometers for FIR/sub-mm



“Spiderweb” bolometer

The Future: Energy-Resolving Arrays

Superconducting Tunnel Junctions (STJ),
And Transition-Edge Sensors (TES)

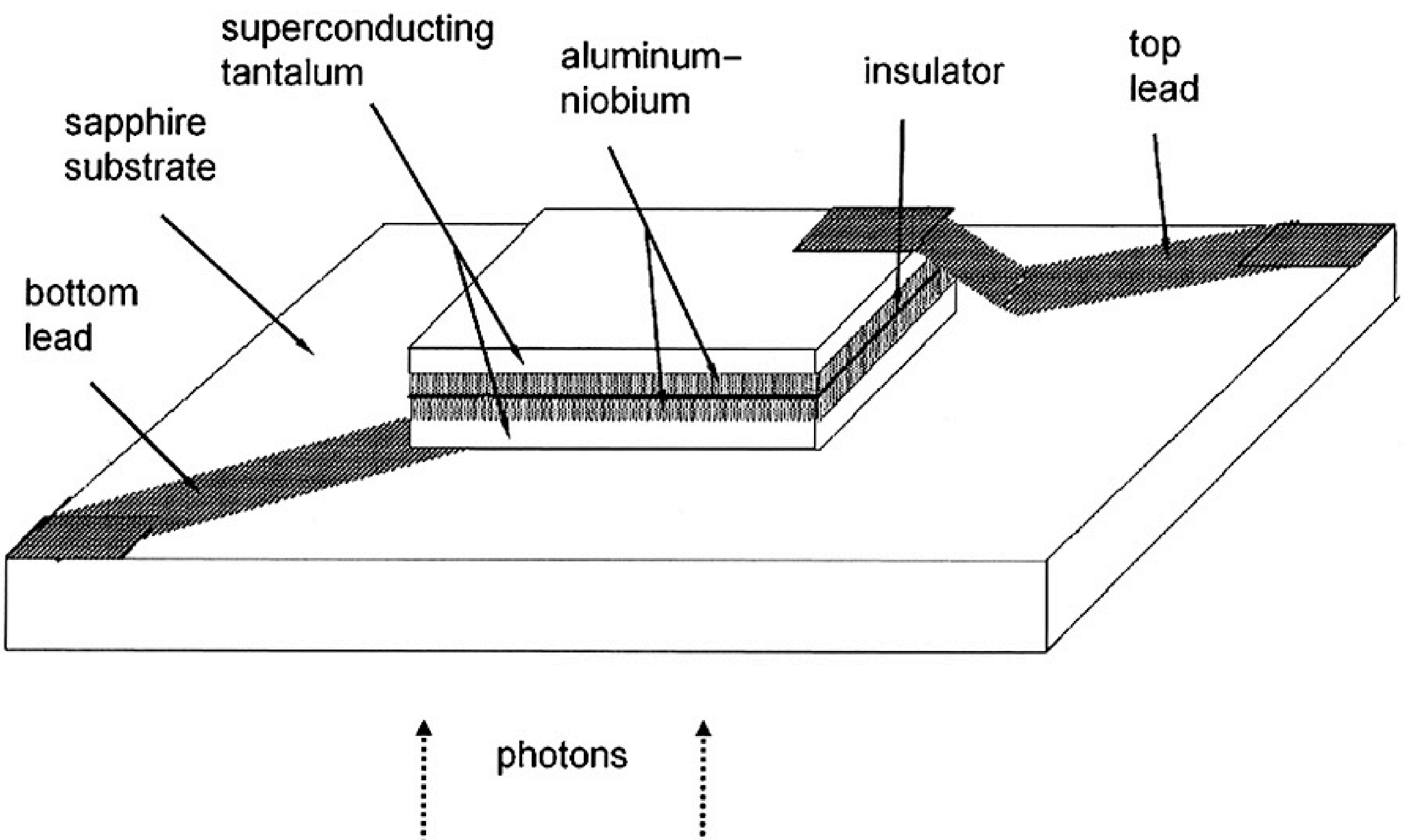
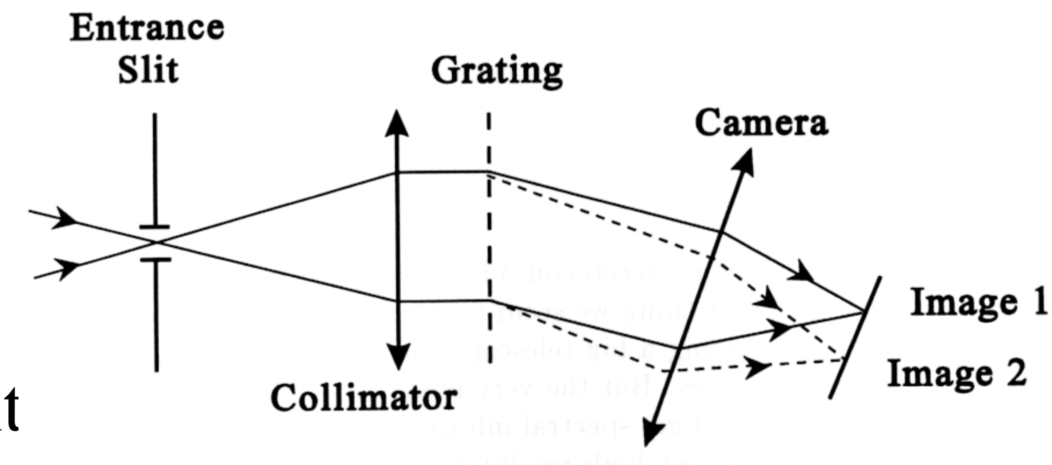


Figure 4.18. Superconducting tunnel junction (STJ) detector.

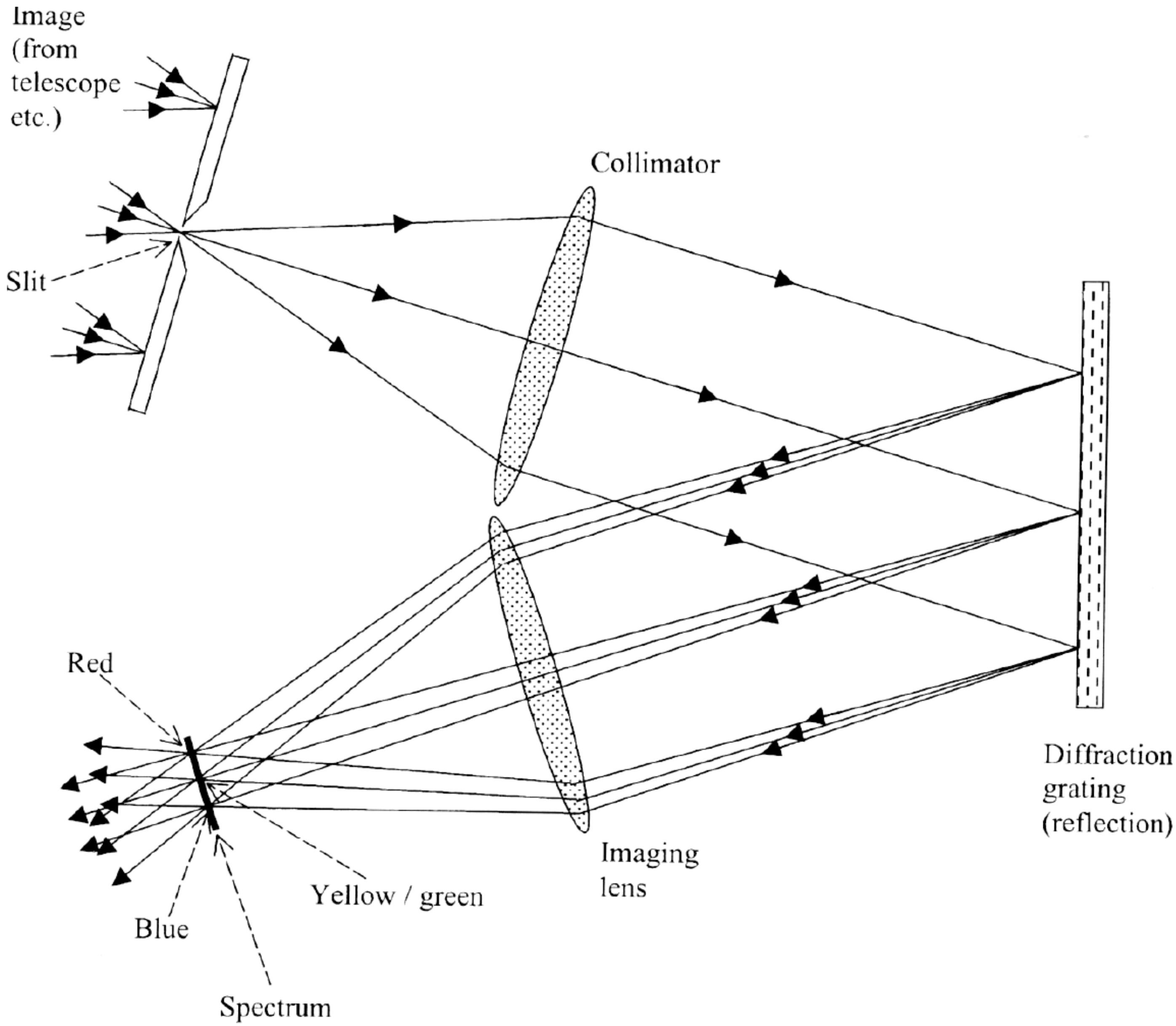
Types of Spectrographs

- By type of dispersing element:
  - Grating (transmission or reflection)
  - Prism (rare, except as a cross-dispersor)
  - Grism = grating on a prism
  - Narrow-band imaging
  - Interferometry



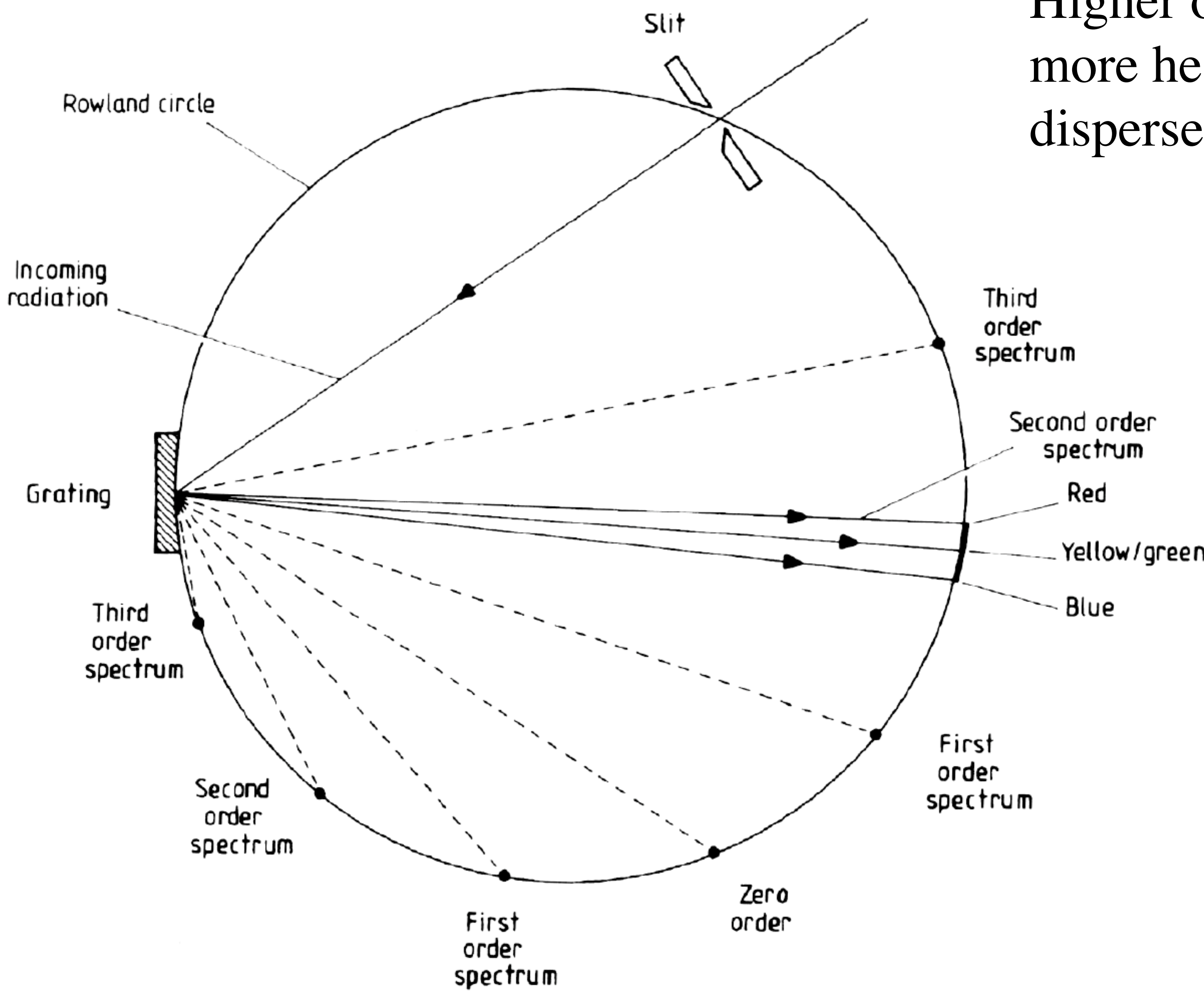
- By geometry:
  - Long-slit or multislit
  - Aperture of multi-fiber
  - Integral field units (IFU): lenslets or fiber bundles
  - Tunable imagers (e.g., Fabry-Perot)

Difraction Grating Spectrograph



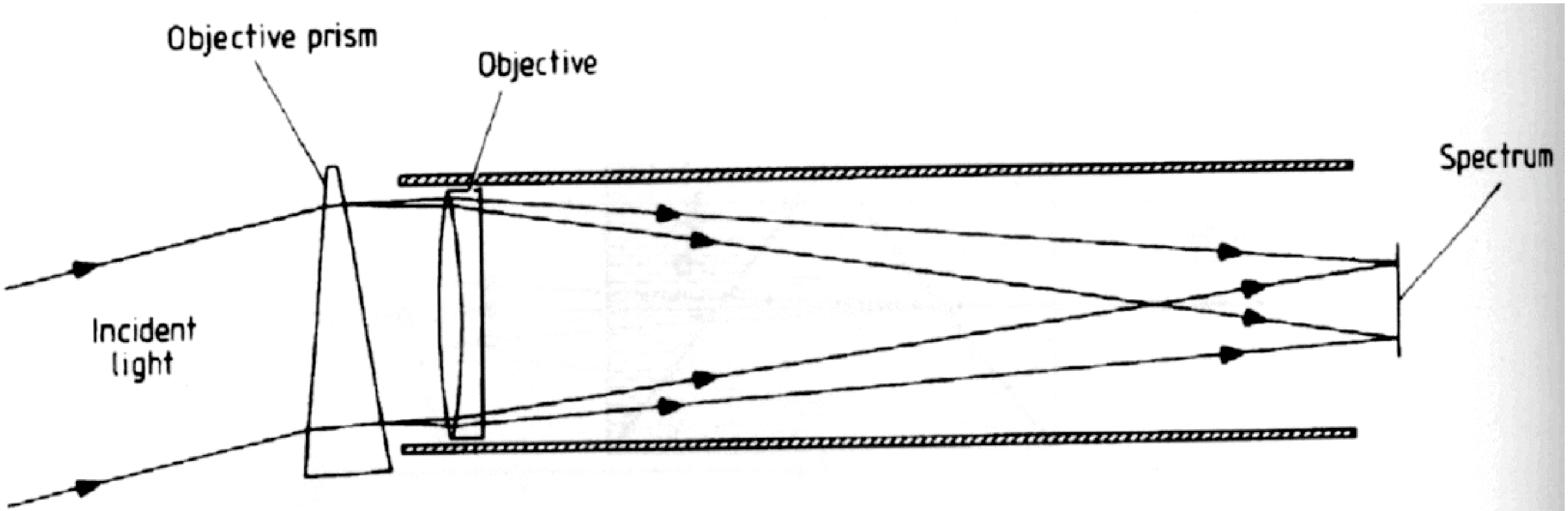
Grating Orders

Higher orders are more heavily dispersed



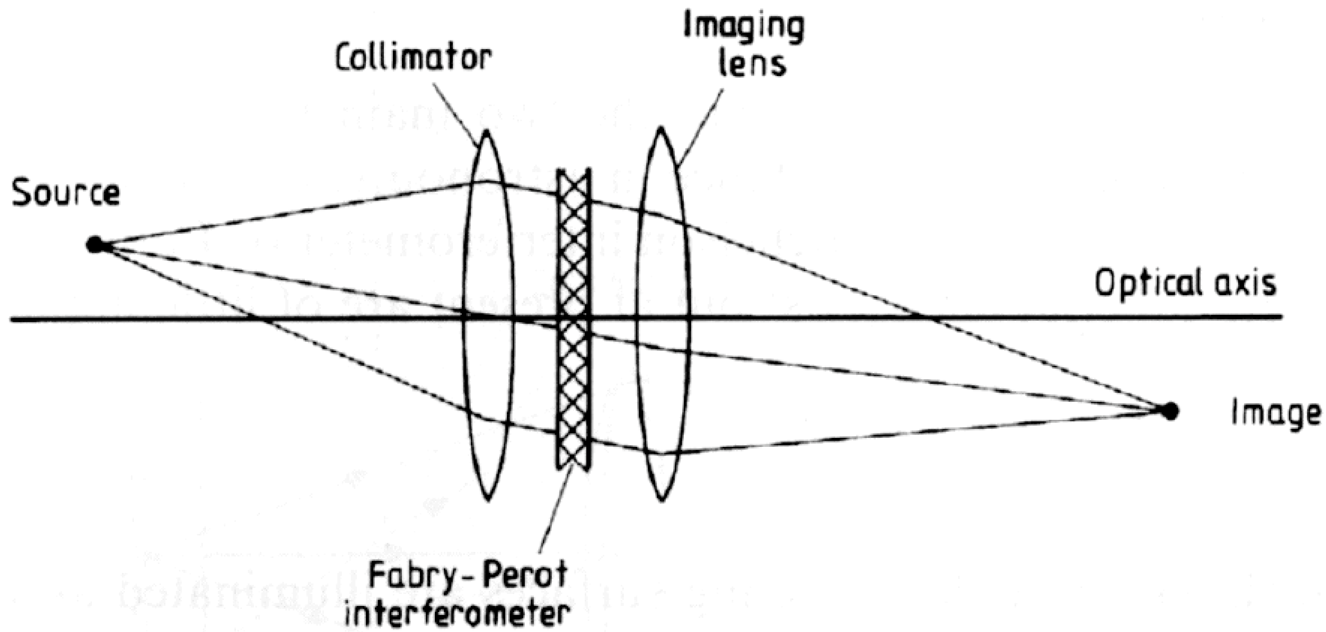
Slitless Spectroscopy

Place a dispersing element in the front of the telescope/camera:
Each source has a dispersed image (generally a low disp.)



Good for wide-field surveys, but only for bright sources:
the sky foreground still has the light from all wavelengths

Narrow-Band Imaging: Interferrence Filters, Fabry-Perot



Using a filter which is a resonant cavity (thickness = n × □).
Coatings or order-sorting filter can be used to isolate 1 order.
If made of a piezoelectric material ➞ tunable Fabry-Perot etalon.

Fourier-Transform Spectrometer

Really a Michelson Inetrefometer

Baseline scans → $\Box_{peak}$