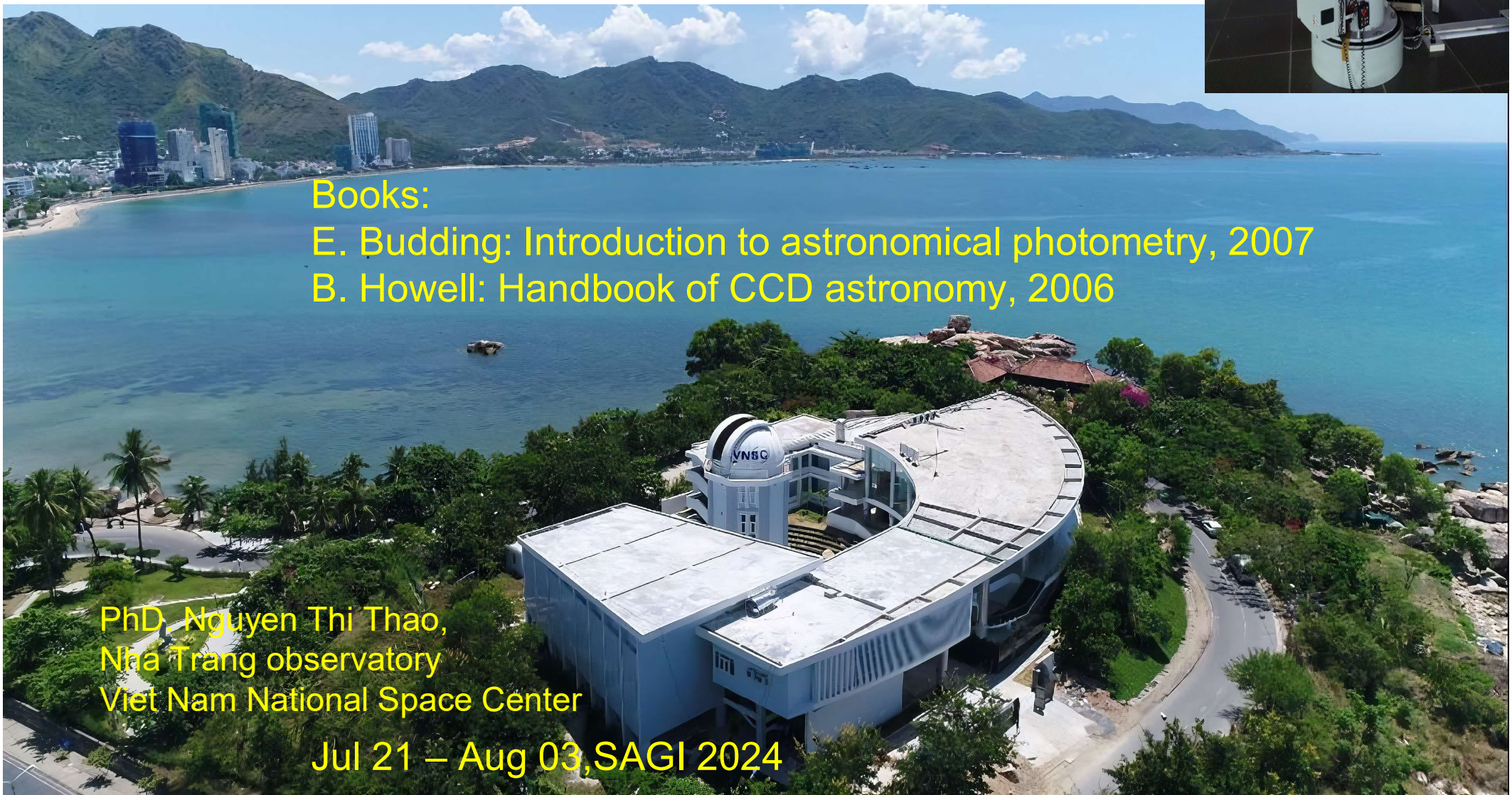
An introduction to photometry and photometric measurements



Books:

E. Budding: Introduction to astronomical photometry, 2007

B. Howell: Handbook of CCD astronomy, 2006

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An outline

1. Early observations and methods
2. Basic concepts and terminology
3. Photometric systems
4. Measuring magnitudes on CCD array
5. Applications of photometry

1. Early observations and methods

190 BC - 120 BC

Megalê Syntaxis – Almagestum

(Claudius Ptolemy, 2nd CE)

1. Early observations and methods

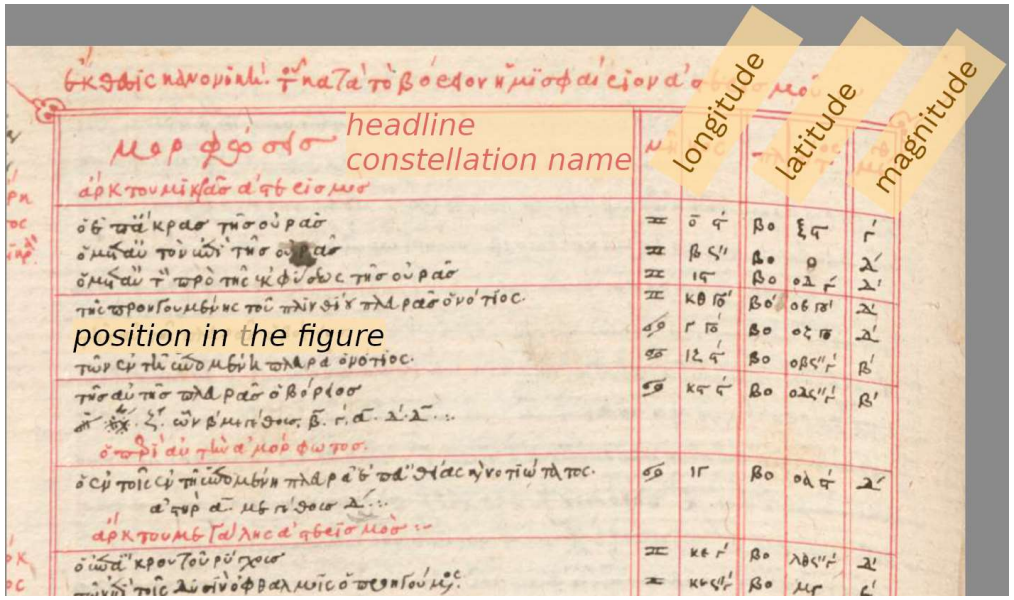
Photometry is the measurement of the brightness of celestial objects such as stars, planets, and galaxies using electromagnetic radiation.

Hipparchus observed stars with naked eyes, classified them based on their apparent brightness as seen from Earth, and categorizing them into six magnitudes

Magnitude 1: being to the brightest stars
Magnitude 6: being to the faintest stars

Each grade of magnitude was considered twice the brightness of the following grade.

The human eye has a **logarithmic** response to incident light.



Astronomer	Timeline	Contributions
Hipparchos	**130 BCE**	**Compiled a catalogue of stars with magnitude values; his work was preserved through Ptolemy's Almagest.**
Claudius Ptolemy	**2nd CE**	**Authored the Almagest, which included Hipparchos' star magnitudes and positional determinations.**
Abdullah al-Mamun	Early 9th CE	Founded the observatory at Baghdad, promoting advancements in astronomical instrumentation and methods.
Al Battani (Albategnius)	Early 9th CE	Improved Ptolemy's value for the precession constant through new observations.
Abd al-Rahman Sufi	10th CE	Revised and checked the magnitudes and positions of stars in the Almagest, publishing a new list with more precise values.
Ulugh Beg	1437	Recompiled the classical stellar catalogue, incorporating Sufi's improved magnitudes.
Tycho Brahe	**Late 16th CE**	**Compiled a new star catalogue; observed a bright nova in 1572 and a bright comet in 1577, challenging the Aristotelian view of an unchanging sky.**
David Fabricius	1596	Announced the appearance of Mira, the first known variable star in the more normally used sense.
Johannes Kepler	Late 16th to early 17th CE	Collaborated with Tycho Brahe; published Tycho's catalogue in the Rudolphine Tables; observed a supernova in 1604.
W. Janszoon Blaeu	1602	Discovered the **variable star** P Cygni.
Johann Bayer	Early 17th CE	Published star charts in *Uranometria* in 1603, including classical constellations and new ones from southern sky data.
Galileo Galilei	**1609**	**Developed the telescope as a scientific instrument; extended the magnitude scale to fainter stars.**
Edmond Halley	Late 17th CE	Observed stars in the southern sky from St. Helena; published an early catalogue of these stars in 1679, speculating on variations in star magnitudes.

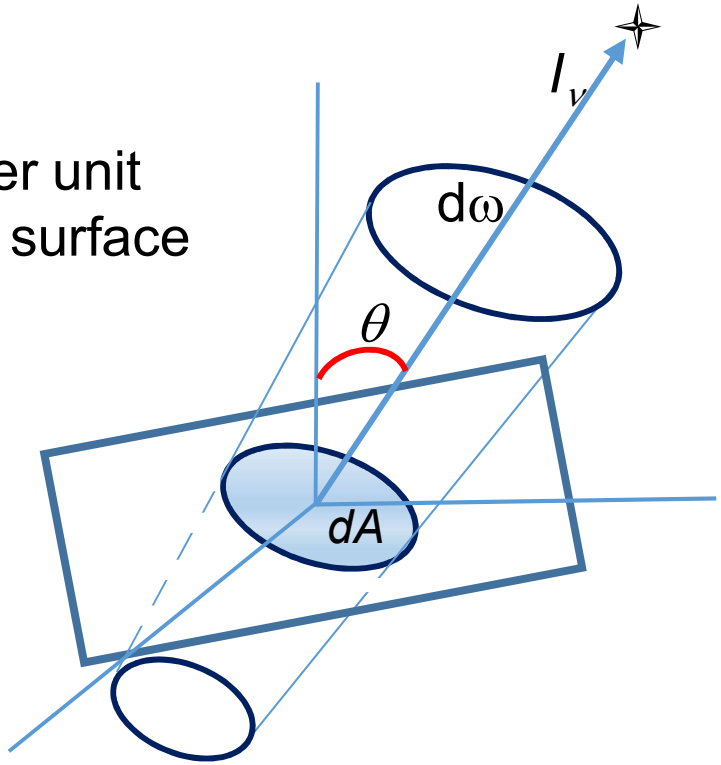
Astronomer	Timeline	Contributions
Pierre Bouguer	**Early 18th Century**	**Studied light extinction, established inverse square law, and observed limb darkening**
John Goodricke	Late 18th	Discovered eclipsing binary systems, notably Algol.
Wiliam Herschel	late 18th Century	Investigated binary stars focused on Algol and variable stars.
John Michell	Late 18th Century	Recognized gravitational binding of double stars; conjectured black holes; determined photometric parallax of Vega.
John Herschel	Mid 19th Century	Improved consistency in magnitude estimates; extensive observational work.
J.K.F.Zollner	Mid 19th Century	Developed advanced photometer designs.
N.R Pogson	**1856**	**Formalized the stellar magnitude scale (logarithmic relation)**
G.M.Minchin & 6. Fitzgerald	**1892**	**Introduced selenium cell for photometry.**
6. Fitzgerald	1892	Obtained significant lunar observations with the selenium cell
E.C. Pickering	Late 19th Century	Developed the meridian visual photometer at Harvard.
Joel Stebbins	Early 20th Century	Achieved first photoelectric light curve of Algol
C.Faby	**Early 20th Century**	**Introduced extra focal image measurement techniques.**
Joel Stebbins	Early 20th Century	Achieved the fist photoelectric light cuve of Algol in 1910.
AE Whitford	1932	Developed electronic amplifier for weak signals
GE Kron	1939	Improve photometer design and procedure.
G.Eiby	**1949**	**Used prototype photomultiplier for photometry.**
H.L Johnson & W. W. Morgan	**Early 1950s**	**Set up the UBV photoelectric system.**
Frank Wanlass	1967	Patent on Complementary Metal-Oxide-Semiconductor (CMOS)
Willard Boyle & George E. Smith	**1969**	**the Charge-Coupled Device (CCD) was invented**
-	-	-

2. Basic concepts and terminology

Specific intensity

$$I_\nu = \frac{dP}{\cos\theta \, dA \, d\nu \, d\omega}$$

Specific intensity is power of radiation per unit area / per unit solid angle / per unit frequency at an angle of θ to the surface



Note that, along a ray, specific intensity is conserved

Note also that specific intensity is not altered by a telescope

$$dE_\nu = I_\nu \cos\theta \, d\omega \, d\nu \, dA \, dt$$

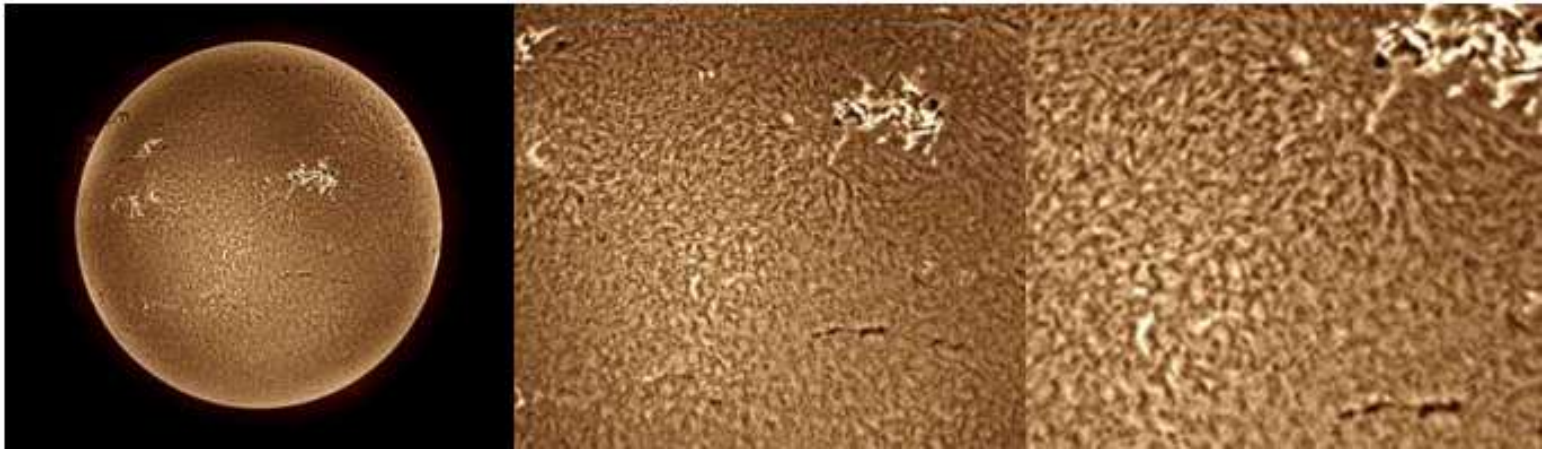
Power is energy per unit time

$$dP = I_\nu \cos\theta \, d\omega \, d\nu \, dA$$

Watts *sr* *Hz* *m*^{2}

I_ν: radiation intensity
dA: surface area
$d\theta$: angle with the surface
$d\omega$ solid angle

Flux density



Brightness or specific intensity is the same in these three images at different distances.
Note: Brightness does not depend on distance, but flux does.

The **flux density** is the amount of energy per unit area per unit wavelength (note it is monochromatic)

Total radiation intensity: $I = \int_0^\infty I_v dv$

Flux density $F \approx \int_{source} I(\theta, \emptyset) d\omega$

Flux density and magnitudes

$$1\ \mathrm{Jy} = 10^{-26}\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{Hz}}\ (\mathrm{SI}) = 10^{-23}\frac{\mathrm{erg}}{\mathrm{s}\cdot\mathrm{cm}^2\cdot\mathrm{Hz}}\ (\mathrm{cgs})$$

Janskies are too large for astronomy: most source are *μJy* or *mJy*.
Many astronomical sources are unresolved, and the specific intensity for resolved sources varies over the object, so objects are characterised by their flux densities

Can easily convert between flux densities and AB magnitudes (see later)

$$F_v\ [\mu\mathrm{Jy}] = 10^6\cdot 10^{23}\cdot 10^{-(\mathrm{AB}+48.6)/2.5} = 10^{(23.9-\mathrm{AB})/2.5}$$

Pogson's ratio (1856)

Magnitude 1

Magnitude 2

Magnitude 3

Magnitude 4

Magnitude 5

Magnitude 6

- A star of magnitude 1 is approximately 100 times brighter than a star of magnitude 6.
- Each step in magnitude corresponds to a brightness factor of about $\sqrt[5]{100} \approx$ **2.512** $\leftrightarrow$ $(2.512)^{(m_2 - m_1)}$
- This leads to the following definition of "instrumental magnitude" (from N. Pogson): the factor **2.5** was chosen to reproduce Hipparchus' scale, where f_i is the source **flux density**

$$m_i = C - 2.5\log_{10} f_i$$

The zero point ***C*** of Pogson's scale was originally defined by assigning Polaris a magnitude of exactly 2.

Astronomers later discovered that Polaris is slightly variable, so they switched to Vega as the standard reference star, assigning the brightness of Vega as the definition of zero magnitude at any specified wavelength.

- Some consequences: Differences in magnitudes correspond to a flux ratio

$$m_2 - m_1 = -2.5\log_{10}\left(\frac{f_2}{f_1}\right)$$

m_1 and m_2 are magnitudes of two stars, f_1 and f_2 are their respective brightnesses.

- Small magnitude differences approximately correspond to small flux differences (e.g, Δ5% mag ~ Δ5% flux).

- Magnitudes of objects with negative flux measurements are **undefined** which can be problematic for faint sources: better to compare fluxes in this case .

Apparent magnitudes (m)

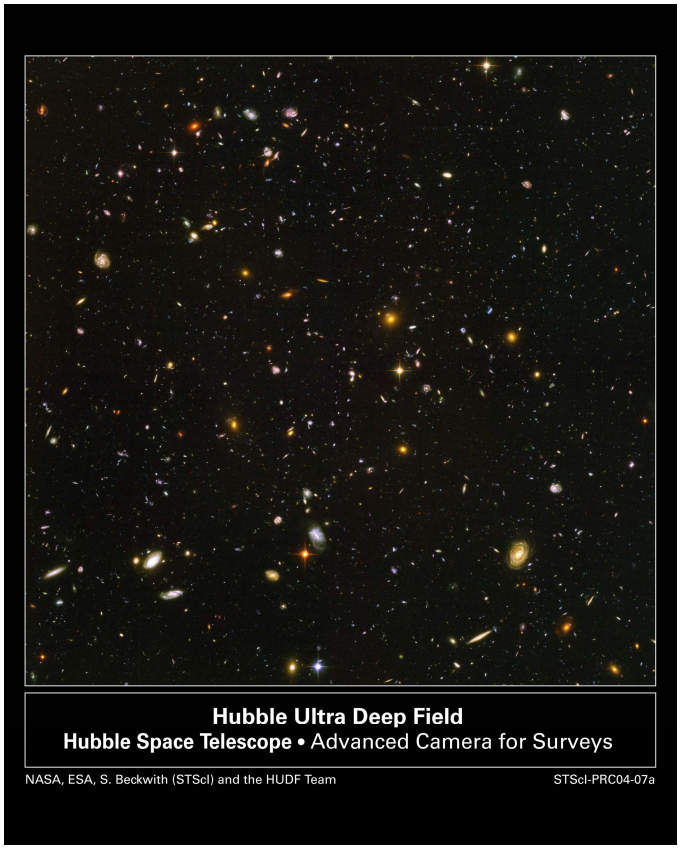
of a celestial object is a measure of its brightness as perceived by the human eye or a telescope from Earth

$$m_{star} - m_{ref} = -2.5 \log_{10}\left(\frac{f_{star}}{f_{ref}}\right)$$

The faintest (deepest) telescope image taken so far is the Hubble Ultra-Deep Field.
At m=29, this reaches more than 1 billion times fainter than what we can see with the naked eye.

$10^{(29-6)/2.5} \sim 10^9$

Object	Apparent mag (V)
Sun	-26.5
Full moon	-12.5
Venus	-4.0
Jupiter	-3.0
Sirius	-1.5
Polaris	2.0
Betelgeuse	0.5
Eye limit	6.0
Pluto	15.0
Reasonable telescope limit (8-m telescope, 4 hours integration)	28
Deepest image ever taken (Hubble UDF)	29



Absolute magnitudes (M)

of a celestial object is a measure of its intrinsic brightness, defined as the apparent magnitude the object would have if it were viewed from a distance of exactly 10 parsecs (32.616 light-years), without extinction.

$$M - m = -2.5\log_{10}\left(\frac{f_M}{f_m}\right)$$

$$F = \frac{L}{4\pi r^2}$$

at a standard distance of 10 parsecs and a distance of *d* parsecs to Earth.

$$M - m = -5\log(d/10)$$

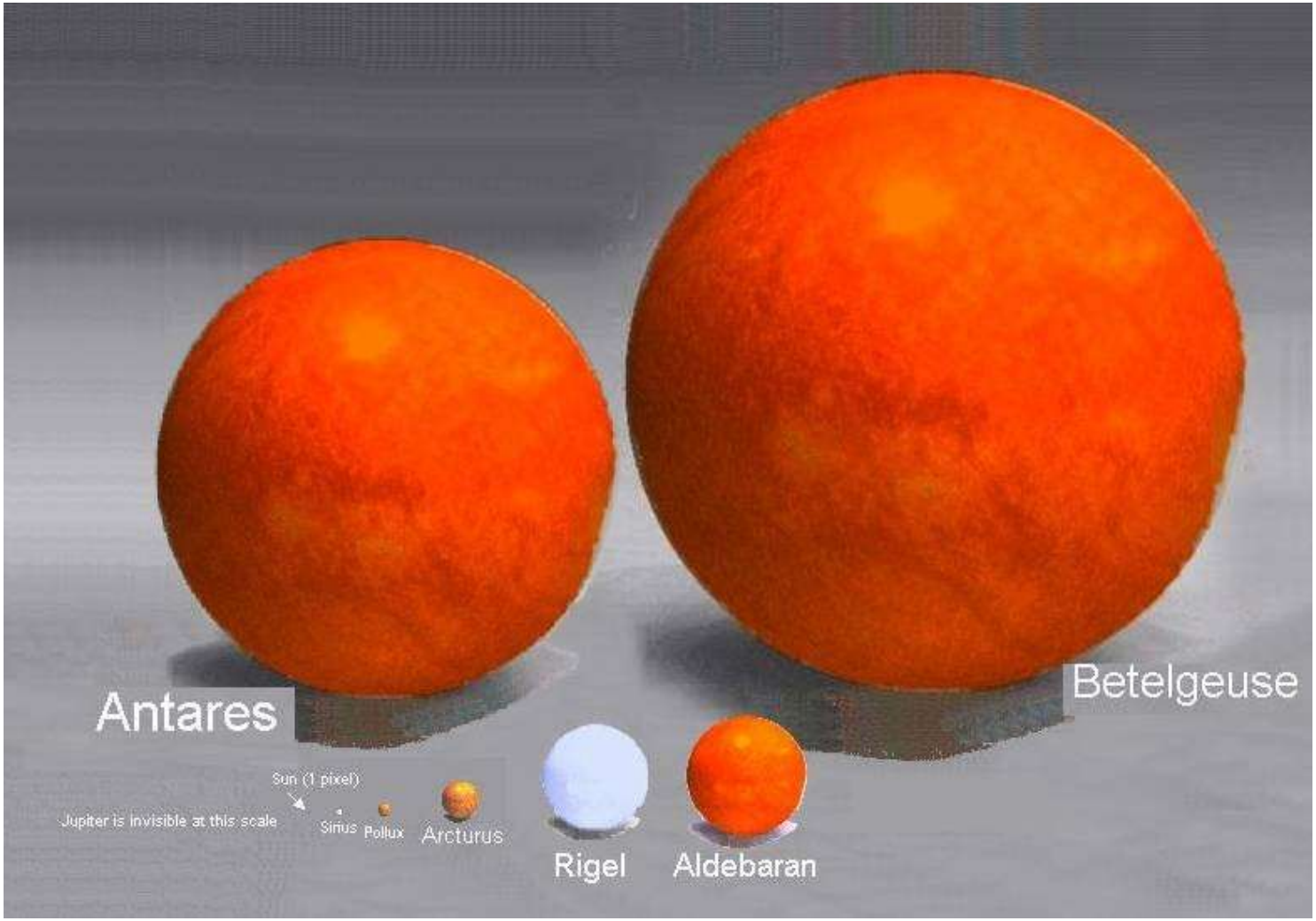
$$M = m - 5(\log d - 1)$$

The value of ***M – m*** is known as the *distance modulus*.

The apparent magnitude of Sun is -26.7 and that of Betelgeuse is 0.5. Sun is 76 billion times brighter than Betelgeuse as seen from the earth.

Meanwhile, at a standard distance of 10 parsecs, the sun (8 *min*) would appear to be a dim star of M_v = 4.8, and Betelgeuse (548 *ly*) is a bright star with M_v= -5.6

Betelgeuse is a red supergiant star roughly 950 times as large as the Sun.



Not All Stars Created Equal

Visible differences in stars not just due to different distances.

Stars have intrinsic differences!

Different colours — which indicate different temperatures

Different sizes

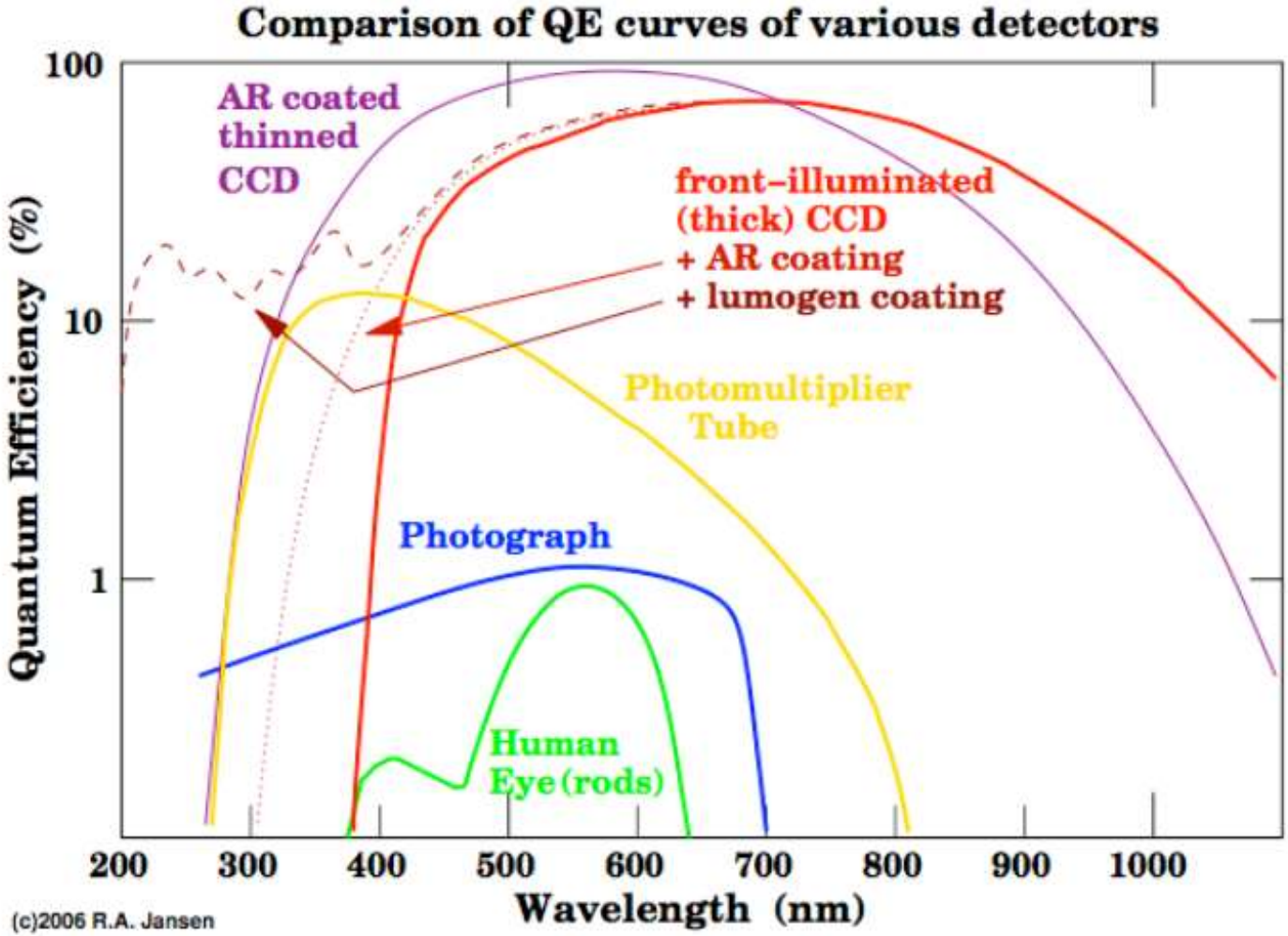
Different masses

The bigger it is, the hotter it is & thus the faster it burns out. Life fast, die young.

3. Photometric Systems

Why do we need magnitude systems?

- Different detectors have different responses; e.g, photograph, photomultiplier tube, CCD
- Would like to have information concerning the underlying spectral energy distribution of the objects under investigation.
- Would like to be able to compare with measurements made by different groups.



Standardising magnitudes

- **Vega magnitudes**
- Based on the visible spectrum of Vega.
- Zero point: V= 0.03 and all colours zero
- used for visible and near-infrared observations where Vega is a stable reference star
- **AB magnitudes**
- A flat spectrum source, where flux per unit frequency is constant.
- mag 0 has a flux of 3720 Jy by definition
- used for broad-band photometry across a wide range of wavelengths, especially in the context of extragalactic astronomy and cosmology
- **SDSS magnitudes**
- extends the AB system with specific filter bands (u, g, r, i, z)
- Based on calibration against spectrophotometric standard stars and defined to match the AB system within each band
- Widely used in large-scale surveys like SDSS for precise photometric measurements and colour studies of stars and galaxies

Note: A magnitude system is not a filter system (you can use a filter in any system)

Vega magnitudes

Vega system is based on the flux of the star alpha-Lyrae or Vega (for a given filter) outside the atmosphere, where f_i is the flux density per unit wavelength:

$$m_i - m_{vega} = 2.5\log_{10} f_i + 2.5\log_{10} f_{Vega}$$

By **definition** we set $\boldsymbol{m_{vega} = 0}$ (in fact 0.03) **at all wavelengths**

This means also that the colour of Vega is zero in all bands

Thus: $$m = 2.5\log_{10} f_\lambda + 2.5\log_{10} f_{\lambda,Vega}$$

The zero-point of this system **depends on the flux of Vega and is different in different bands.**

Vega magnitudes

- Johnson (1966) described a broad-band photoelectric photometric system based on measurements of A0 stars like Vega.
- Other work provides an **absolute flux calibration** linked to Vega.
- Practical difficulties: (1) not everyone can (or should) observe Vega -- it's much too bright -- so a network of **secondary standards** of fainter sources have been established.
- The **Landolt system**, based on A0 stars has become the standard magnitude system for many applications.

Note: Landolt measured stellar magnitudes using **photoelectric photometers** with a 14" (!) aperture; while making measurements with Landolt stars one should take note of this aperture.

Absolute calibration of the Vega system

- Photomultiplier tube based spectrophotometers in the 1970s were used to make spectral measurements of Vega.
- This absolute calibration was carried out by observing laboratory light sources across mountain tops (we don't know how a priori what the absolute flux of Vega is)
- The basic number to remember: ~1000 photons in V at the top of the atmosphere. This is a useful number to remember for the CCD equation!

$$\phi_\lambda^o = f_\lambda^o / h\nu = 1005 \text{ photons cm}^{-2} \text{s}^{-1} \text{A}^{o\,-1}$$

Reminder: $m_i = -2.5 \log_{10} \frac{\int R_i(\lambda)\lambda F_\lambda(\lambda) d\lambda}{\int R_i(\lambda)\lambda F_{\lambda,Vega}(\lambda) d\lambda} + 0.03$

The AB magnitude system

- In Vega magnitudes, the flux density corresponding to m = 0 is **different for each filter**: to get absolute quantities we need to know the spectrum of Vega. The spectrum of Vega is poorly defined at longer wavelengths.
- It is also difficult to relate Vega magnitudes to physical quantities such as energy.

In the AB system, the reference spectrum is simply a constant line in f_ν (flux per unit frequency)

$$f_\nu \, [\mathrm{ergs\ s^{-1}\ cm^{-1}\ Hz^{-1}}] = \frac{\lambda^2}{c} \, 10^8 \, f_\lambda \, [\mathrm{ergs\ s^{-1}\ cm^{-2}\ A^{-1}}]$$

The absolute calibration of the AB system is based on Vega: $m_\nu^{vega} = m_\nu^{AB} = 0$

Thus, an AB magnitude can be calculated for any f_ν

$$m = -\ 2.5 \log f_\nu - (48.585 \pm 0.005)$$

Vega-dependent zero point

AB magnitudes

- With the AB system, one can relate magnitudes directly to physical quantities like Janskies (note modern detectors are essentially photon counting devices such as CCD)
- One can easy to compare with theory or physical quantities.
- One can easily convert between AB magnitudes, janskys and electrons:

Thus, in AB magnitudes, **mag 0 has a flux of 3720 Jy**

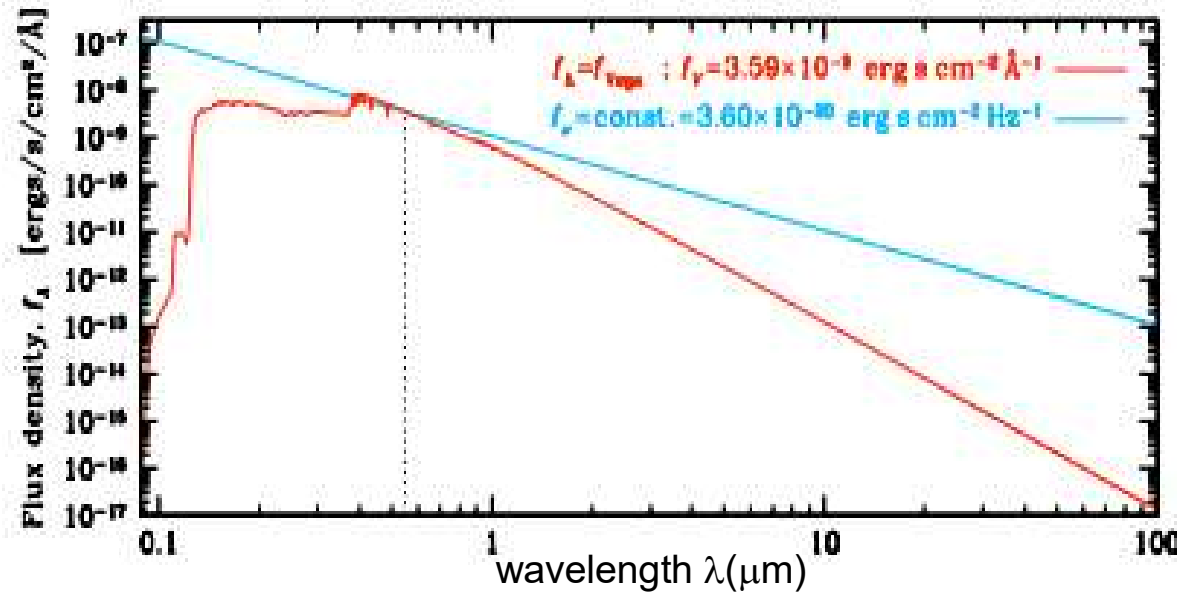
A source of flux 10^{-3} Jy has a magAB = $2.5\ log10\ (3270/10^{-3})$ = 16.43

Equally, if your photometric system has a zero-point of 23.75, this corresponds to a flux of 3720 Jy / $2.5124^{23.75}$ = 1.2×10^{-6} Jy and produces one detected electron per second

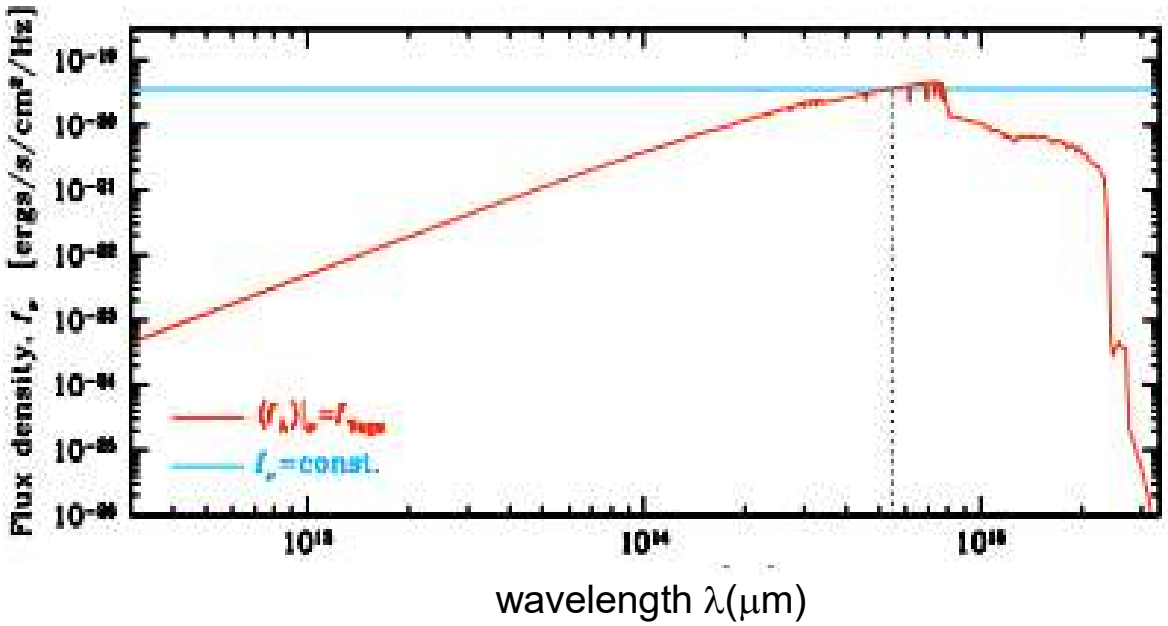
An AB mag of 16.43 produces a flux of $2.5124^{(23.75 - 16.43)}$ = 847electrons/second

AB magnitudes are much more common today thanks to multi-wavelength surveys (useful for comparisons over a very wide range in frequencies)

AB and Vega systems compared



The difference between AB and Vega magnitudes becomes very large at redder wavelengths!



The spectrum of Vega is very complicated at IR wavelengths and often model atmospheres are used adding to uncertainties

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Filters

There are different filters systems created for different astrophysical problems

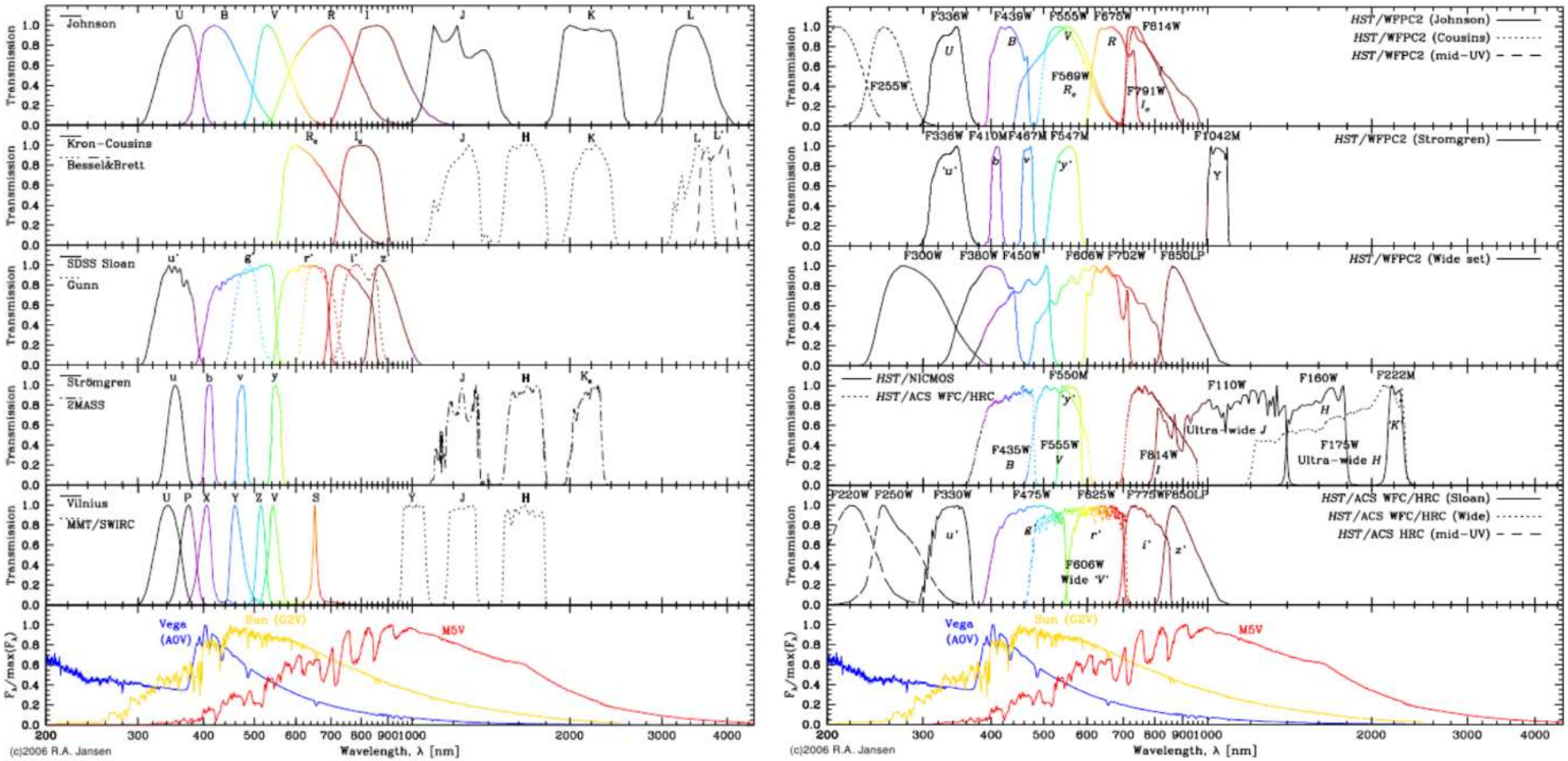


Figure 3: Overview of various filter sets (as labeled) and comparison with the spectra of an A0V (Vega), G2V (Sun) and M5V star.

Common response functions

- Note the difference between “response function” and “filter system”

- The response function includes the effects of atmosphere, detector, instrument

- Landolt system: origins in Johnson & Morgan (1951,1953); UBV magnitudes are on the “Johnston” systems, RI magnitudes added later are on the “Cousins” system (1976).

- SDSS u’g’r’i’z’ system: Currently the SDSS has a preliminary magnitude system (u’g’r’i’z’) based on measurements of 140 standard stars. Fluxes of several white dwarfs are measured relative to Vega and define the absolute flux calibration.

- Work is under way to define new photometric systems not reliant on Vega (which is actually a variable star!).

A general comment: Instrumental magnitudes

- In general converting between different magnitude systems is **difficult**: conversion factors depend on **the spectrum** of each object.
- For many applications, it's best to leave magnitudes in the instrumental system. Model colours can be computed using the filter and telescope response functions. **Colours do not depend on an absolute transformation**.
- In general, for **galaxies** transforming between different photometric systems is difficult because we don't know what the underlying colour of the objects under investigation are. This may be different for stars!

Photometric calibrations

- In general, standard stars (usually from the compilations of **Landolt** or **Stetson** should be observed at a variety of zenith distances and colours.
- They should be at approximately the same air-masses at the target field.

$$m_{\mathrm{calib}} = m_{\mathrm{inst}} - A + Z + \kappa X$$

- In this case, A is a constant like the exposure time, Z is the instrumental zero point and kX is the extinction correction.
- This is a simple least-squares fit. But in general a system of equations will have to be solved:

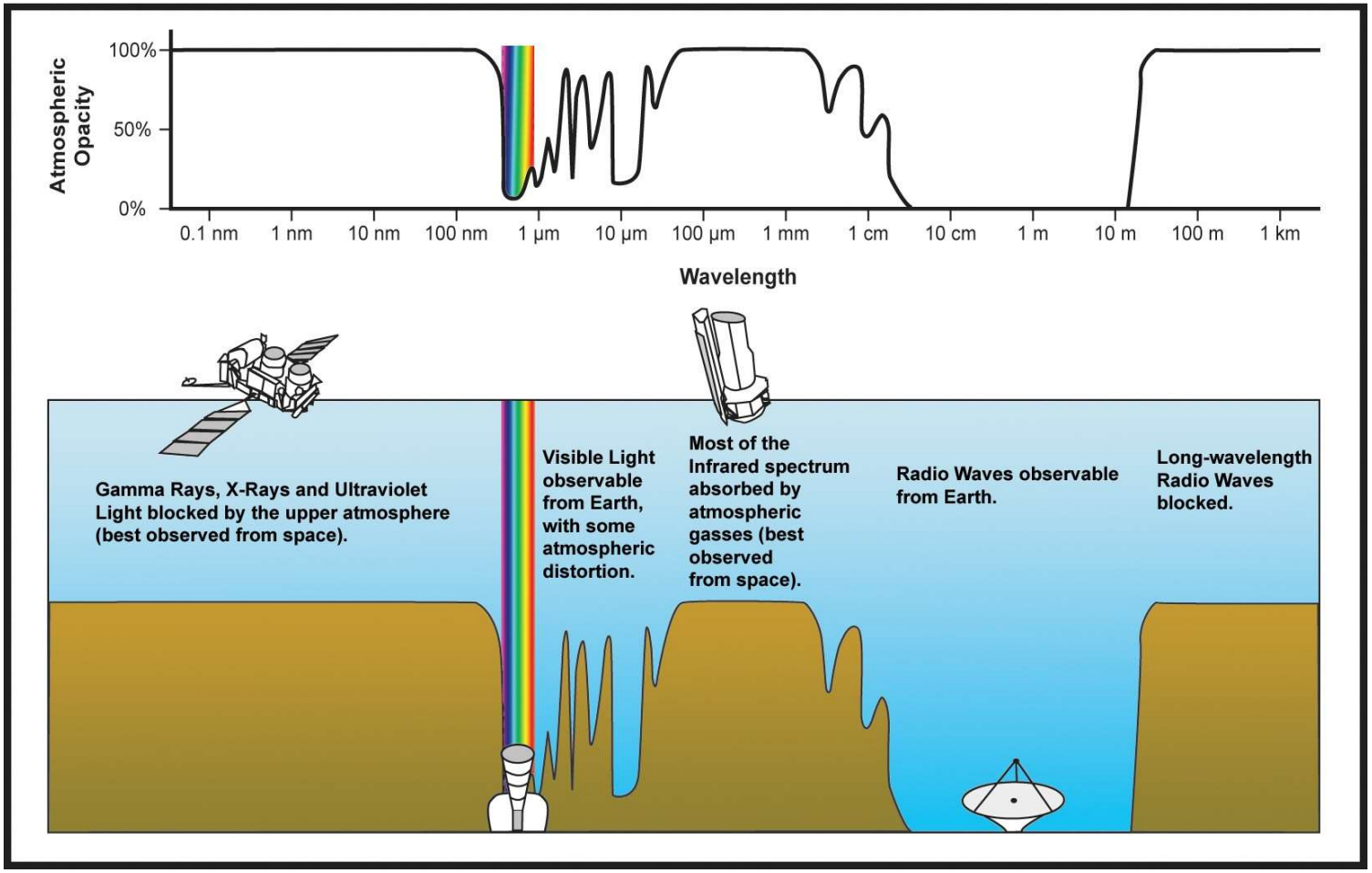
$$\begin{aligned} U &= U_{\mathrm{inst}} - A_u + Z_u + C_u(U - B) + \kappa_u X \\ B &= B_{\mathrm{inst}} - A_b + Z_b + C_b(B - V) + \kappa_b X \\ V &= V_{\mathrm{inst}} - A_v + Z_v + C_v(B - V) + \kappa_v X \end{aligned}$$

Atmospheric Extinction

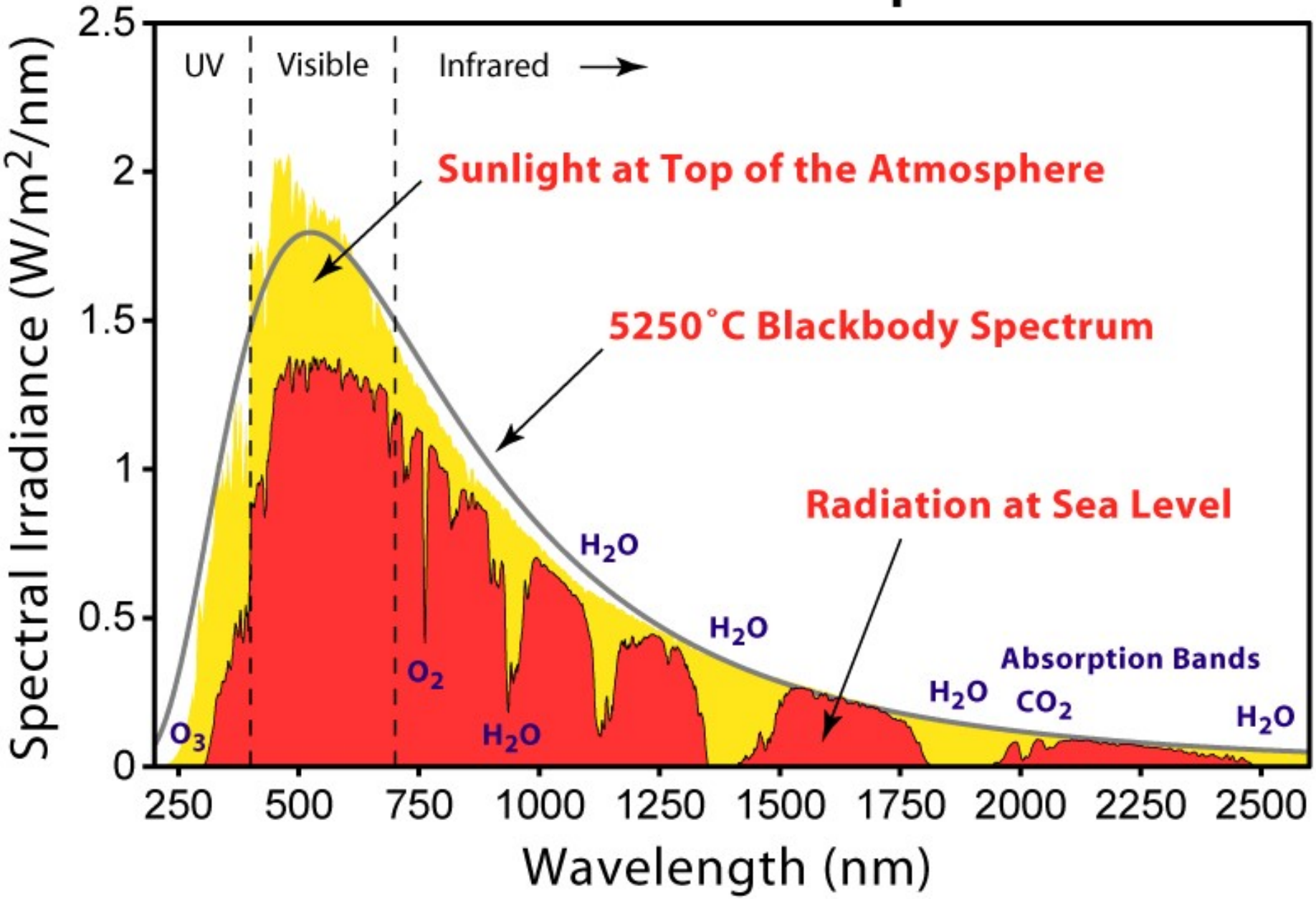
It was first observed by Pierre Bouguer around 1729. Bouguer's law, also known as the Bouguer-Lambert law, relates the extinction or attenuation of light to the properties of the material through which the light travels

$$I_d = Io\, e^{-\mu d}$$

I_d the intensity of light at a distance (d) into the absorbing medium.
I_o the initial intensity of the incident light.
μ represents the **optical density** of the medium.
d is the thickness of the atmosphere.

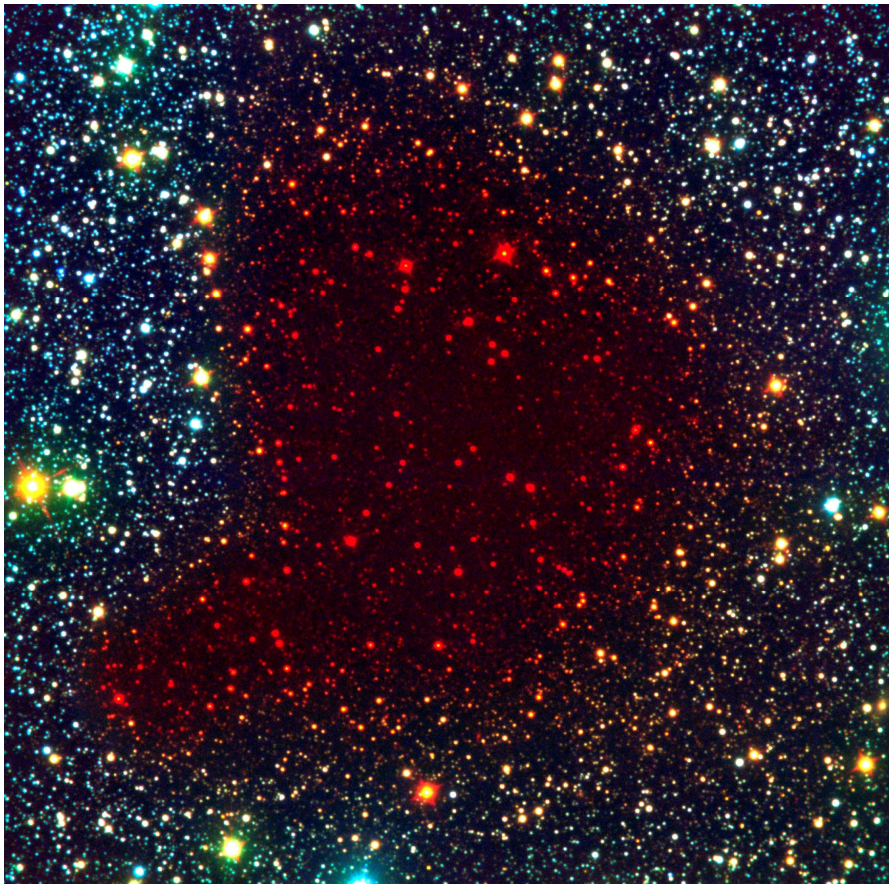


Solar Radiation Spectrum



Interstellar Reddening

Visible

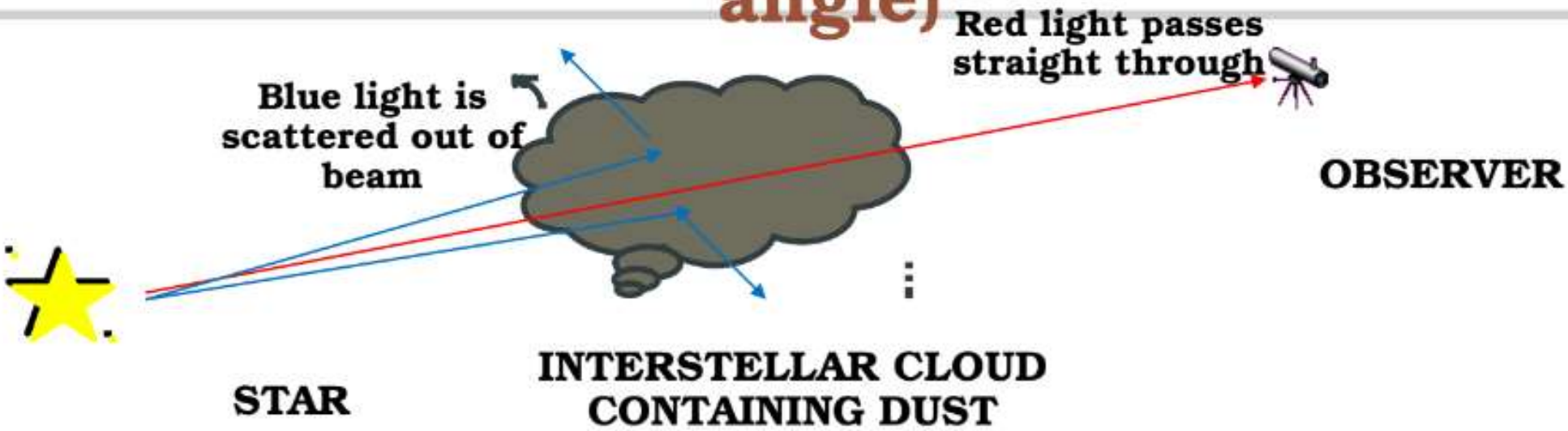


Infrared (VLT)

Interstellar clouds make background stars appear redder

Interstellar Extinction

(Blue Sky Effect viewed from different angle)



Infrared radiation is hardly absorbed at al

Here the scattering is caused by interstellar dust grains

The more interstellar gas along the sight line, the more reddening occurs

Distant stars appear redder than nearby ones

Astronomer have to correct (de-redden) a stellar spectrum to account for this and to derive the star's true colour.

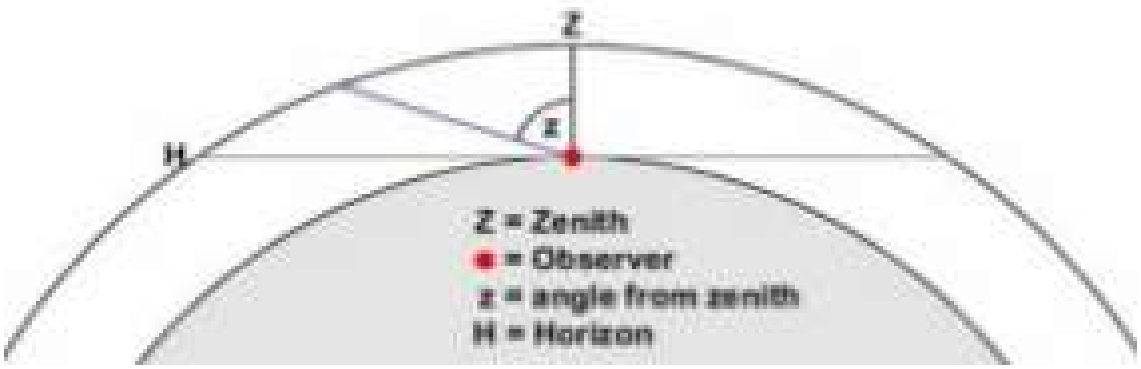
Atmospheric extinction and transmission

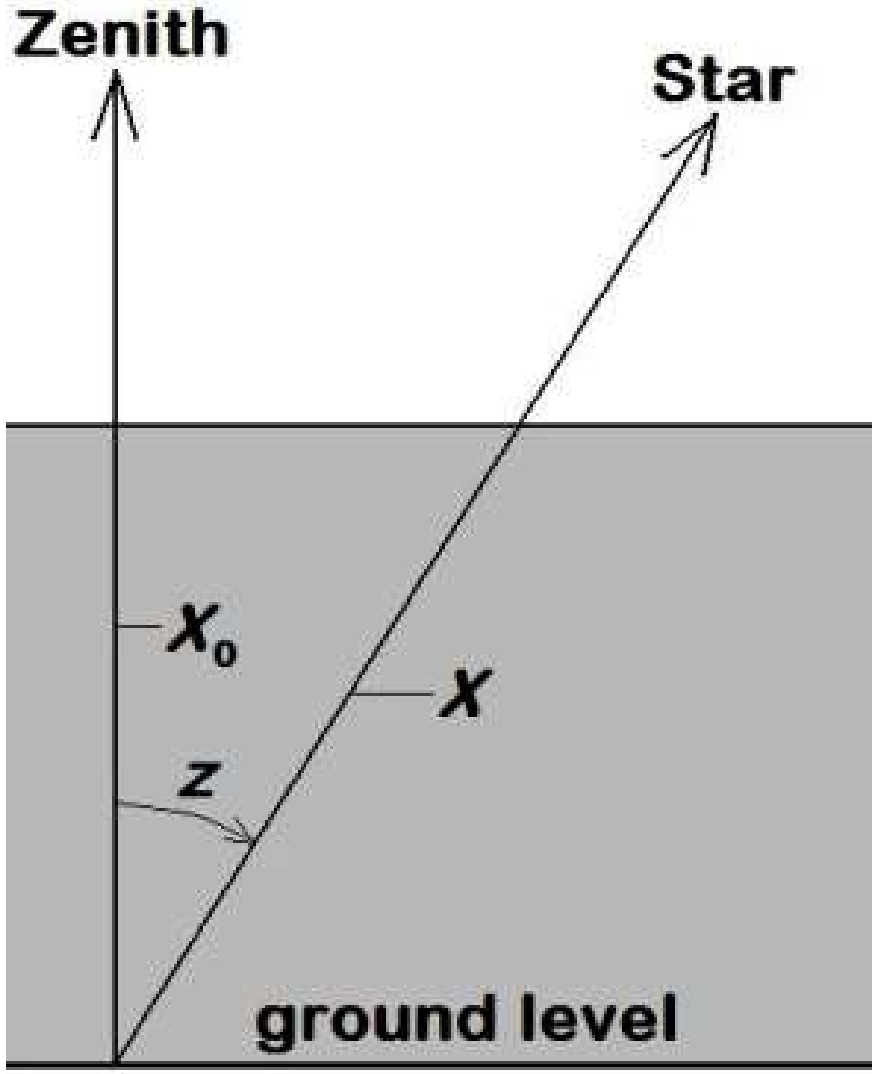
In the simple case where observations are made at small zenith distances, *z*, one can approximate the atmosphere using a flat slab model. In that case, the air mass, *X*, along the line-of-sight to a star at zenith distance *z* is given by:

$$\chi(z) = \sec(z) = 1/\cos z$$

$$m(\lambda) = m_0(\lambda) + \ldots + \kappa(\lambda)\,\chi(z)$$

The extinction coefficients can be determined by observing a set of standard stars at different air masses throughout the night





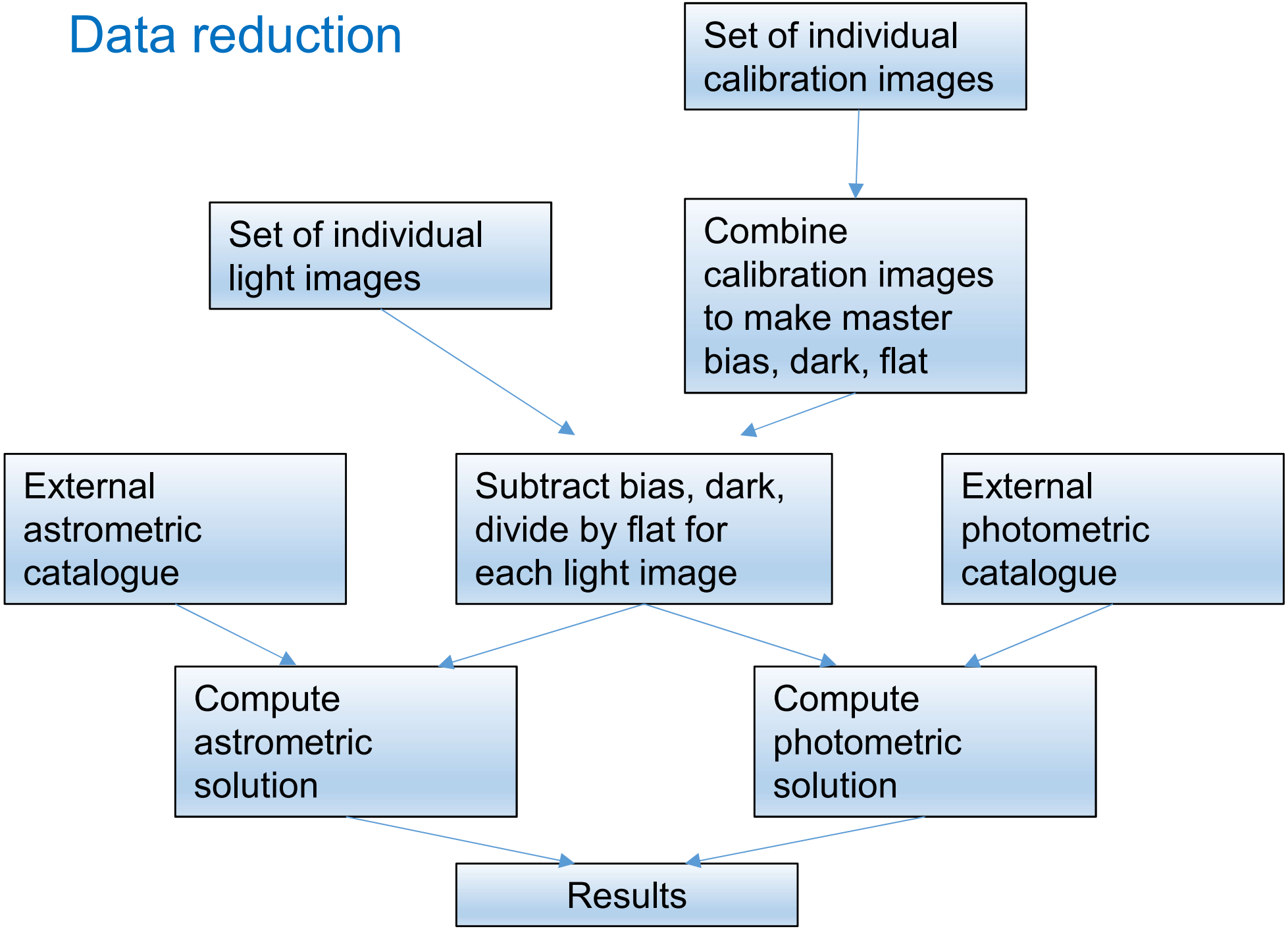
A practical recipe for photometric calibrations

- Observe a set of standard star fields (such as those observed by Landolt) in the filters you wish to calibrate.
- Measure instrumental magnitudes for Landolt's stars in your field and cross-match these stars with Landolt's catalogue.
- If you don't care about colour terms, then a simple least-squares fit will give you the **zero point** (the axis intercept) and (optionally) the extinction coefficient.
- If you do care about colour terms, you will have a system of linear equations to solve.
- Make sure your observations cover a large enough range in airmass

Note: Zero point of telescopes can evolve due to dust build-up inside the telescope or mirror changes

4. Measuring magnitudes on CCD array

Data reduction



CCD equation

- Read noise follows a Gaussian or normal distribution
- Shot noise follows a Poissonian distribution (counting statistics)

$$P_n = \frac{m^n e^{-m}}{n!}$$

$$\sigma = \sqrt{m}$$

$$N = \sqrt{S_\star + S_S + t \cdot dc + \mathcal{R}^2}$$

Total counts per pixel, electrons

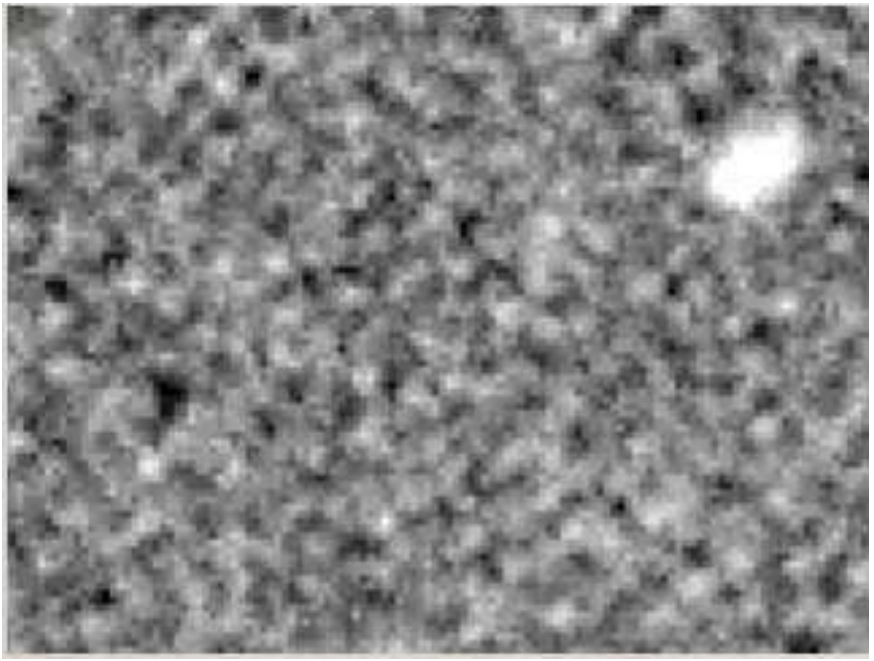
Astronomical Source

Sky background

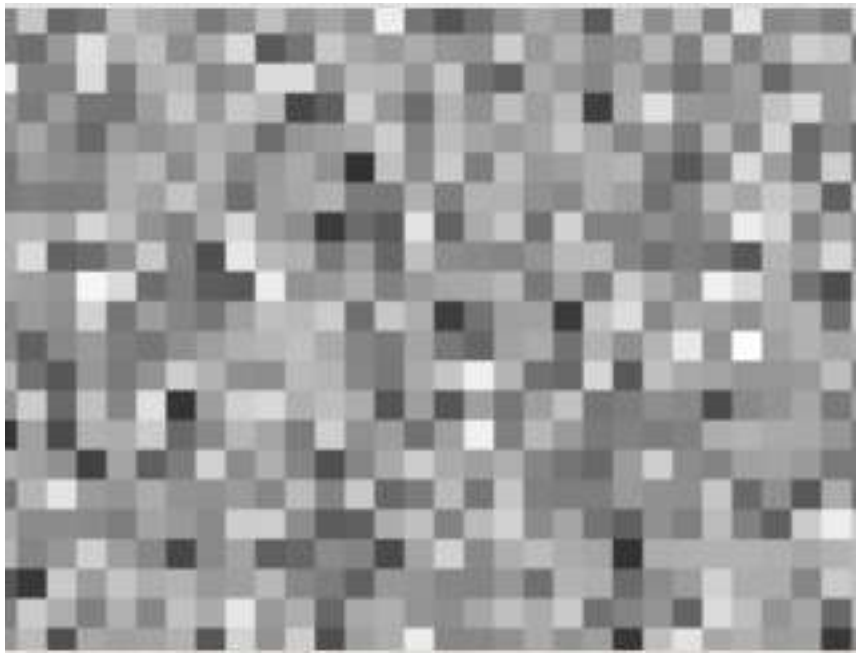
Dark current

Read noise

Sometimes the sky noise isn’t Gaussian...

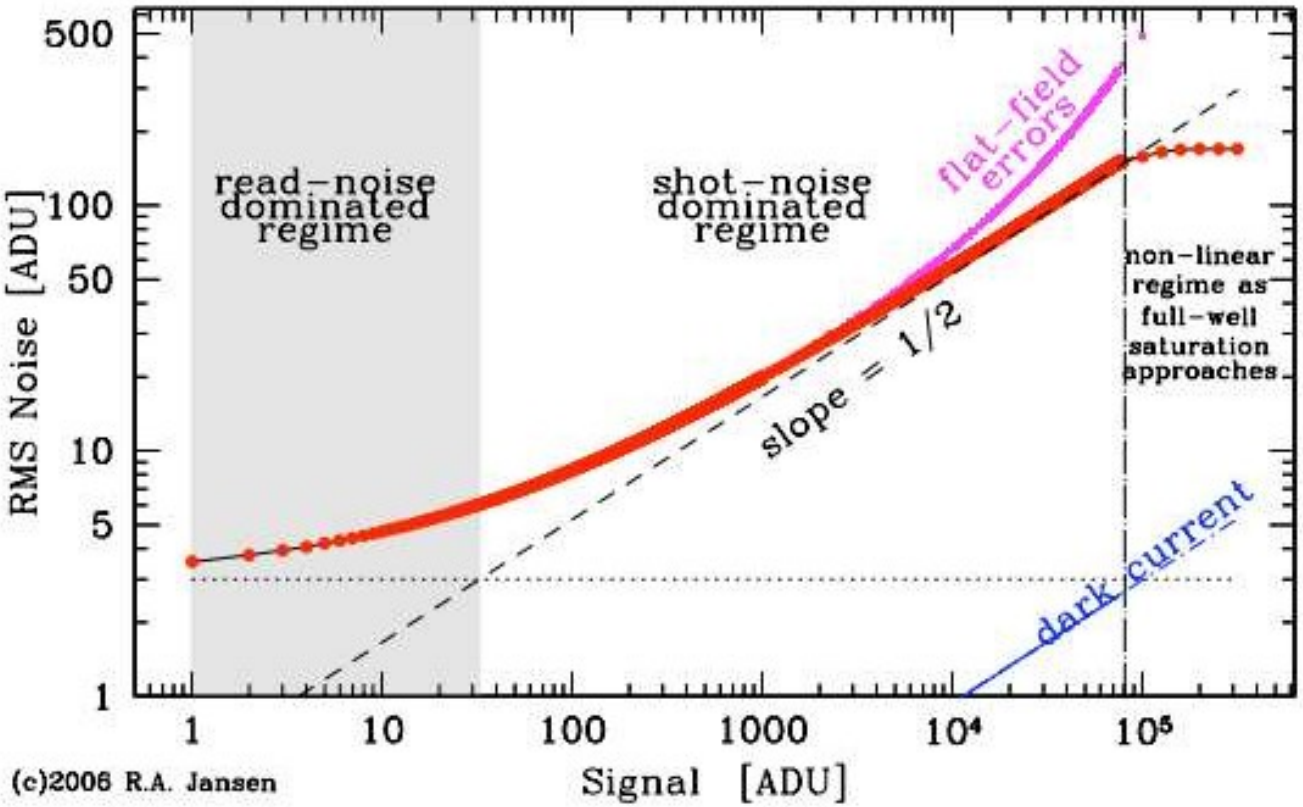


Contributions from unresolved faint astronomical sources



Normal “white” noise

$$\frac{S}{N} = \frac{S_\star}{\sqrt{S_\star + n_{\rm pix} \cdot \left(1 + \frac{n_{\rm pix}}{n_{\rm sky}}\right) \cdot (S_S + t \cdot dc + \mathcal{R}^2 + \mathcal{G}^2 \sigma_f^2)}}$$



Photometric errors

- Bright sources like stars are dominated by photon counting noise; faint source like galaxies are dominated by background noise.
- However in “real” data which may have been resampled the noise background could be under-estimated and for faint objects, magnitude errors will be incorrect.
- Often need to do simulations right answer or find the “fudge factor”

$$\Delta m \approx \frac{-2.5}{ln10}\frac{1}{SNR} \sim 1.0857\frac{1}{SNR}$$

This does not take into account systematic errors which could be caused by bad photometric calibration

Incompleteness and reliability

What it is

On a given astronomical image to a given flux limit can define the concepts of incompleteness and reliability

Incompleteness: does the catalogue contain all sources to a given flux limit?

Reliability: are all the sources real sources (i.e., not false detections)?

Obviously it is best to science with catalogues which are complete and reliable preferably many sigmas from the detection limit.

How to estimate it

Reliability: where do the sources lie in a flux - radius size plane?

Reliability: in a “negative” image at the same flux limit how many sources are there?

Completeness: How do the number density of objects compare with deeper surveys?

Completeness can also be estimated by numerical simulations

Detection limits and sky noise

- The signal to noise ratio is simply 1/(magnitude error)
- The detection limit indicates to what magnitude limit an image can be scientifically exploitable.
- Magnitude errors rise rapidly as one approaches the detection limit
- Can make a simple estimate the detection limit from the sky noise

$$\text{detection limit} = ZP - 2.5 \log\left(\frac{S}{N} \times \sigma\sqrt{N}\right)$$

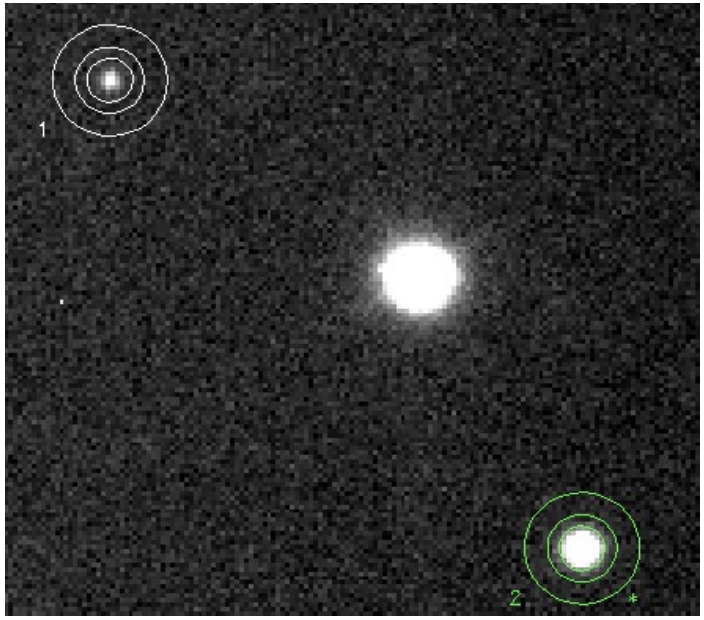
•**Zero-Point Magnitude (ZP)**: This is a calibration constant that represents the magnitude corresponding to a reference flux. It depends on the specific instrument and observational setup.

•**Signal-to-Noise Ratio (S/N)**: This ratio determines how much stronger the signal is compared to the noise. A higher S/N ratio means a more confident detection.

•**Sigma** is the standard deviation of the background noise per pixel in the image

• **N** given by the number of pixels in the aperture (the area considered)

Aperture magnitude



- In aperture photometry one simply measures the total flux inside a(normally circular) aperture and subtracts the sky flux.
- If the size of the aperture is too small, flux is lost.
- However, if the aperture is too large, too much sky is included(measurement becomes noisy).
- In a curve of growth analysis, the flux in a series of apertures is measured. In this way a correction to total magnitude can be estimated for the smallest apertures (which are the least contaminated by crowding, but miss the largest amount of flux).
- Note that aperture magnitudes can be sensitive to point-spread-function (PSF) variations.

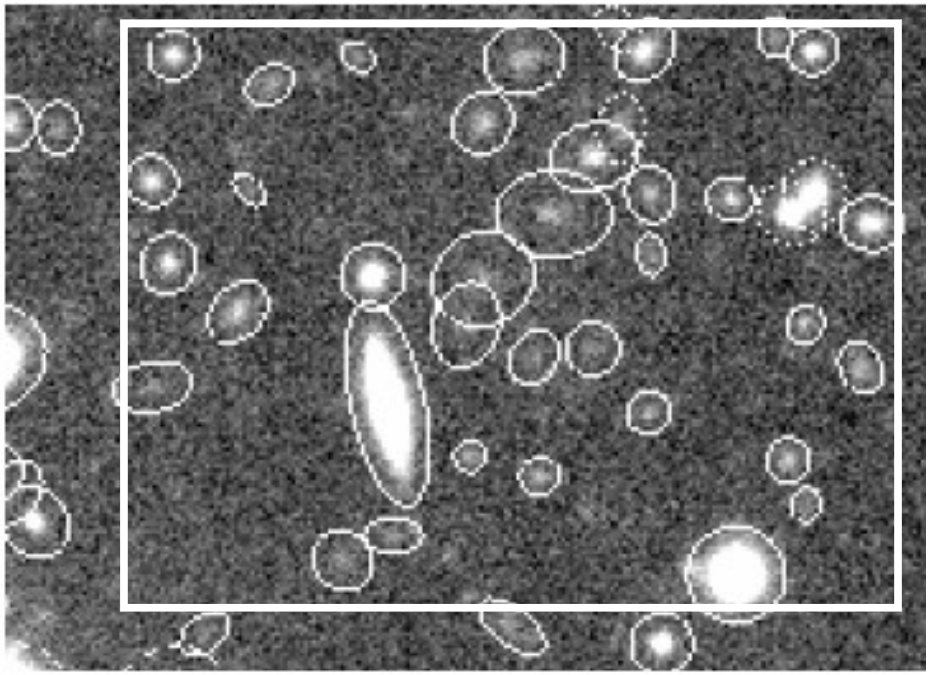
Photometry of faint sources

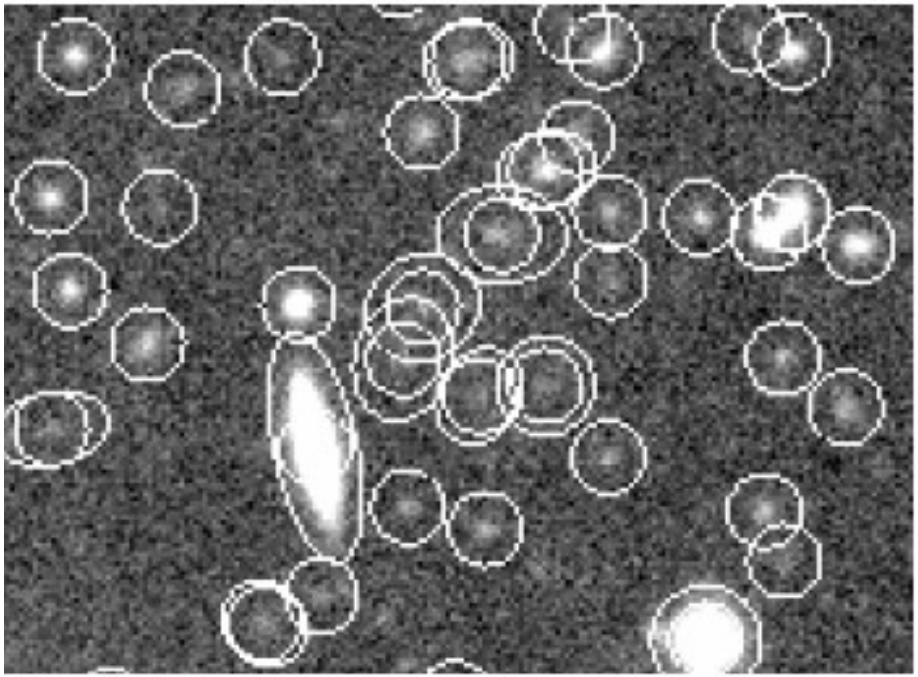
- In **variable-aperture photometry** a photometry aperture is chosen and then the flux is summed up out to this radius.
- Kron (1980) magnitudes use the first image moment to determine the radius of the elliptical or circular aperture for flux integration.

Sextractor integrates the galaxy profile out 2.5*r1; Simulations show that this recovers around 95% of the galaxies flux.

- There can objects with unusual profiles where the amount of flux lost is much greater.
- In **crowded fields**, Kron magnitudes are perturbed by the presence of nearby sources. In these cases it's almost better use **PSF-fitting photometry** (at least for stars)

Optimal settings for deep imaging data





For very faint objects it can be difficult to measure accurately the size of the Kron radius

Point-spread fitting photometry

- For crowded fields (like globular clusters) blending can become important. Kron magnitudes are corrupted.
- Iterative point-spread fitting programs like **DAOPHOT** and **DAOFIND**(IRAF) are very good for crowded stellar fields (for example, globular clusters)
- Obviously PSF-fitting photometry can only work for stellar fields! Current generation psf-fitting software also assumes the object PSF is constant over the field of view.

What magnitudes to use?

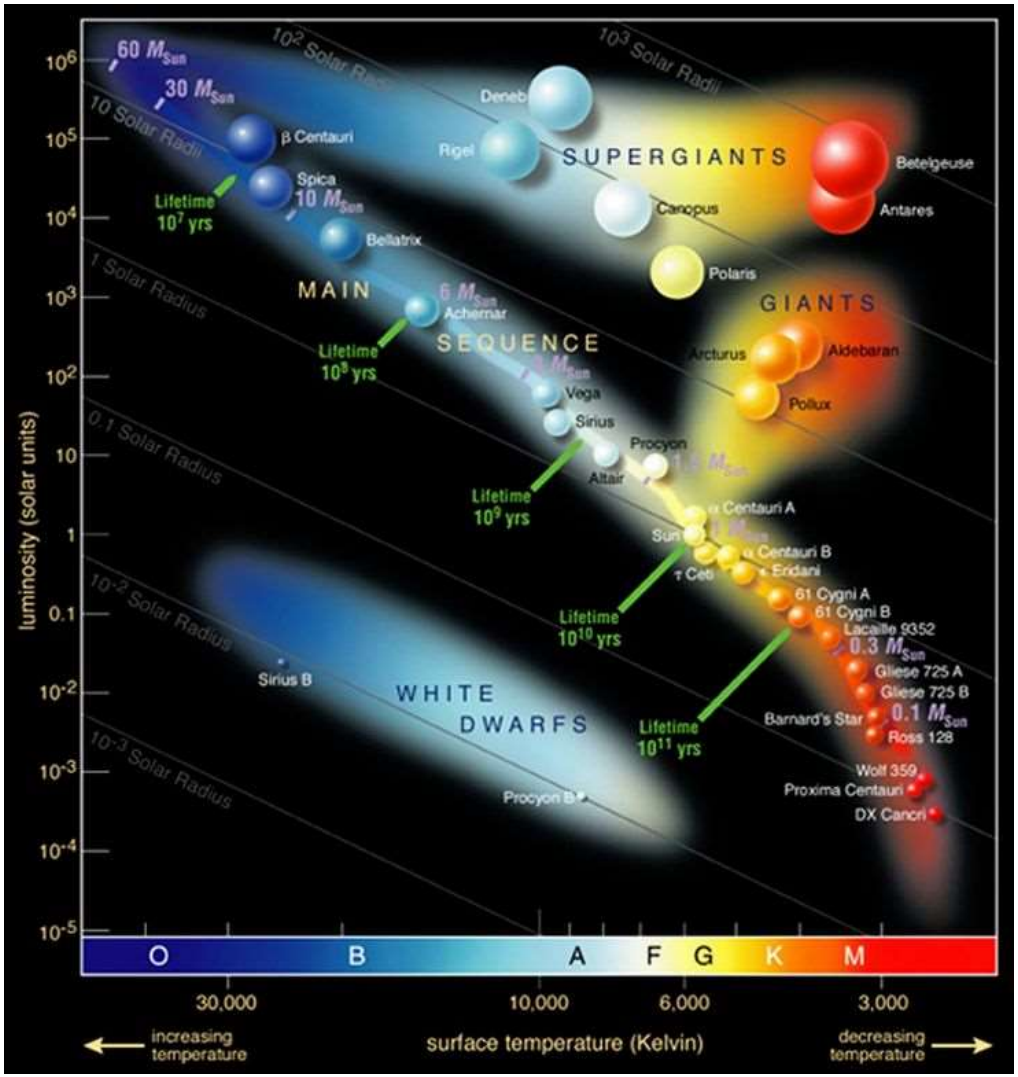
Best magnitudes to use depends on the astrophysical application: nearby, bright galaxies; distant unresolved point-like objects; crowded stellar fields; deep galaxy fields.

Making multi-band catalogues

- In many astrophysical applications we are interested in measuring not only the magnitude of objects but also their **colour** - the difference in magnitude between two bands.
- An easy way to do this is to use the ‘dual image mode’ in sextractor, where one image is used as a **detection image** and another image is used as a **measurement image**. In this way object lists are matched as the same detection image is used in all bands.
- Another way is simply to cross-correlate the two catalogues, but you may not be sure you are measuring the **same aperture on the same galaxy**
- The choice of the detection image is important and once again depends on the type of astrophysical application. Generally however we want to choose the reddest possible bandpass.
- The “**chisquared” image** is a useful way to make multiple band images

5. Applications of Photometry

- Stellar classification and evolution
- Variable star studies
- Exoplanet detection
- Galaxy photometry
- Cosmological implications



Thank you for your attention!