Observational Astronomy

Lesson I
Light

How is the information getting here?

- Multiple channels.
- Neutrinos, meteorites, cosmic rays, gravitational waves, electromagnetic waves.
- Two conveyors of information: particles with mass or without.

Particles with mass

- Cosmic rays.
- Primary cosmic rays, mostly high-speed atomic nuclei, mainly hydrogen (84%) and helium (14%). The rest: heavier nuclei, electrons, and positrons.
- Some primary cosmic rays are produced in solar flares, but many, come from outside the Solar System.
- About 6000 cosmic rays strike each square meter of the Earth's upper atmosphere every second. Very high kinetic energies due to their speed.
- A convenient unit for measuring particle energies is the electron volt (eV):

$$1 \text{ eV} = 1.602\ 3\ 10^{-19} \text{ joules}$$

- Primary cosmic rays have energies ranging from 10^6 to 10^{20} eV, with relative abundance declining with increasing energy. The mean energy is around 10 GeV = 10^{10} eV.
- Energy $E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$

- The rest mass of the proton (mc^2) is 0.93 GeV. The highest-energy cosmic rays have energies far greater than any attainable in laboratory particle accelerators.

- The origin of cosmic rays is suspected to be explosions resulting from the stars' demise (supernovae explosion) or active galactic nuclei.

- **Secondary cosmic rays** are particles produced by collisions between the primaries and particles in the upper atmosphere – generally more that 50 km above the surface.

- Kinetic energy is conserved during collisions.

- A cosmic-ray collision produces many fragments, including pieces of the target nucleus, individual nucleons, and electrons, as well as particles not present before the collision: positrons, gamma rays, and a variety of short-lived particles.

- Particle physicists methods are used to detect them: cloud and spark chambers, Geiger and scintillation counters, flash tubes, and solid-state devices.

- Detection of primaries requires placement of a detector above the bulk of the Earth’s atmosphere, and only secondary cosmic rays can be studied directly from the Earth’s surface.

Neutrinos

- Neutrinos are particles produced in nuclear reactions involving the weak nuclear force.

- They most likely have very small rest masses (the best measurements to date are uncertain but suggest something like 0.05 eV).

- Due to their very low interaction with matter very large arrays are constructed to detect them.

Meteorites

- Meteorites are macroscopic samples of solid material derived primarily from our Solar System's asteroid belt, although there are a few objects that originate from the surfaces of the Moon and Mars.

- They all provide clues about the origin, age, and history of the Solar System.

- The age of the Solar System (4.56 Gyr) is calculated from radioisotopic abundances in meteorites.

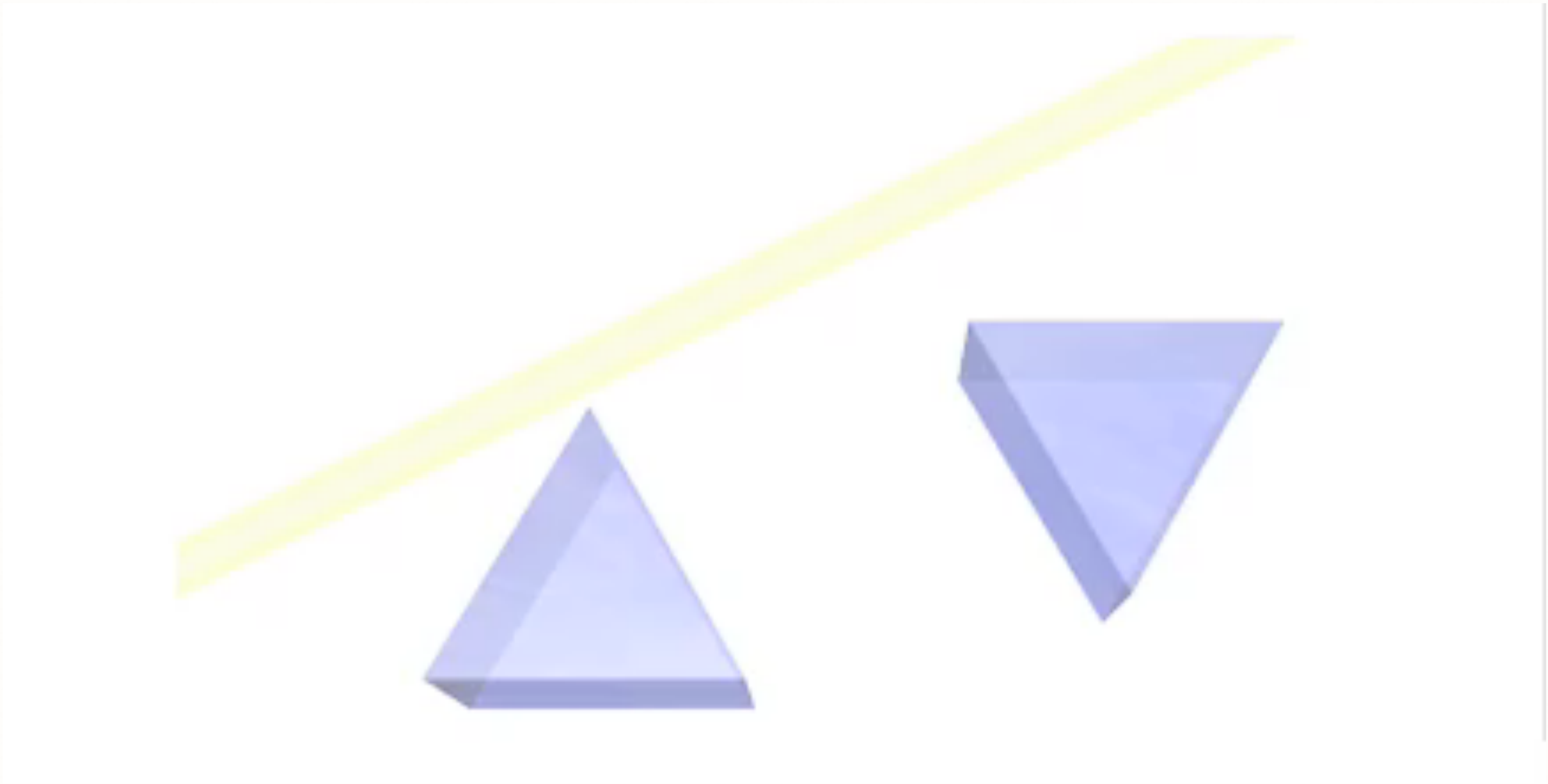
- Some meteorites suggests an association between a supernova, which would produce isotopes being found on them, and the events immediately preceding the formation of our planetary system.

Massless particles

- Gravitational waves, have been detected directly for the first time on September 14, 2015.

- Photons are particles of light that can interact with all astronomical objects. Light, in the form of visible rays as well as invisible rays like radio and X-rays, has historically constituted the most important channel of astronomical information.

NEWTON'S PRISM



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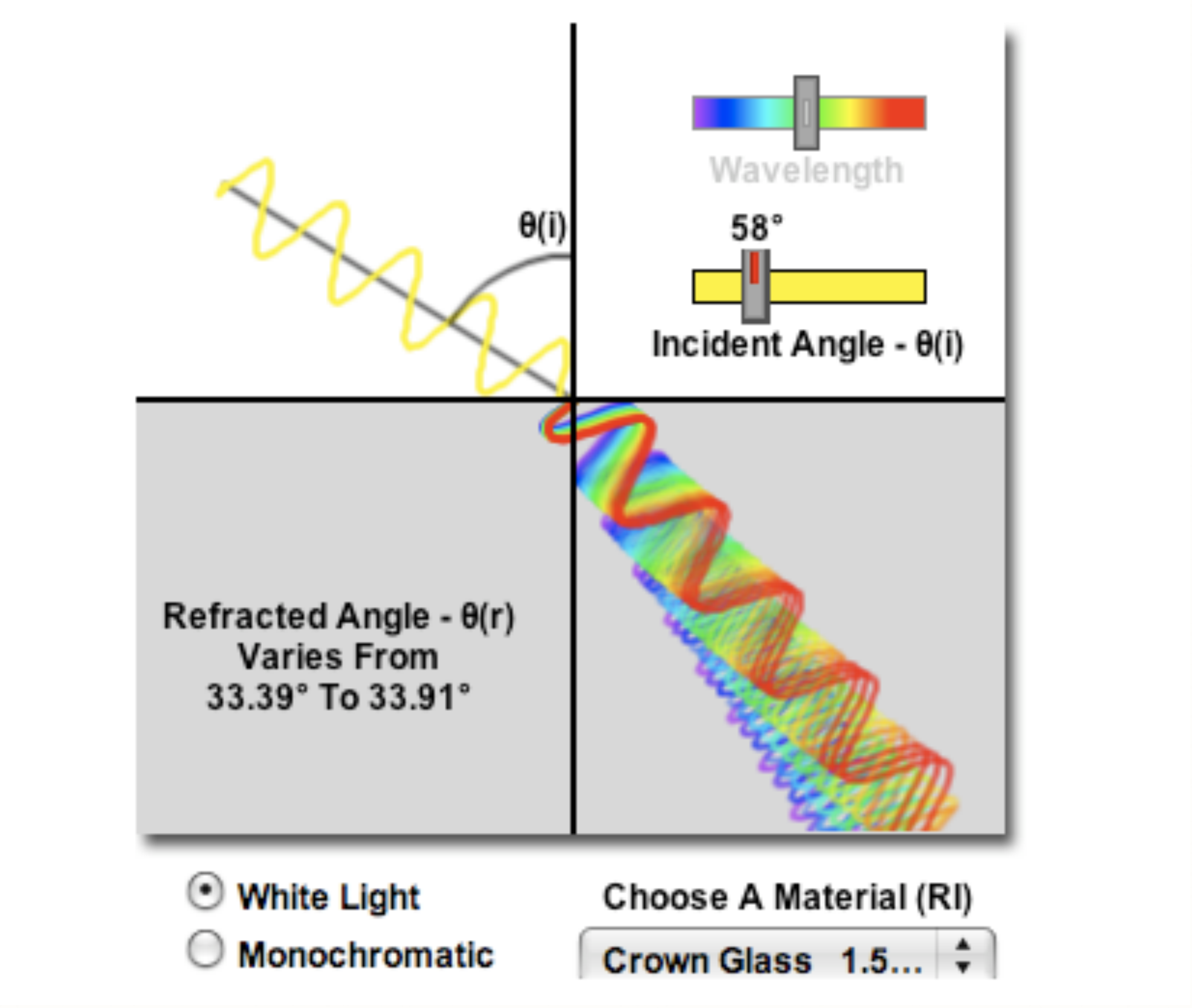
REFRACTION



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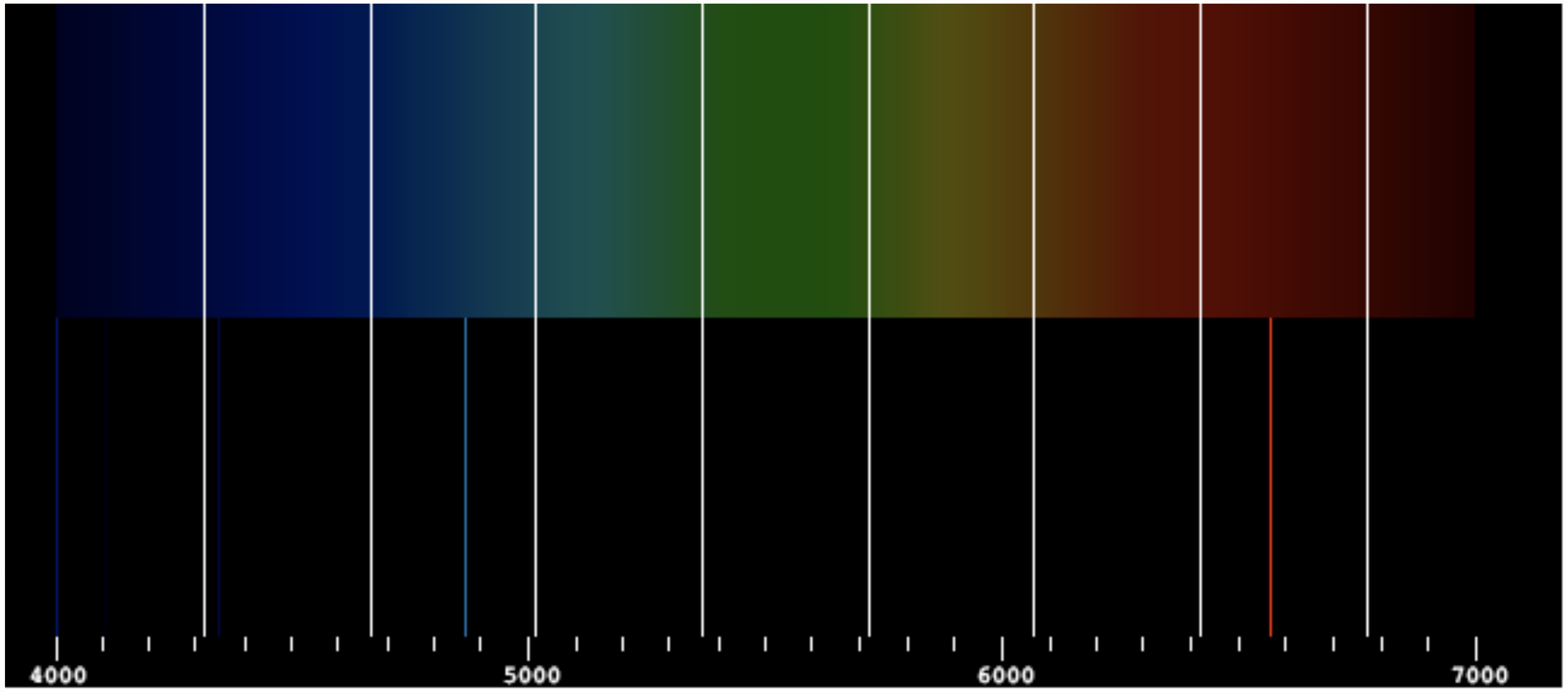
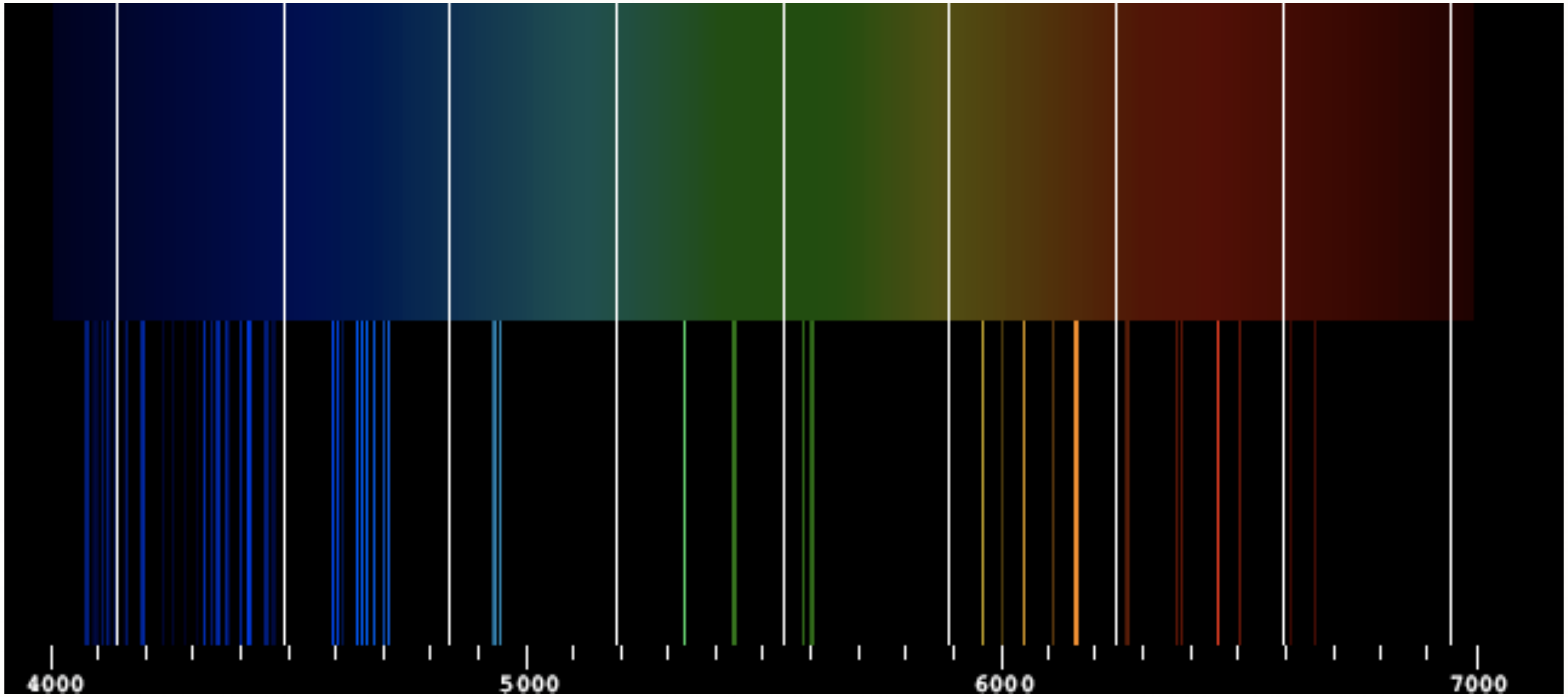
HYDROGEN SPECTRA

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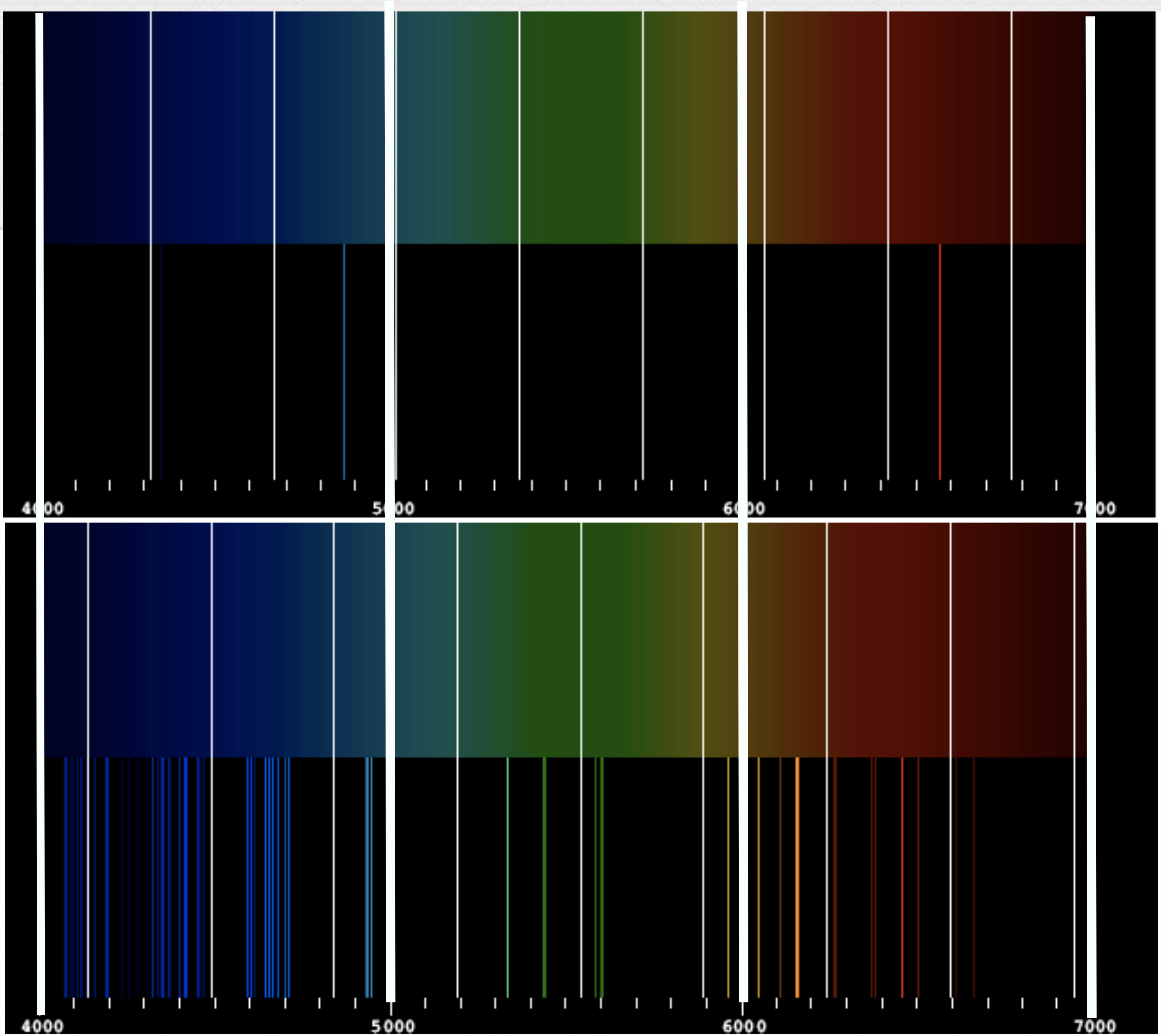
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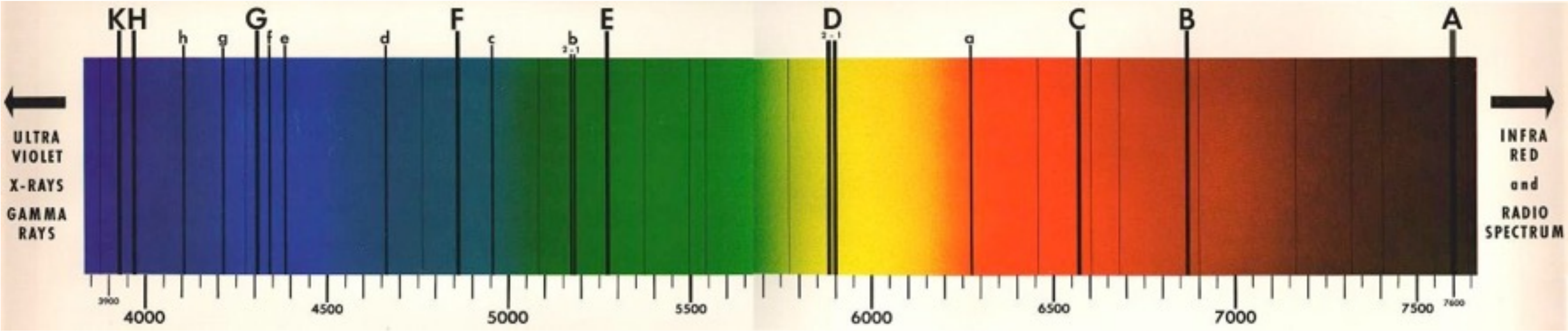
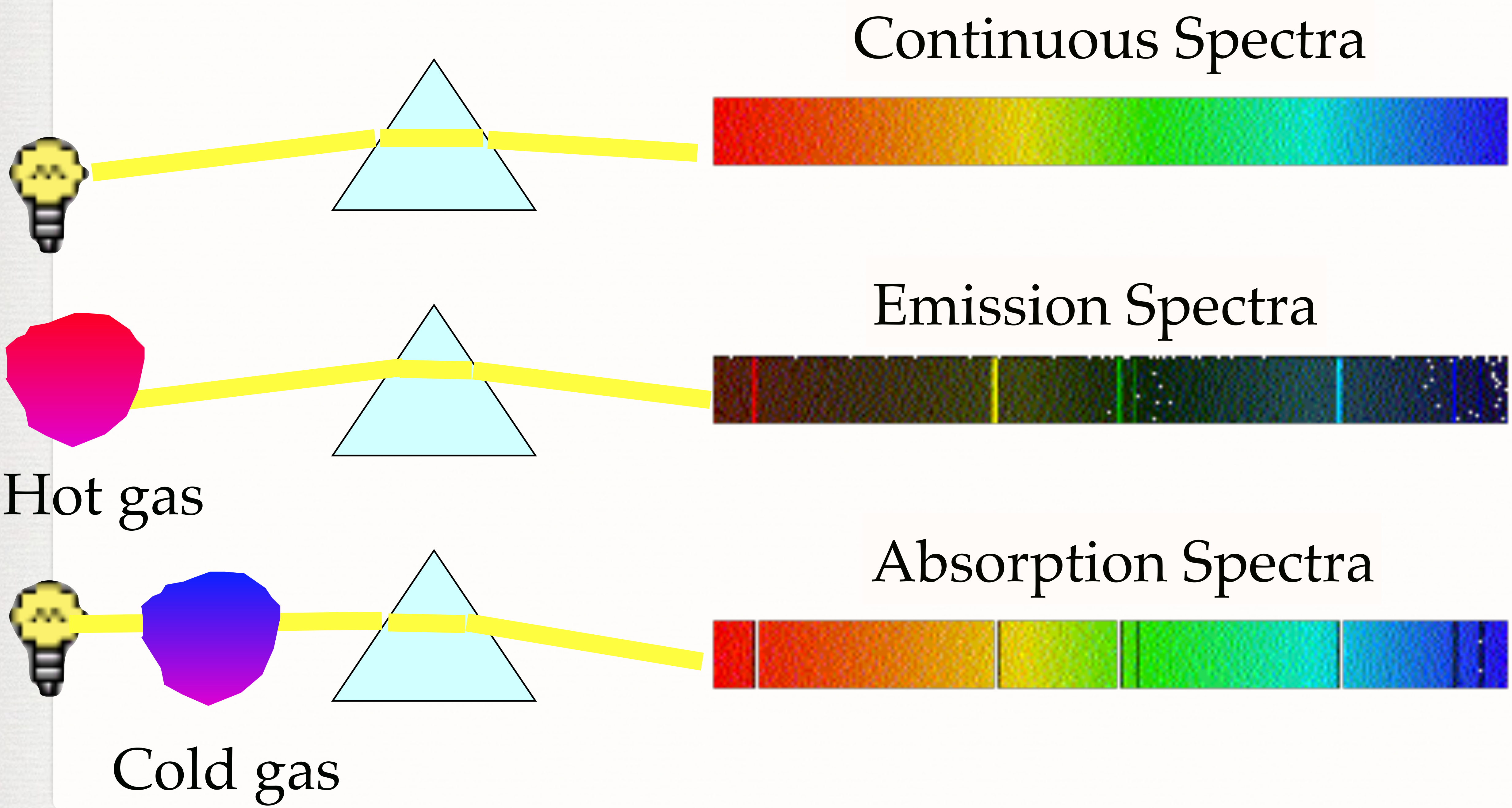
LOOKING AT THE SUN

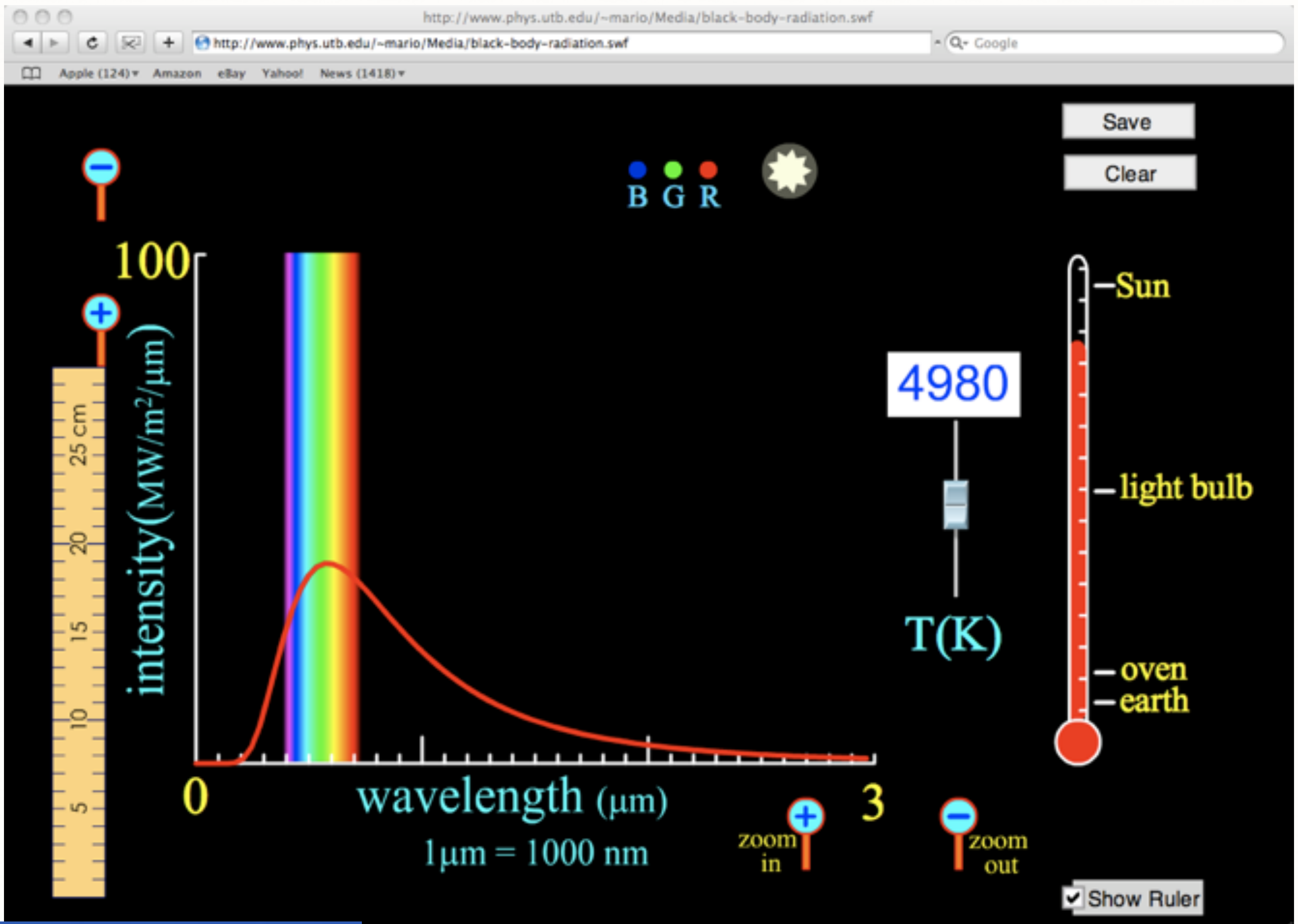


Wollaton (1802), Fraunhofer (1817)

SPECTRA TYPES



BLACK BODY SPECTRUM



Physics Education Technology
University of Colorado at Boulder

http://www.phys.utb.edu/~mario/Media/black-body-radiation.swf

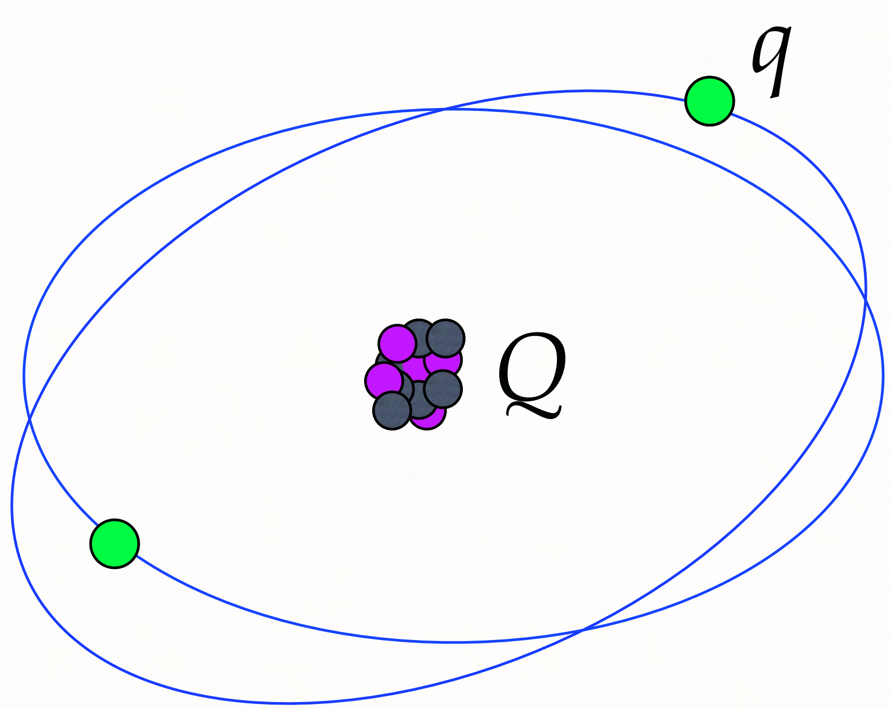
TEMPERATURE AND WAVE

- Two key ingredients:
- Stars radiate following a distribution of energy called black body radiation spectrum.
- The peak of radiation follows a relationship for temperature and wavelength called Wien's Law of radiation:

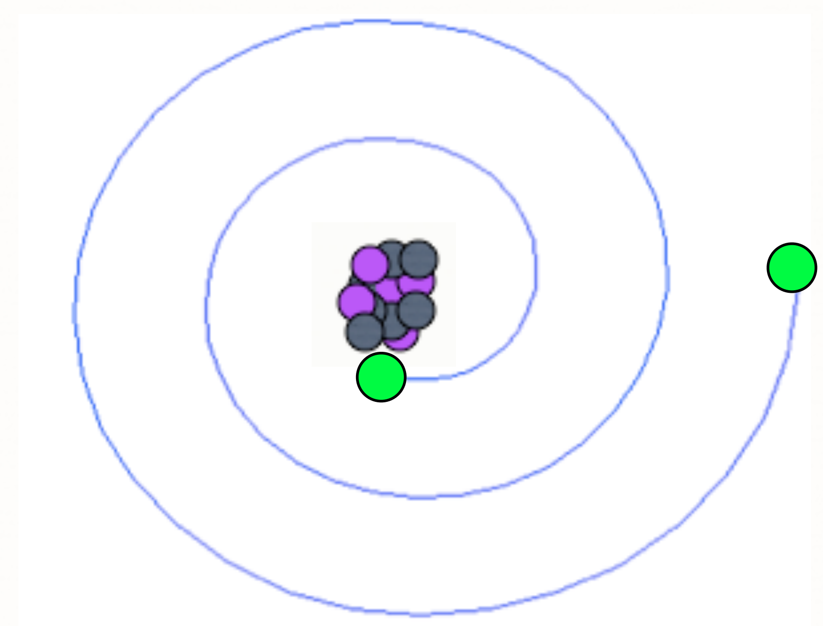
$$\lambda_{max} = \frac{0.3}{T}$$

WHY DO DIFFERENT ELEMENTS HAVE DIFFERENT SPECTRA?

A mechanical view of an atom

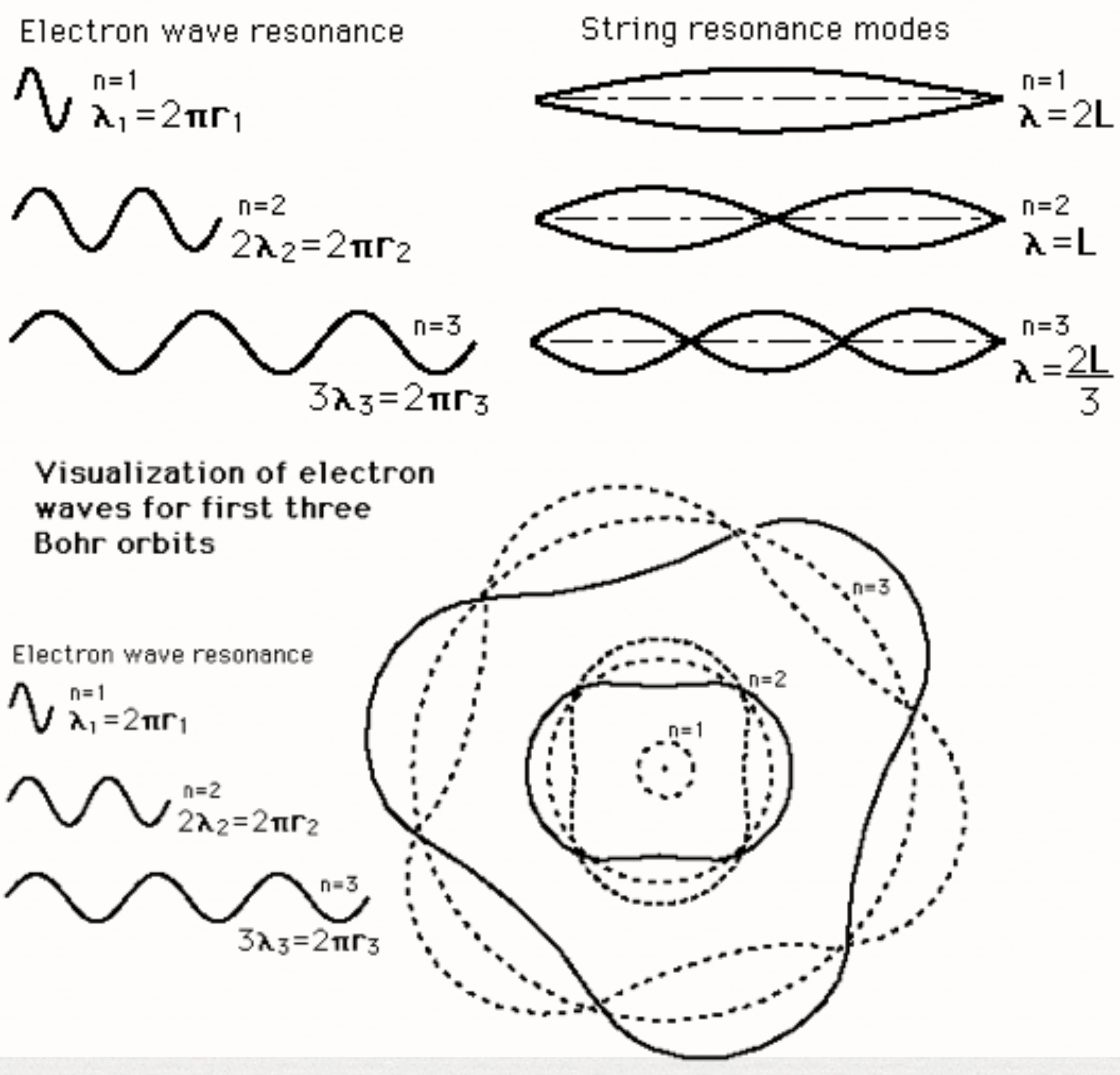


$$F_{Coulomb} = k\frac{qQ}{r^2}$$



But if the electron radiates it looses energy!!! and if it looses energy

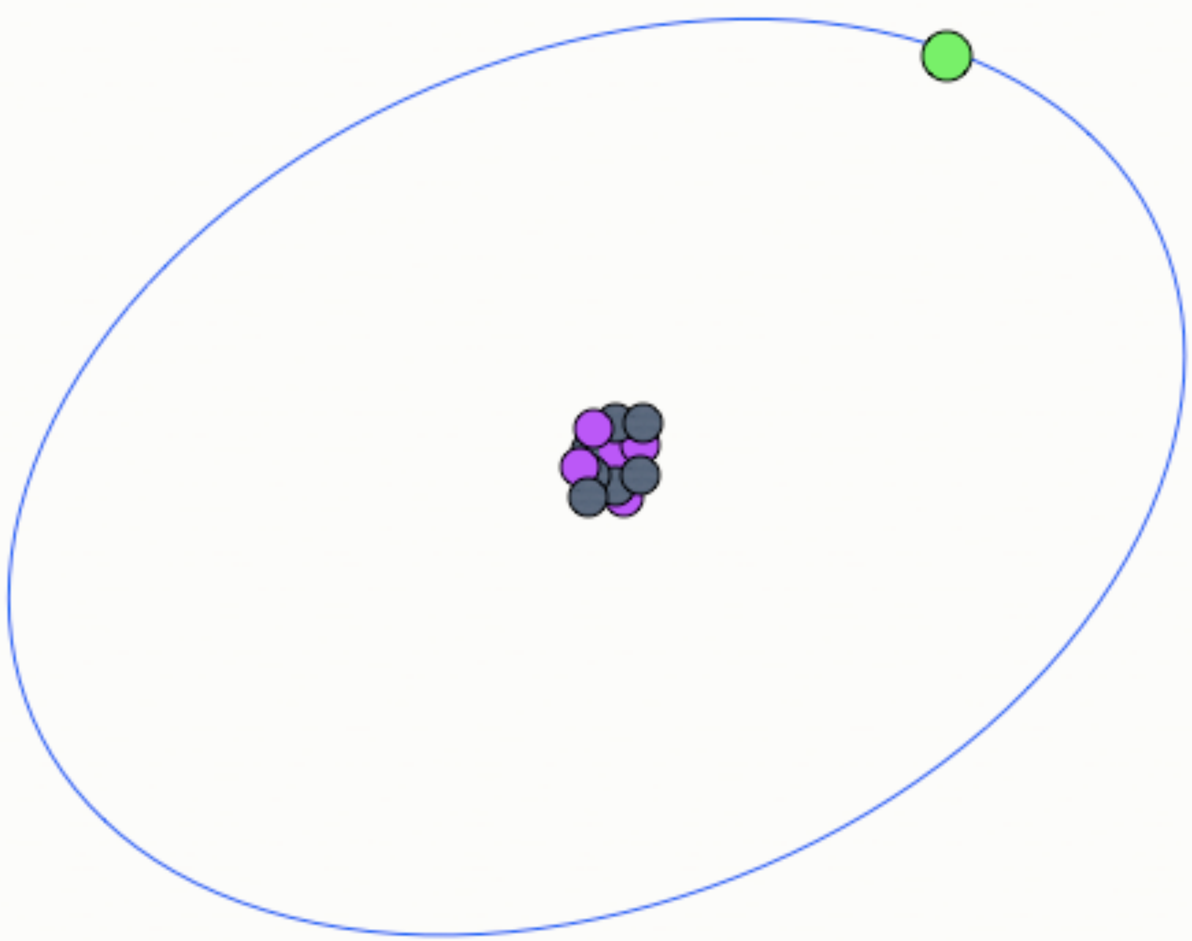
BOHR'S ATOM I



Electrons behave also like waves (dual nature of matter).

Electrons can have orbits such that the energy corresponds to a standing wave on that particular orbit.

BOHR'S ATOM II



Electrons behave also like waves (dual nature of matter). Electrons can have orbits such that the energy corresponds to a standing wave on that particular orbit. The light emitted is proportional to the energy lost.

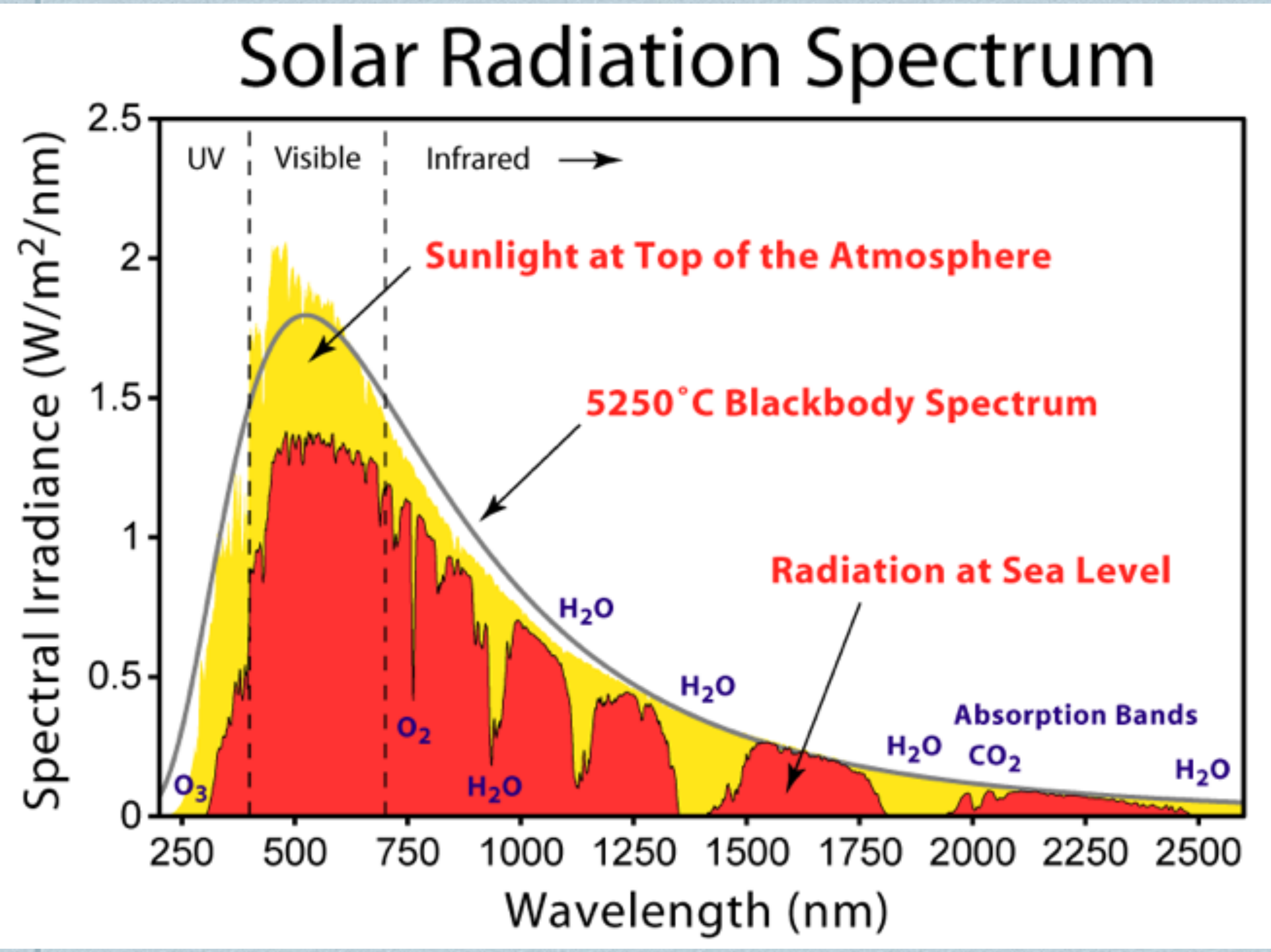
A bit more about light

- Two key ingredients:
- Stars radiate following a distribution of energy called black body radiation spectrum.
- The peak of radiation follows a relationship for temperature and wavelength called Wien's Law of

$$\lambda_{max} = \frac{0.3}{T}$$

Example

It peaks at 475 nm = 475 10^{-9}m = 475 10^{-7} cm



$$T = \frac{0.3}{\lambda_{max}}$$

$$T = \frac{0.3}{475 \times 10^{-7}}$$

$$T = 6316K$$

Betelgeuse peaks @ 855nm

$$T = 3508K$$

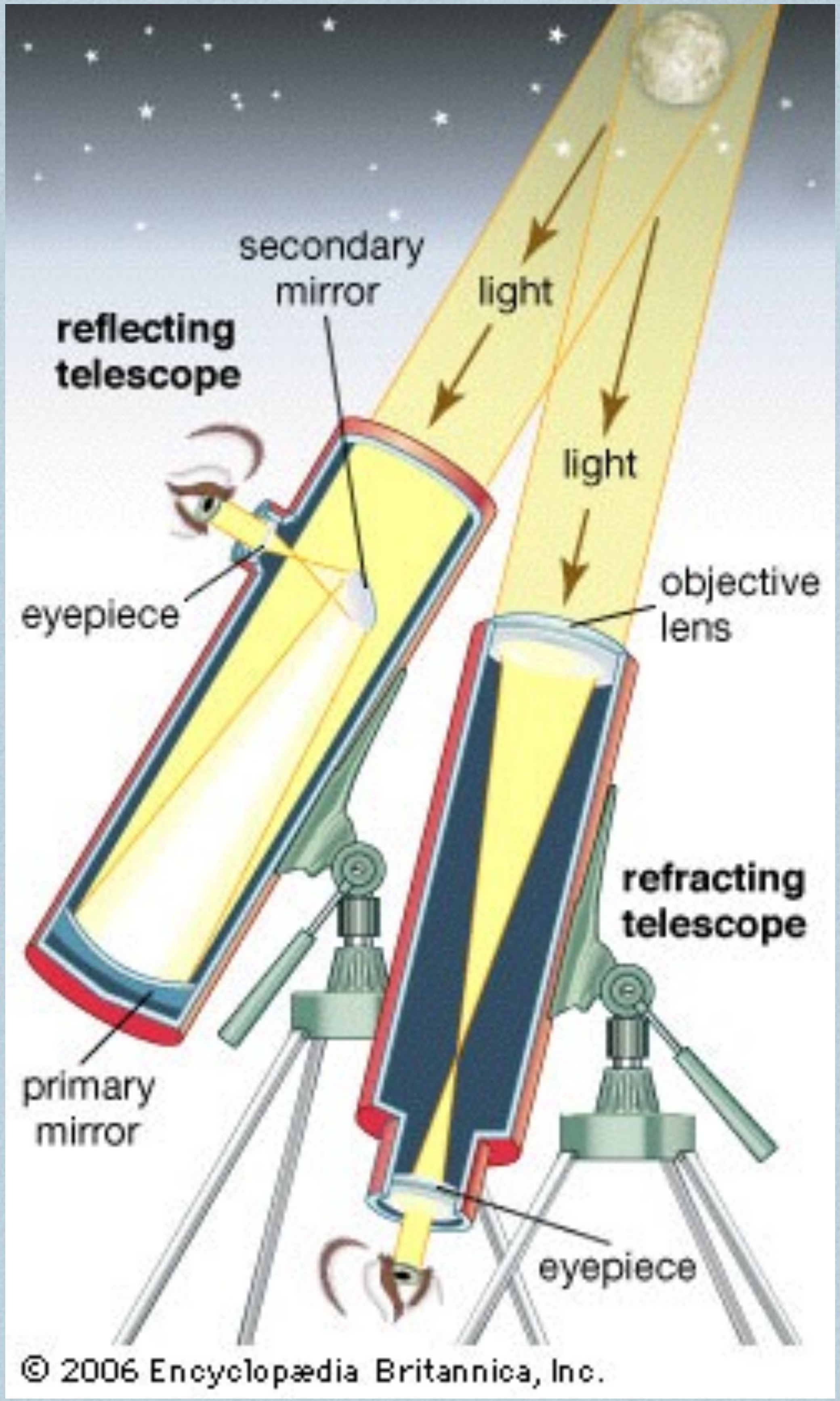
Stefan Boltzman radiation law

- The total energy emitted by a blackbody is proportional to the fourth power of the temperature.
- Temperature is a measure of the average energy (specifically energy of motion (which goes like the square of the velocity) of a body.
- WHen the temperature is higher the particles (molecules) in a body are moving faster...

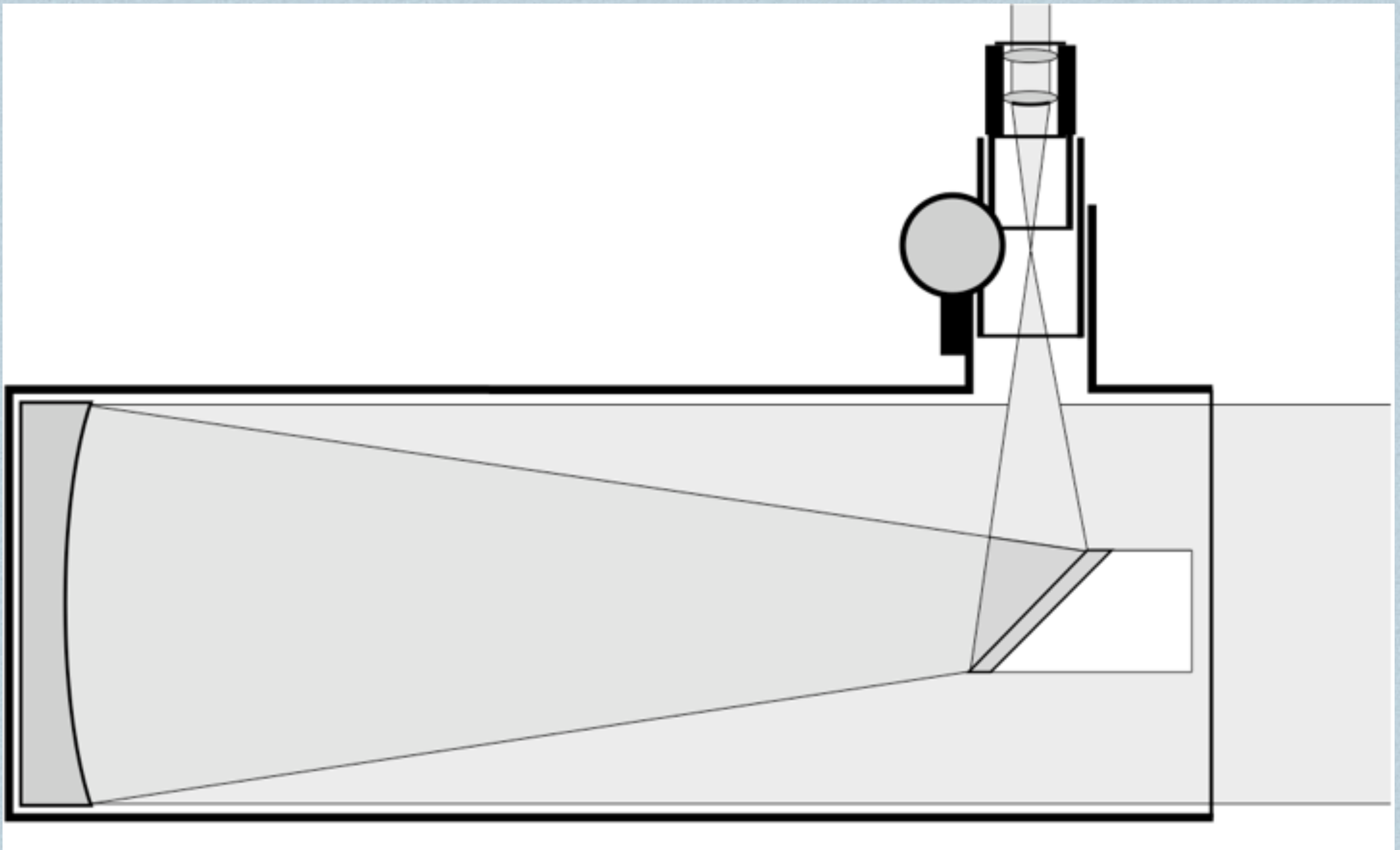
Optical telescope

- They can form an image of faint and distant objects.
- They collect much more light than the human eye can.
- They are of two different kinds:
- reflectors, and
- refractors.

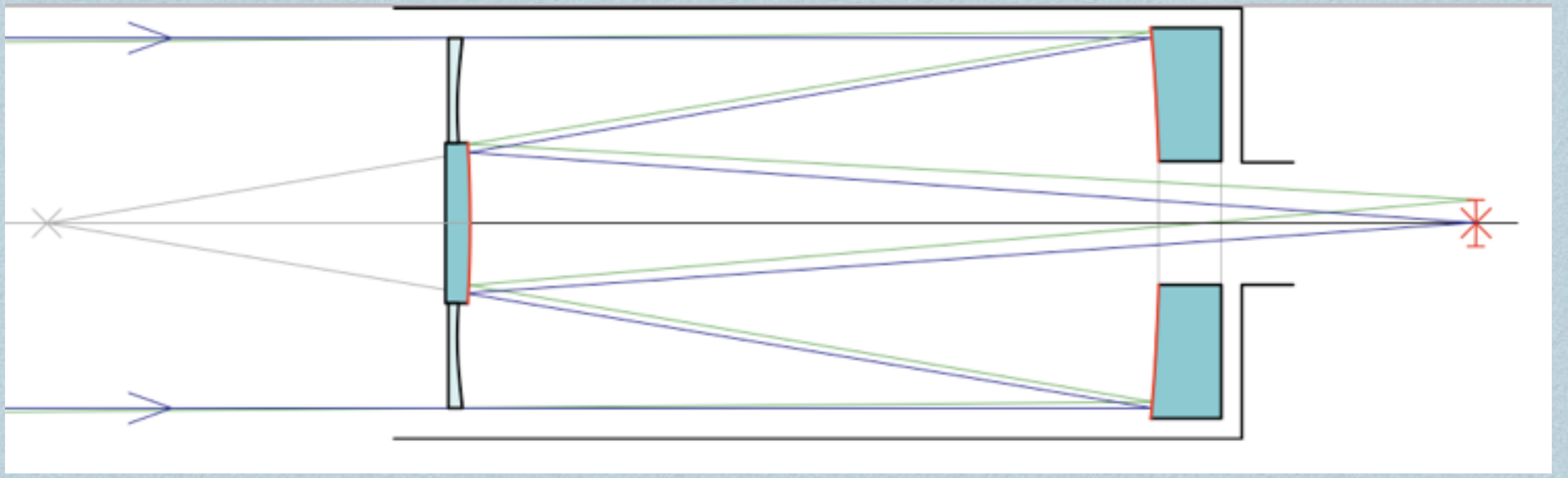
- The key pieces are an eyepiece and a main lens or mirror.
- Its function is to gather light from a sky object and focus it to form an image.



Newtonian reflector



Schmidt-Cassegrain



Nompuewenu Observatory

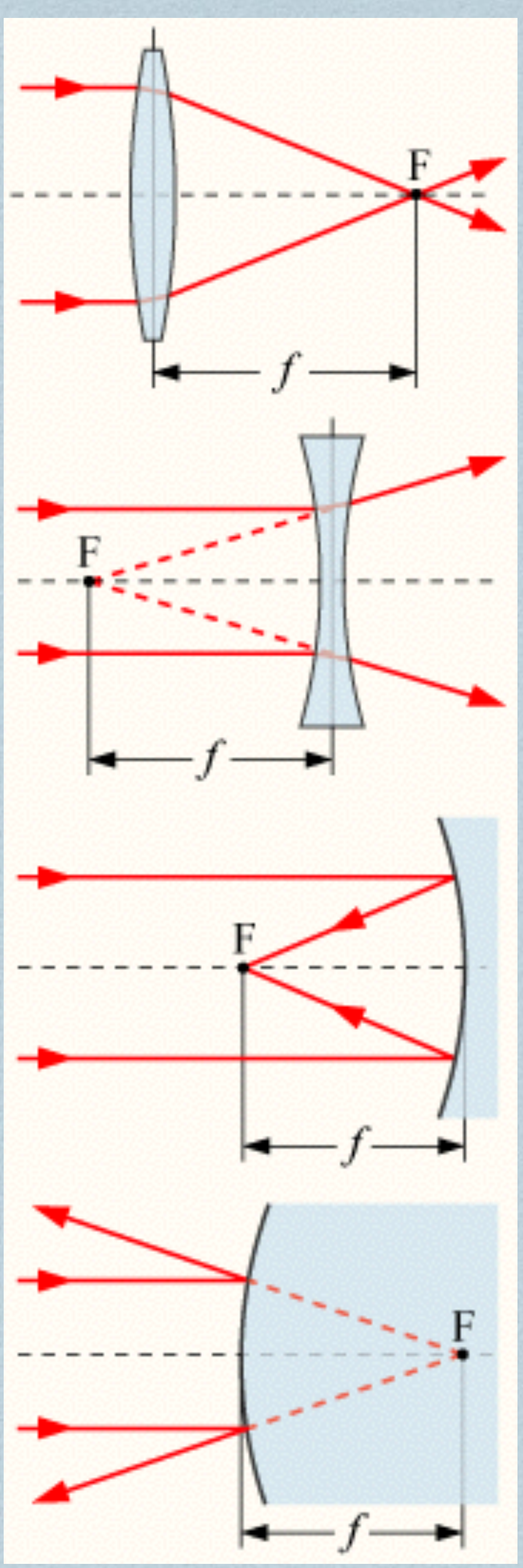
- The ability of the telescope to collect light is called its **light-gathering power.**

- Light gathering power is proportional to the area of the collecting surface, or to the square of the aperture (clear diameter of the main lens or mirror).

- The size of a telescope refers to the size of its aperture.

- The human eye lens is 5 mm. A 6 inch (150 mm) telescope has an aperture over 30 times bigger. Light gathering power is 30^2. So the light gathering power is 900 times greater than than one's eye.

- A 16 inch (400 mm) telescope is 80 times bigger. It has a gathering power 1600 times that of a human eye.



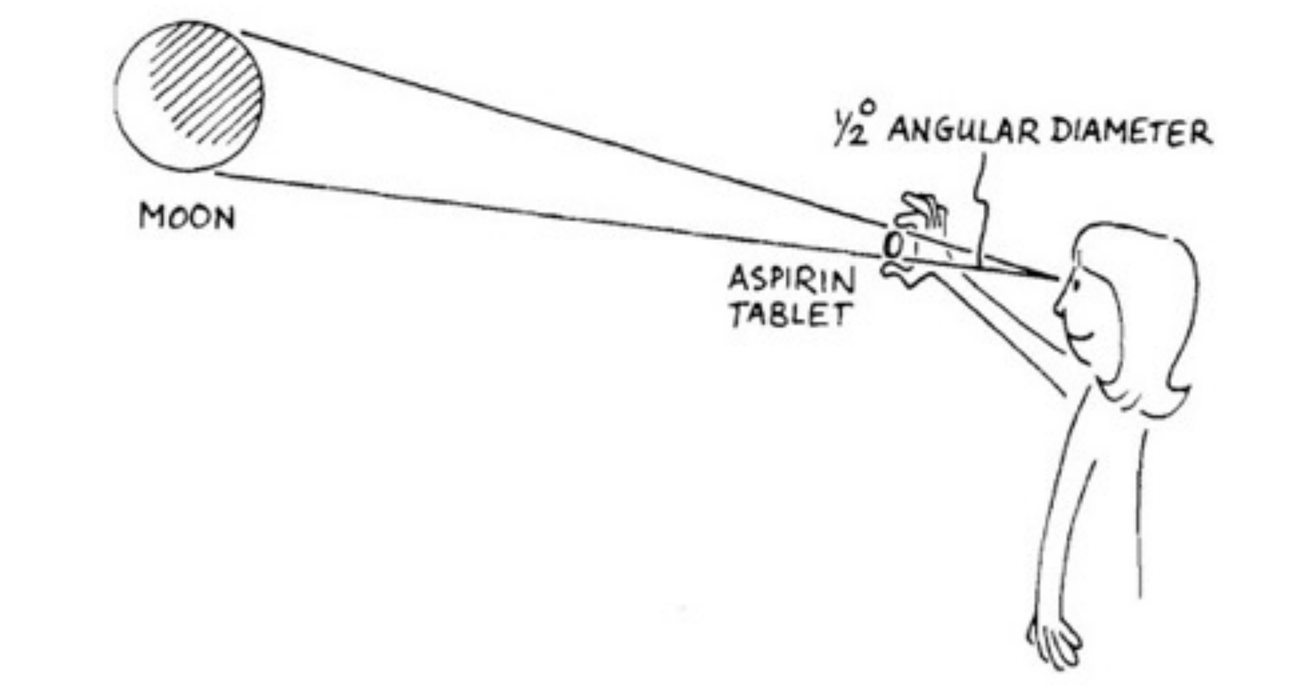
f number

- F number is the **ratio** of the focal length of the main lens or mirror to the aperture.
- Brightness, size and clarity of image depend on both aperture and focal length.
- i.e. 6 inch, f/8 reflector means the primary mirror is 150 mm in diameter and has a focal length of 8 x 150 =1200 mm.

Resolving power

- Is the ability to produce sharp, detailed images under ideal observing conditions.
- Resolving power depends directly on the size of the aperture and inversely on the wavelength of the incoming light.
- diffraction is a problem.
- resolving power determines the smallest angle between two stars for which separate, recognizable images are produced.
- the smallest resolvable angle for the human eye is 1' of arc, which is the size of an aspirin tablet at 35 m.

MAGNIFICATION

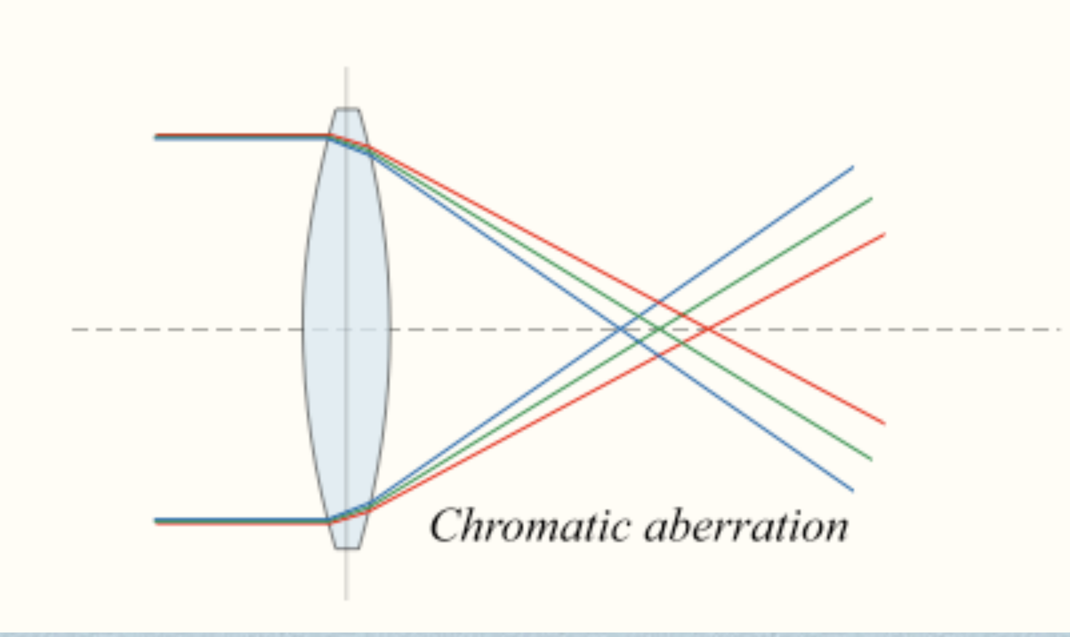


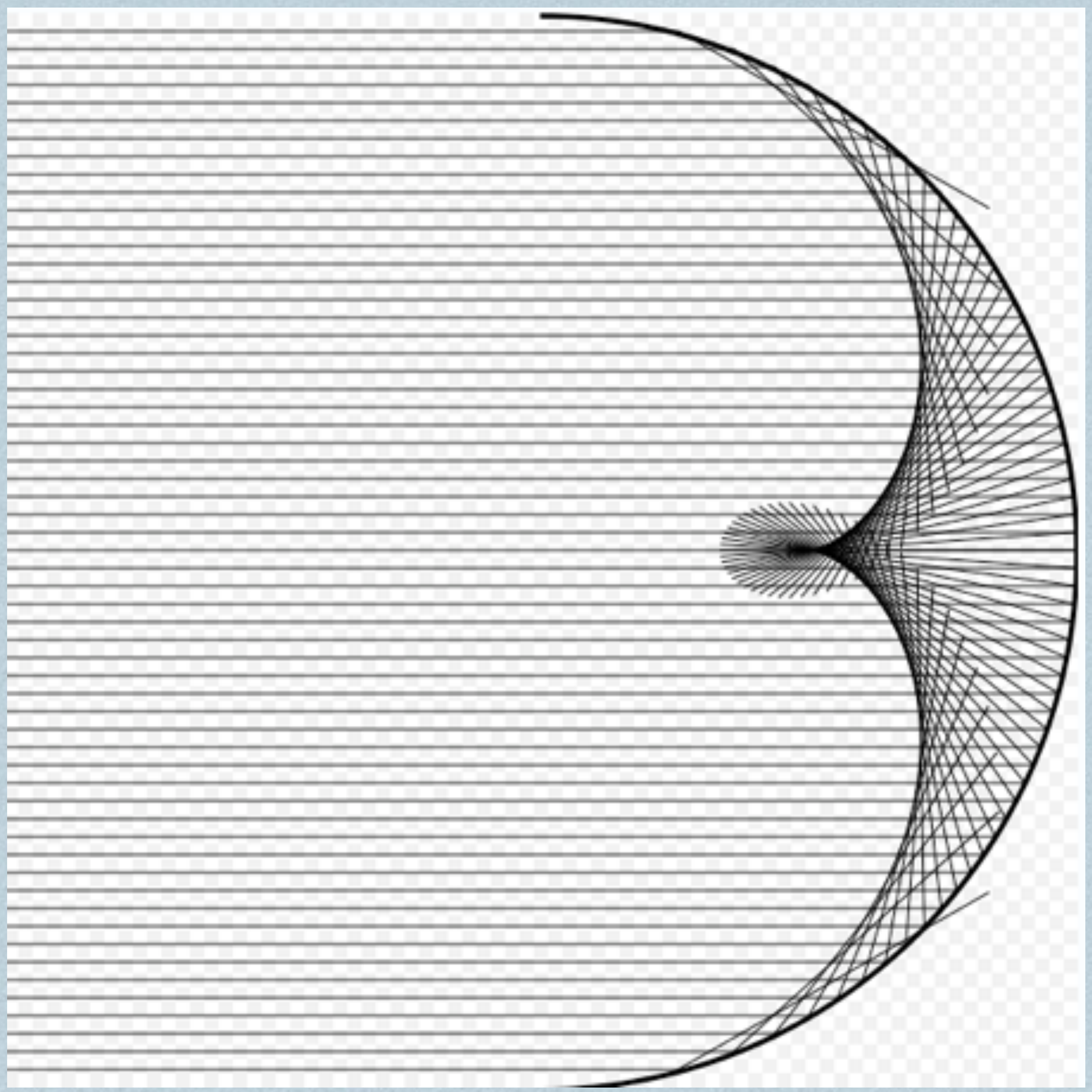
- A telescope magnifying power is the ratio of the apparent size of an object seen through the telescope to its size when seen by the eye alone, i.e. 0.5° seen as 10° is 20x.

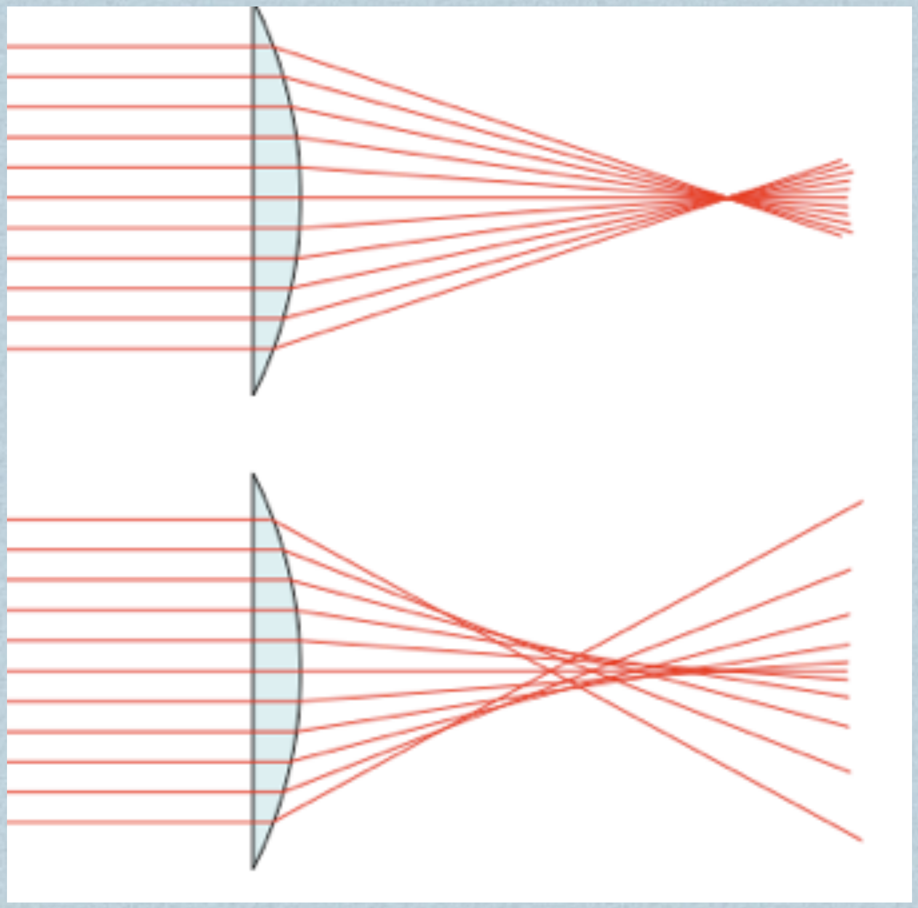
$$Magnifying\ \ Power = \frac{Focal\ \ length\ \ of\ \ telescope}{focal\ \ length\ \ of\ \ eyepiece}$$

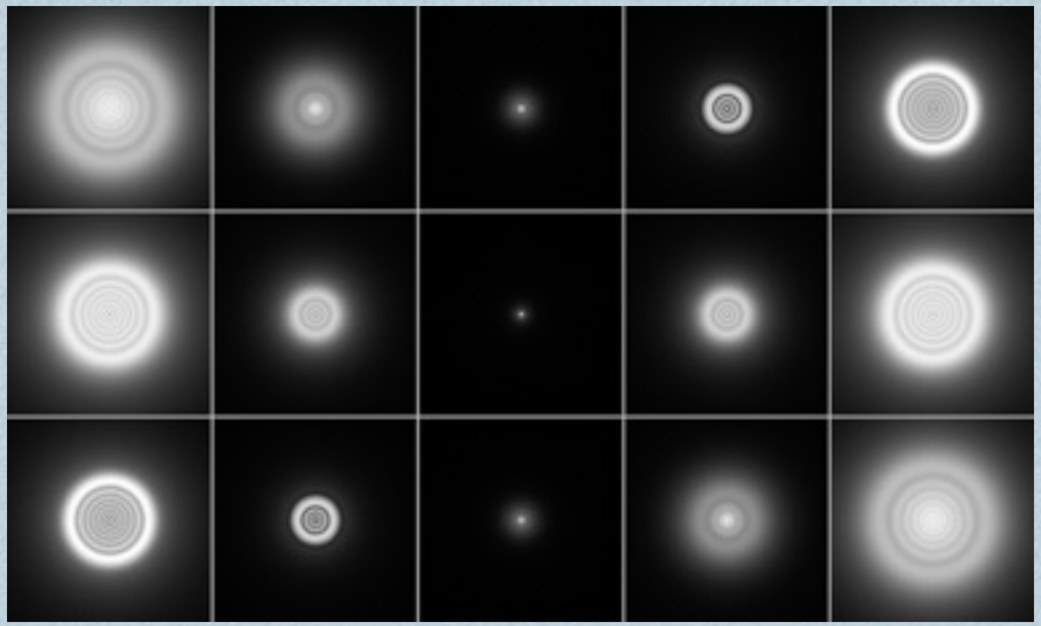
- Magnifying power for an 150 mm (6 inch) telescope, f/8 when an eyepiece of 12. 5 mm is used?
- $$Magnifying\ \ Power = \frac{1200mm}{12.5mm} = 96$$
- maximum useful magnification. Practical useful magnification is twice its aperture in millimeters, 50 times in inches.

Aberrations

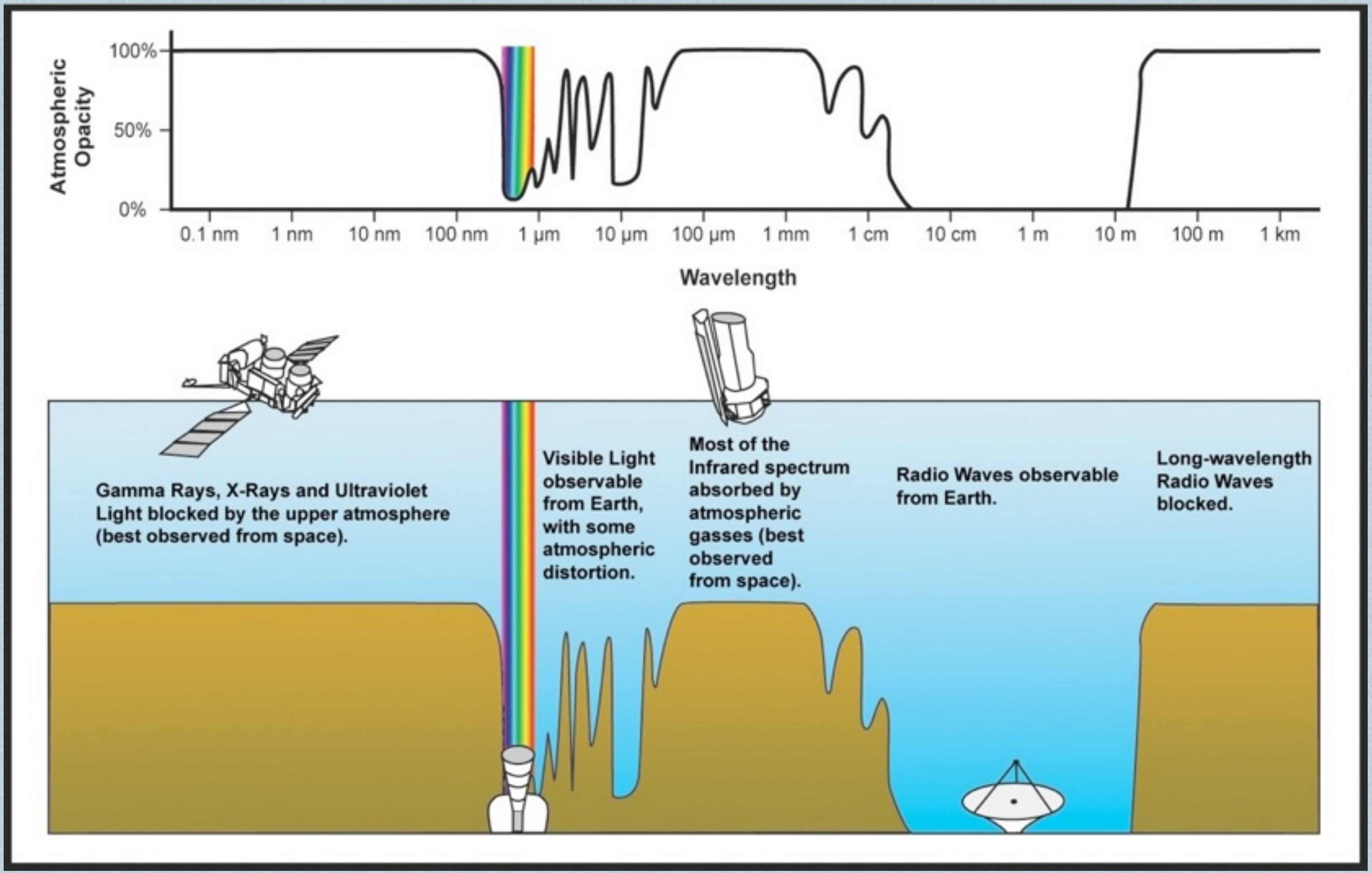








Atmospheric opacity



How bright is an object?

- Introduce the notion of bandpass.
- standard photometric systems.
- Effects that alter light: spectrum shifts, absorption by interstellar material,characteristics of the observing system, terrestrial atmospheric conditions.
- correction techniques.

History

- Ptolemy introduced the magnitude system in the II century.
- Astrometry has a much longer history than photometry.
- Started with optical-mechanical devices.
- Visual photometers started to be used at the end of the XIX century.

- Edward Pickering built the two telescope meridian photometer using crossed polarizers to equalize the images of two stars.
- Between 1879 and 1902 Harvard astronomers measure the magnitudes of 47,000 stars with precision of 0.08 magnitudes and a precision of 0.25 magnitudes.
- 1900 the Pogson normal scale:

$$\Delta m = -2.5 \log(b_1/b_2) \qquad (10.1)$$

- Telescopic scales are closer to the log scale.

- Dry photographic plates 1871.
- 1900-1910 the first photographic magnitude scale.
- 1910-1920 first physical photometers to measure images on plates, uncertainties 0.015-0.03 magnitudes.
- 1940 first photomultiplier tube (PMT), uncertainties of 0.005 magnitudes.
- 1950-1980 Harold Johnson defined the UBV system.
- Terrific precision on spacecraft.

The response function

- A photometric device is sensitive over a restricted range of wavelengths called its **bandpass**.
- Depending on the type of observation we can distinguish three different type of photometry:
- Single-band
- Broad-band multicolor.
- Narrow- and intermediate-band.

Single Band photometry

- Typically it is used when the phenomenon to be observed does not require a particular range of wavelengths.
- In general that's the case when a time-series is obtained (brightness as a function of time).
- i.e. occultations, like searching for extra solar planets.

Broad band multicolor

- We may want to know more than just the brightness of the source, but also the shape of its spectrum.
- Broad band mc measures an ultra low resolution spectrum by sampling brightness in several different bands.
- Broad generally means $\Delta\lambda/\lambda_c > 7\text{-}10\%$. $R = \lambda_c/\Delta\lambda < 10\text{-}15$.
- R is called the spectroscopical resolving power.

- UBVRI system (the most common in the optical) uses bandwidths in the range 65-160nm (*R*=*4*-*7*). It provides information on surface temperature of stars, and more limited information on luminosity, metal content and interstellar reddening.
- Each band is a “color”. For historical reasons the results are reported by giving one magnitude and the color index difference.
- i.e. a 2-color BV will be reported as a V magnitude and one (B-V) color.

Narrow band

- Typically R>50.
- It intents to isolate a specific line or molecular band.
- A weaker signal with more detailed spectral information.
- i.e.measuring the absorption features like the Balmer-alpha or sodium D or the ratio of intensities of emission lines in gaseous nebulae.

Intermediate band

- $15<R<50$.
- It measures spectroscopic features which can not be resolved with broader bands.
- Discontinuities in spectra, i.e. Balmer discontinuity (due to the effect of continuous absorption by hydrogen in stellar atmospheres at 364.6 nm.
- Very broad absorption features (due to blended lines) like TiO in the spectra of M stars (extends from 705 to 730 nm).

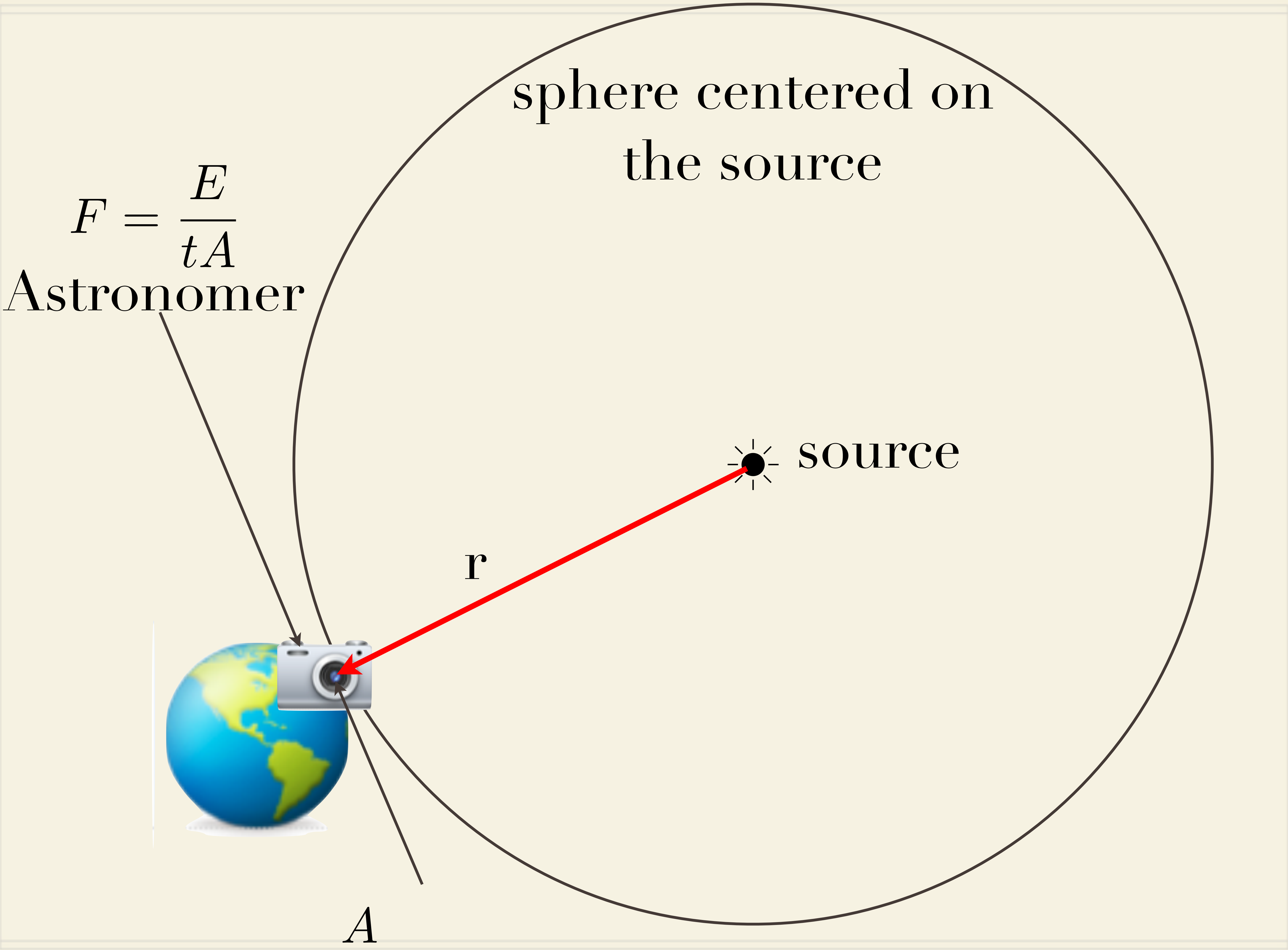
A recap of concepts

- (EM) **Luminosity**: is the total amount of energy that leaves the surface of the source per unit of time (in photons), i.e., the Sun

$$L_{\odot} = 3.85 \times 10^{26}\, W \qquad (10.2)$$

- **Apparent brightness**

$$F = \frac{E}{tA} \qquad (10.3)$$



sphere centered on the source
$F = \frac{E}{tA}$
Astronomer
source
r
A

- F is the flux or flux density (in physics irradiance). units Wm^{-2} i.e. the Sun F at the top of the atmosphere is 1370 Wm^{-2}.
- Luminosity is also called radiant flux by physicists.
- The figure in the previous slide shows that

$$\langle F \rangle = \frac{L}{4\pi r^2} \qquad (10.4)$$

- Surface brightness, L is the luminosity of the star, a its radius

$$s = \frac{L}{4\pi a^2} \tag{10.5}$$

- If the object has a detectable size its solid angle subtended at a distance r:

$$\Omega \cong \frac{\pi a^2}{r^2} \tag{10.6}$$

- The apparent surface brightness

$$\sigma = \frac{F}{\Omega} \tag{10.7}$$

and from *(10.4)*-*(10.6)* we get

$$\sigma = \frac{s}{\pi} \tag{10.8}$$

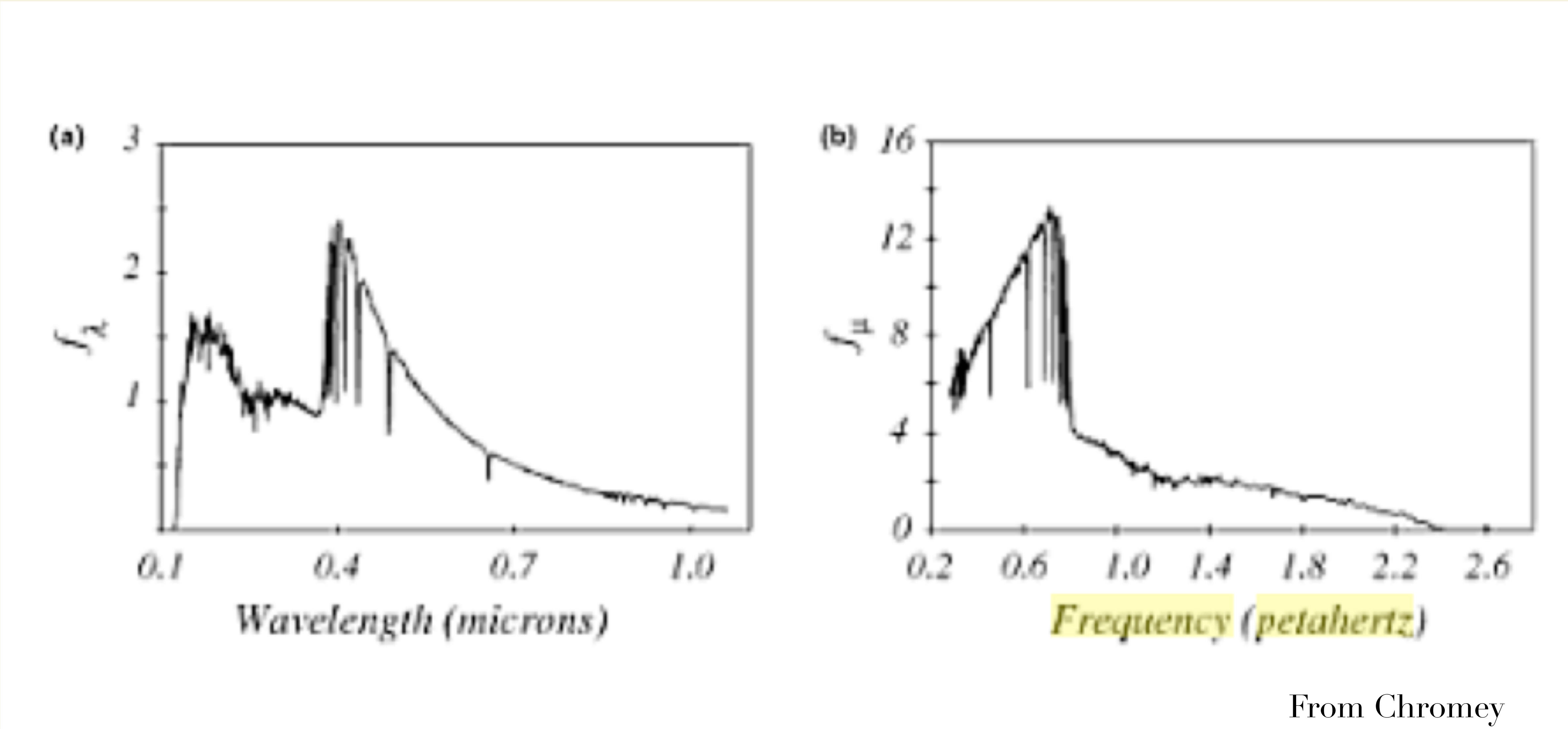
Monochromatic flux

- if the observer can measure photons between ν and $d\nu$ we define monochromatic flux:

$$f_\nu = \frac{F(\nu, \nu + d\nu)}{d\nu} \qquad (10.9)$$

- Integrating over $d\nu$ over some range we would get the spectrum $(Wm^{-2}Hz^{-1})$.
- Similarly we can define:

$$f_\lambda = \frac{F(\lambda, \lambda + d\lambda)}{d\lambda} \qquad (10.10)$$



The spectrum of Vega in wavelengths and in frequencies

Band flux

- Bolometer is a device that measures power received by measuring the heat transferred to it.
- Bolometric flux: $$F_{bol} = \int_0^\infty f_\lambda d\lambda \qquad (10.11)$$
- In practice the flux between the 1-2 pass-band:

$$F_{(\lambda_1,\lambda_2)} = \int_{\lambda_1}^{\lambda_2} f_\lambda d\lambda$$

$$(10.12)$$

$$F_{(\nu_2,\nu_1)} = \int_{\nu_2}^{\nu_1} f_\nu d\nu$$

- Besides cutting on, cutting off we have to consider the efficiency of the process, dependent on the device used (and the place!) where the function R characterizes both:

$$F_{A(\lambda_1,\lambda_2)} = \int_{\lambda_1}^{\lambda_2} R_A(\lambda) f_\lambda d\lambda \qquad (10.13)$$

- The used of filters is standard practice in astronomy.
- The table on the next slide shows some names plus the center wavelength of the band and its width.

Common broad band passes

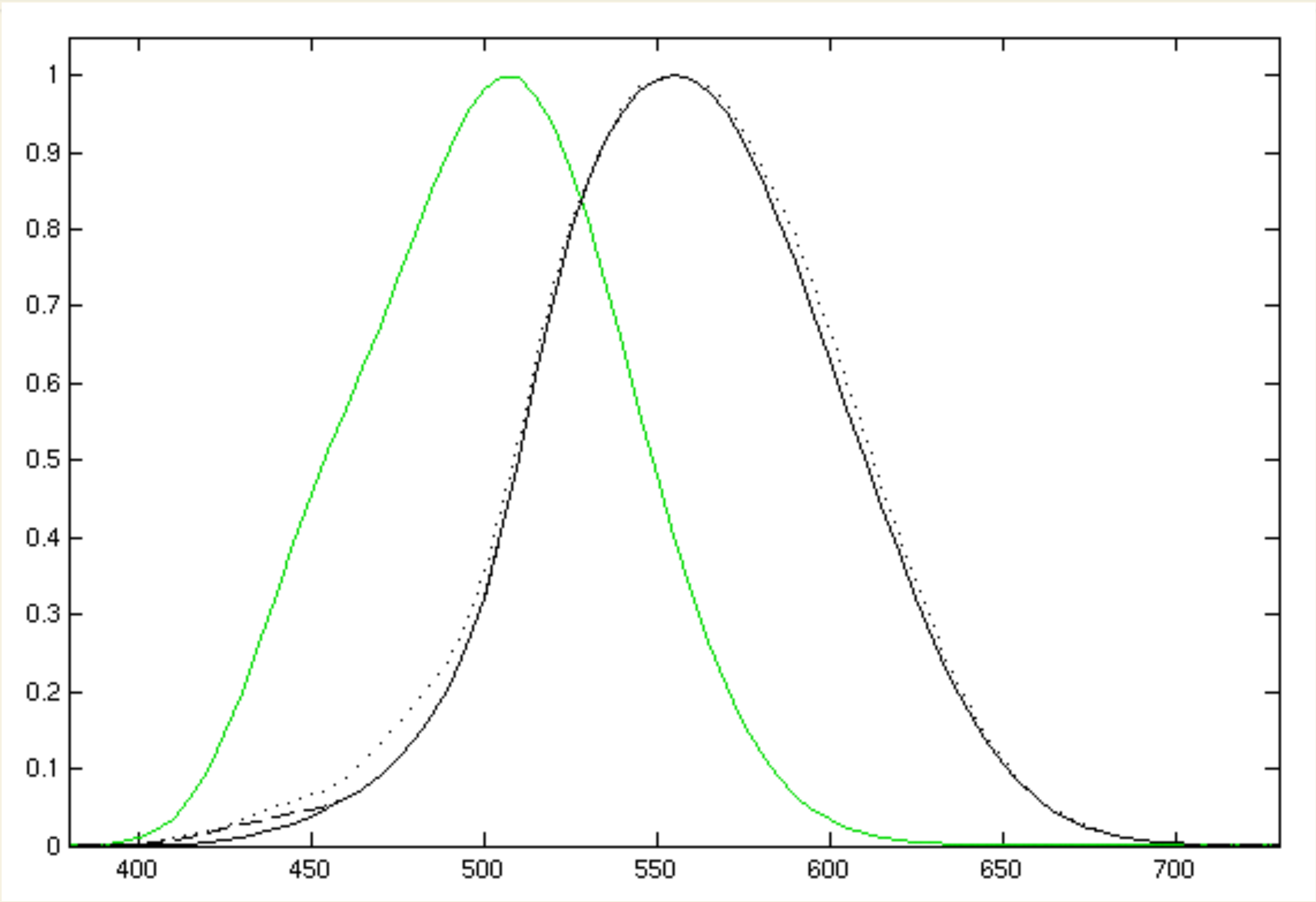
Name	λ_c nm	width nm	Region
U	365	68	Ultraviolet
B	440	98	Blue
V	550	89	Visual
R	700	220	Red
I	900	240	Infrared
J	1250	380	
H	1630	310	
K	2200	480	
L	3400	700	
M	5000	1120	
N	10200	431	
Q	21000	8	

Magnitude again

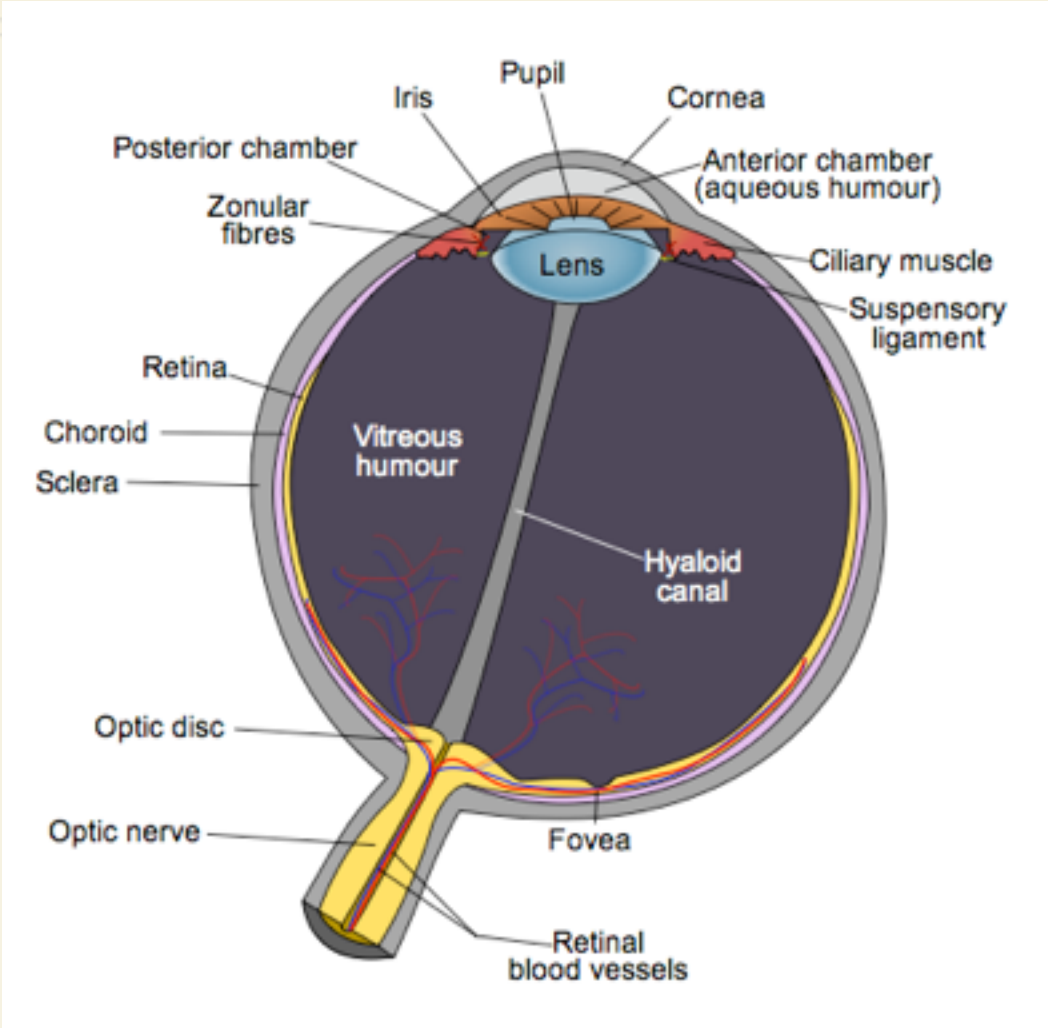
When magnitude was first defined (Hipparchus) what it was used was an effective bandpass: the visual one. But the eye itself has two response functions (rods and cones, the receptor cells in the eye):

> rods operate alone at low levels of light (scotopic vision)→ sensitivity is enhanced towards the blue (it max at 505 nm).

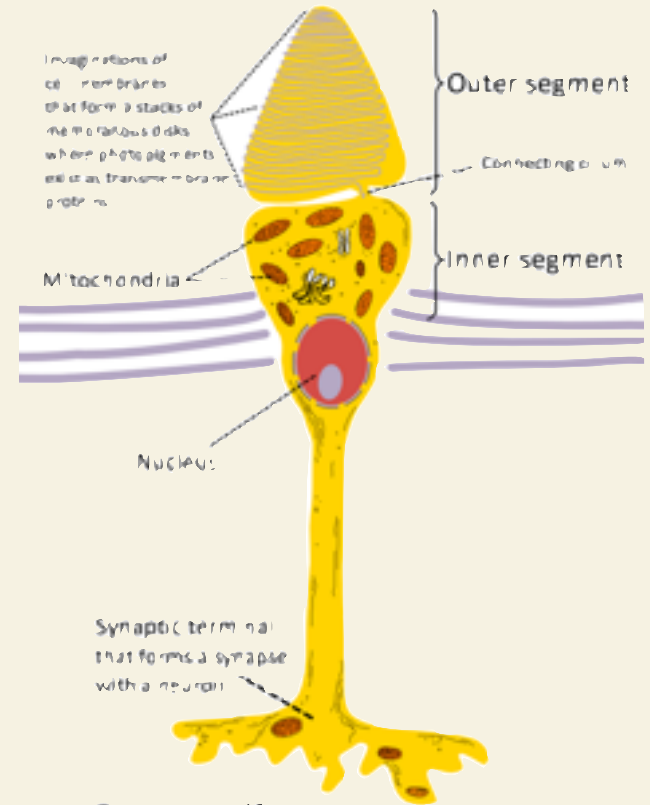
> cones take over at high levels → (photopic vision) towards red and max at 555 nm.



- Scotopic (green) 10^{-2}-10^{-6} cd/m^2
- Photopic (black) 1-10^{6} cd/m^2 (normal luminance).

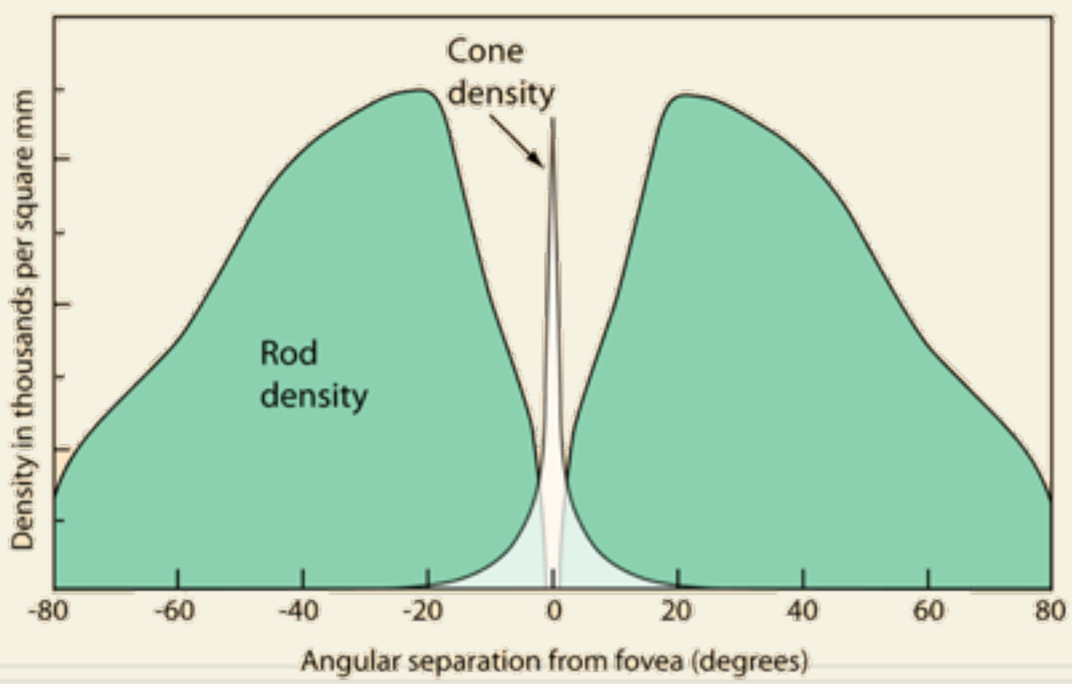


Eye cross section

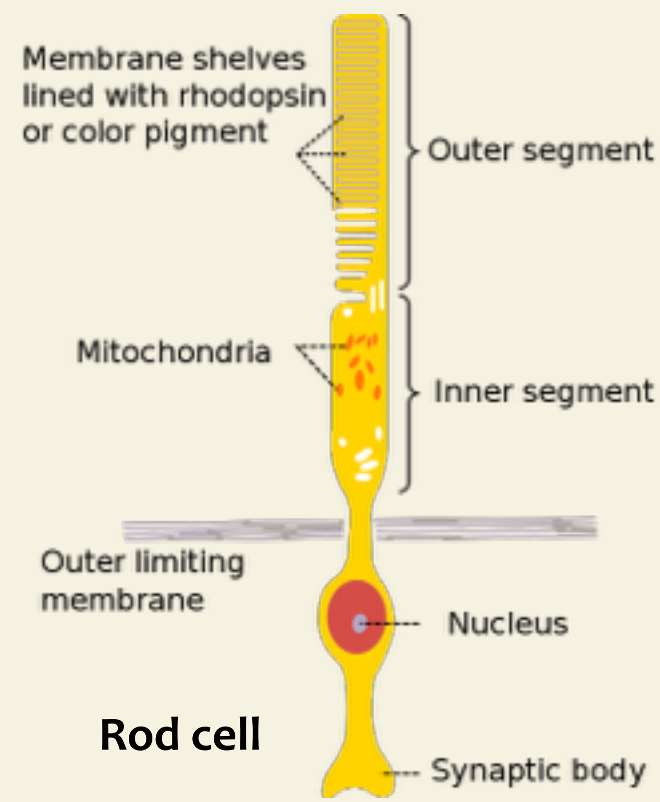


Cone cell

From Wikipedia



Retina



Rod cell

We already saw the Pogson scale.

The relationship between brightness and apparent magnitude is given by

$$m = -2.5log_{10}(F) + K \qquad (10.14)$$

If F is the bolometric flux then we have the apparent bolometric magnitude m_{bol} Even if the measurements are made with a bandpass filter *(10.14)* remains as the definition. It is typically set so that $m=0$ for Vega in any band.

The previous definition is used even if F is not the same in all bands, which of course implies that (10.13) is not the same when the limits change:

$$F_{A(\lambda_1,\lambda_2)} = \int_{\lambda_1}^{\lambda_2} R_A(\lambda) f_\lambda d\lambda$$

It is customary to work with the differential

$$\Delta m = m_1 - m_2 = -2.5 log_{10}(\frac{F_1}{F_2}) \quad \textit{(10.15)}$$

And then the relative flux (or ratio) can be inferred from inverting:

$$\frac{F_1}{F_2} = 10^{-0.4\Delta m} = 10^{-0.4(m_1 - m_2)} \quad \textit{(10.16)}$$

Absolute Magnitude

It is the magnitude, bolometric or bandpass that the source would have if it were at a distance of 10 parsecs in empty space.

$$m - M = 5log(r) - 5 \qquad (10.16)$$

(m-M) is called the distance modulus. *(10.16)* must be modified if the source is not isotropic or if a filter is used. We need to use subscripts indicating the band name, like the Sun has:

$$M_B = 5.48$$

$$M_V = 4.83$$

$$M_{bol} = 4.75$$

If we want to measure a star we look at the pixels that are more or less representatives of the photons coming from the star and add up all of them, getting then:

$$F = \frac{1}{tA} \sum_{x,y} E_{xy}$$

But the CCD has recorded both the light from the star and the sky background so:

$$E_{xy} = S_{xy} - B_{xy}$$

Then we should calculate the flux:

$$F_{star} = \frac{1}{tA} \sum_{x,y} [S_{xy} - B]_{star}$$

If we want to compare the magnitude of our star with Vega

$$m_{star} - m_{Vega} = -2.5log_{10}\frac{F_{star}}{F_{Vega}}$$

and we can evaluate it:

$$m_{star} - m_{Vega} = -2.5log_{10}\left\{\frac{\sum(S_{xy} - B)_{star}}{\sum(S_{xy} - B)_{Vega}}\right\}$$

Magnitudes

For some band the apparent magnitude of the source is:

$$m_p = -2.5\log(F_p) + C_p = -2.5\log\int_0^\infty R_p(\lambda) f_\lambda \, d\lambda + C_p \qquad (10.17)$$

Where m_p is the bandpass magnitude, F_p is the energy flux (the irradiance) within the band, f_λ is the monochromatic flux or irradiance (units of W/m^3). C_p conforms to some standard scale (i.e. the magnitude of Vega is 0).

$R_p(\lambda)$ is the fraction of energy registered on the photometer.

Photon detectors count photons, rather than measure energy. But we can relate the monochromatic photon flux $\phi(\lambda)$, from *(10.10)* to f_λ:

$$\phi(\lambda) = \frac{\lambda}{hc} f_\lambda$$

Detectors do not measure F_p but

$$\Phi_P = \int_0^\infty R_{pp}(\lambda)\phi(\lambda)\, d\lambda = \frac{1}{hc}\int_0^\infty R_p(\lambda) f_\lambda\, d\lambda$$

which is the photon flux within the band. $R_{pp}(\lambda)$ is the photon response (fraction of photons w/ λ detected.)

- Photon counting detectors and energy measuring detectors will perform measurements on the same magnitude scale if:

$$m_p = -2.5 \log(\Phi_P) + C_{PP} = -2.5 \log(F_P) + C_P$$

which requires $R_{PP}(\lambda) \propto R_P(\lambda)/\lambda$.

- A monochromatic magnitude can be defined:

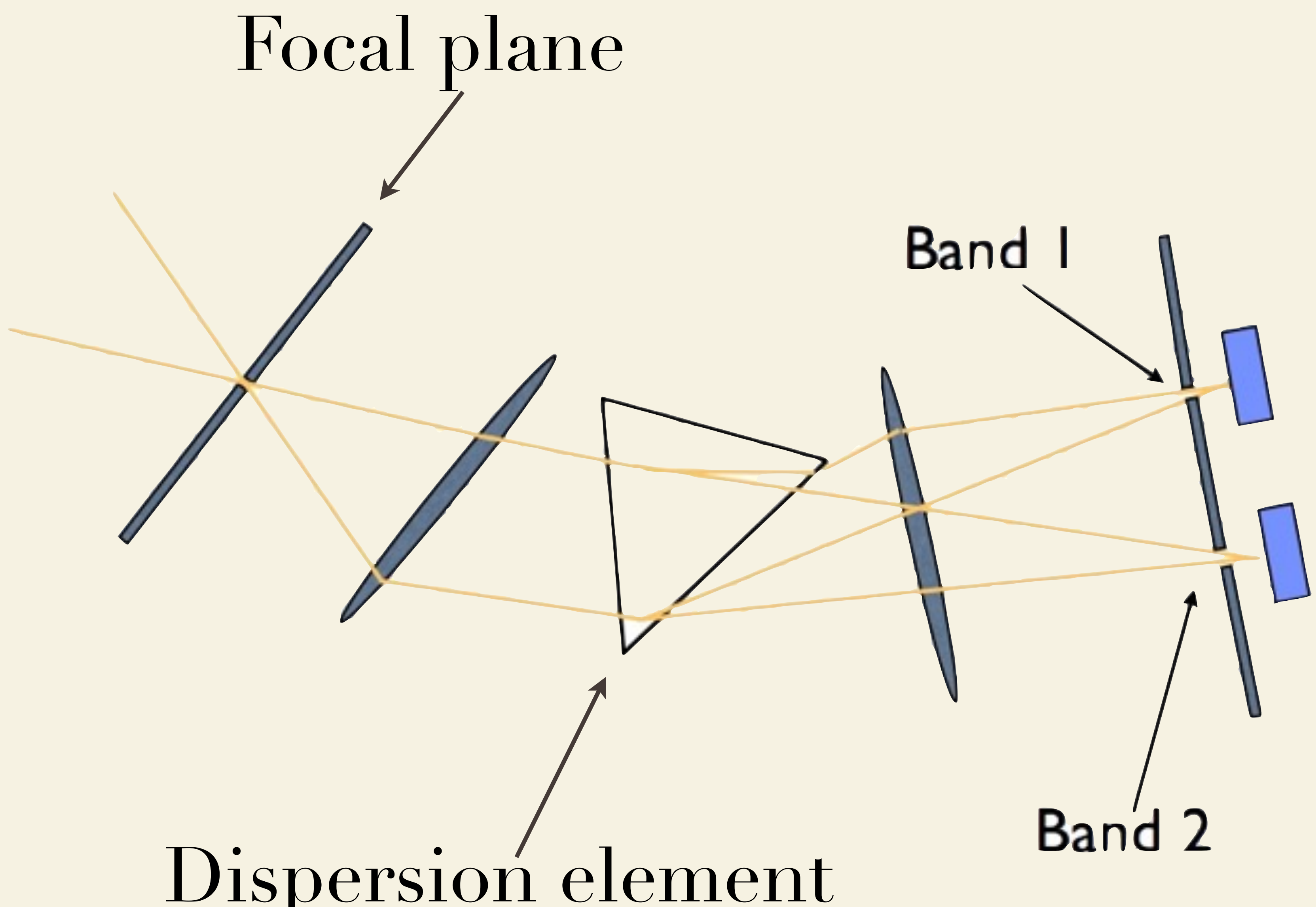
$$m_\lambda = -2.5 \log(f_\lambda) + C'(\lambda) = -2.5 \log\{hc\phi(\lambda)/\lambda\} + C'(\lambda)$$

- $C'(\lambda)$ is arbitrary, but is chosen i.e like that of a monochromatic magnitude of Vega.

Response function

- Practical limits and imposed instrumental controls determine the functional form of $R_{PP}(\lambda)$ or $R_P(\lambda)$.
- Visual limitations imposes a band (460-550 nm).
- Filters are usually the method of choice. A bandpass filter delimits both ends by blocking outside the desire band.
- A filter can be a low-pass or high-pass by

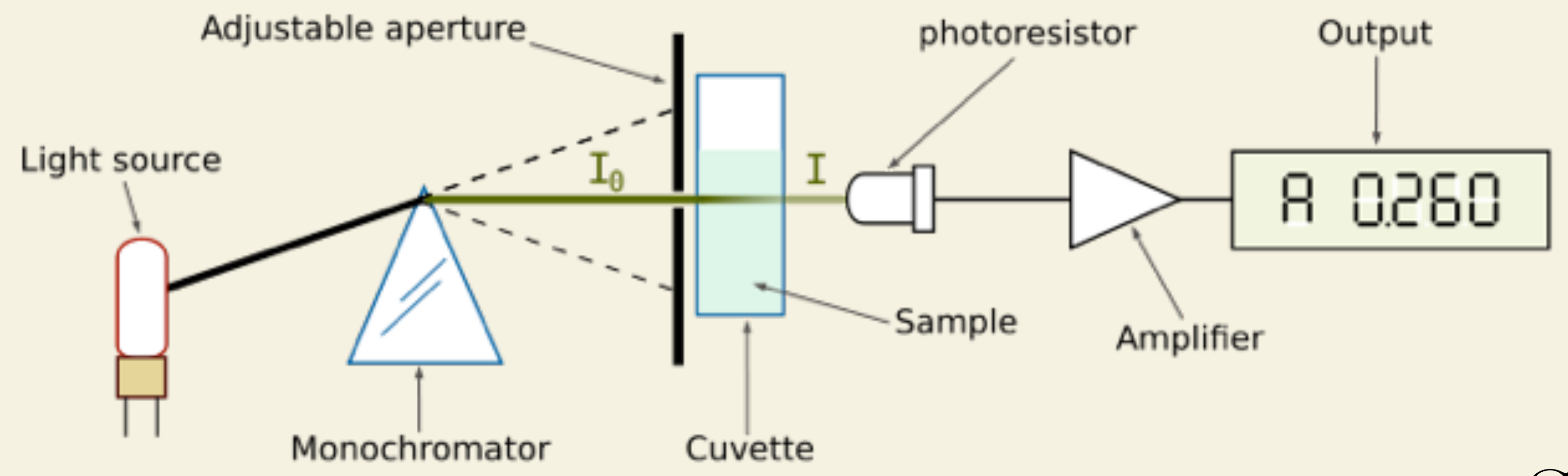
Multi band photometry



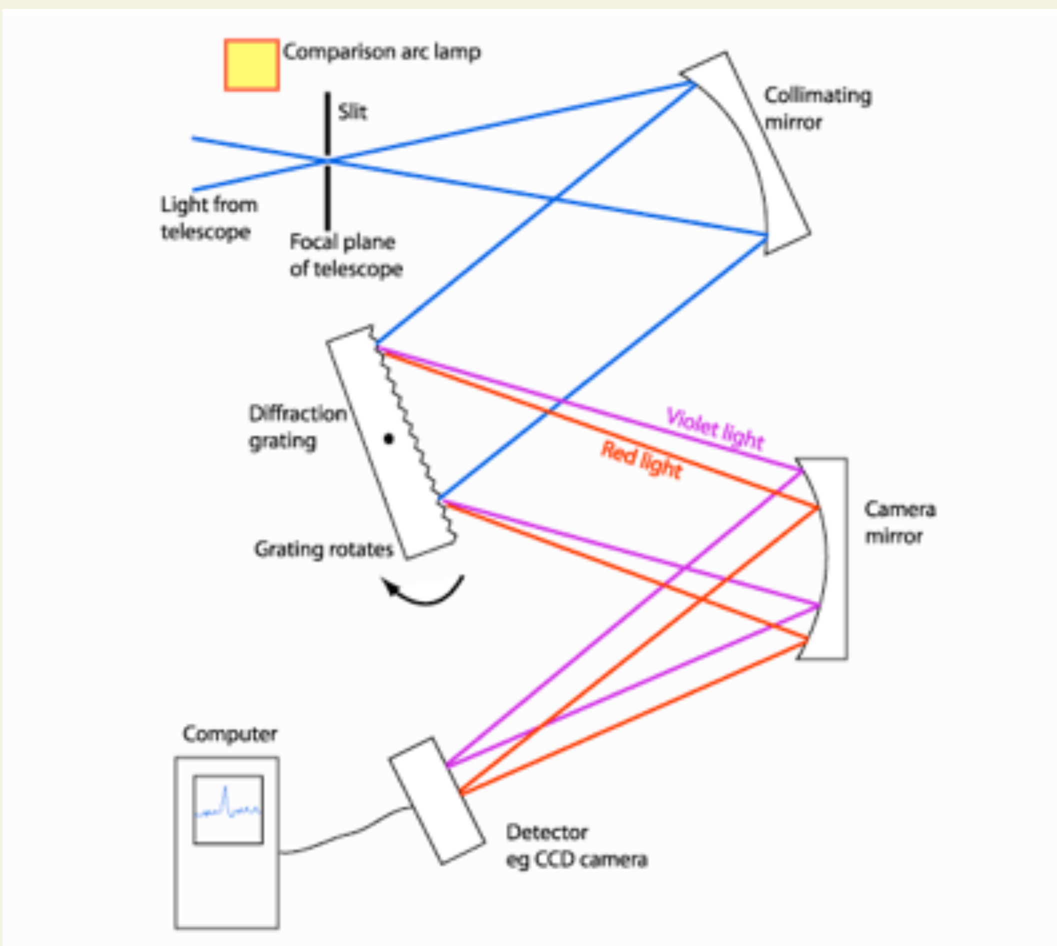
Adapted from Chromey

A spectrophotometer (spectrum scanner)

From Wikipedia



Single beam spectrophotometer



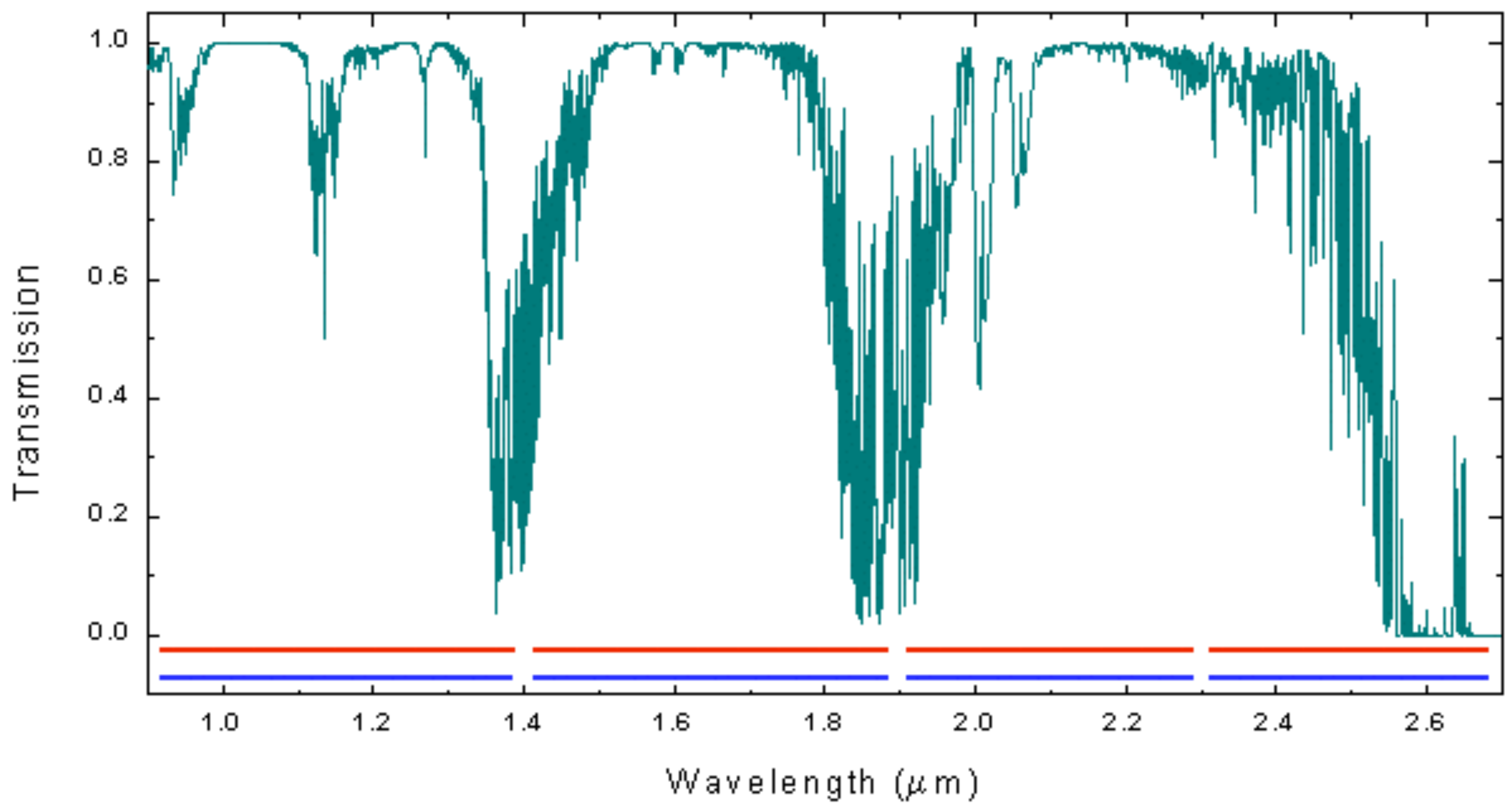
A Schematic Diagram of a Slit Spectrograph

spectrograph schematics

Adapted by Australia Telescope from a diagram by *James B. Kaler, in "Stars and their Spectra," Cambridge University Press, 1989.*

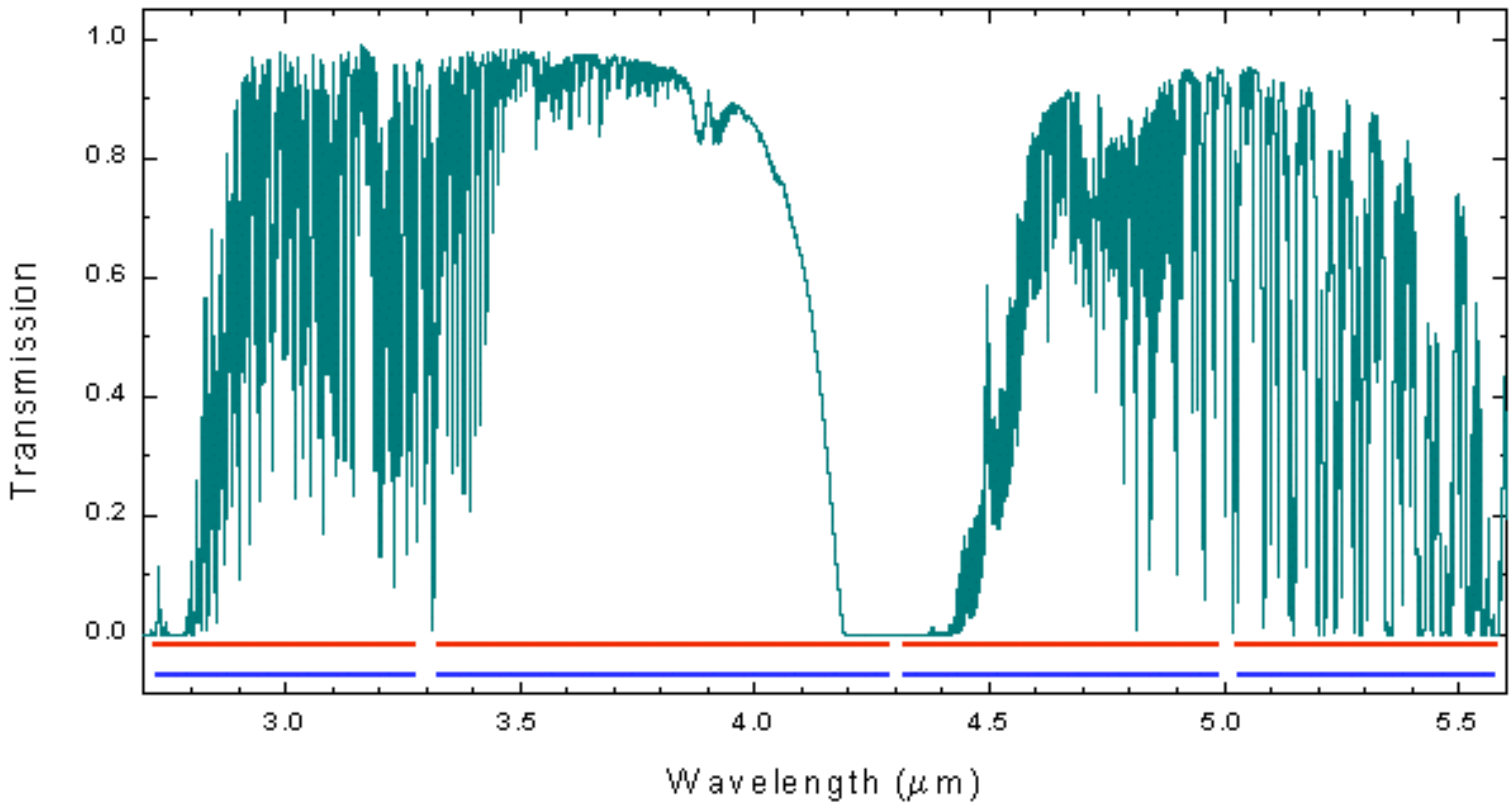
- The previous slide shows a spectrophotometer.
- CCDs blurs the distinction between a spectrophotometer and an spectrograph.
- Atmospheric transmission, $S_{atm}(\lambda)$ limits the wavelengths that are accessible defining the facto a response function, i.e. it set the short wavelength cutoff for old photographic photometry at 320nm.
- In the infrared, absorption by water vapor is significant.

Atmospheric transmission in the infrared 990-2650 nm



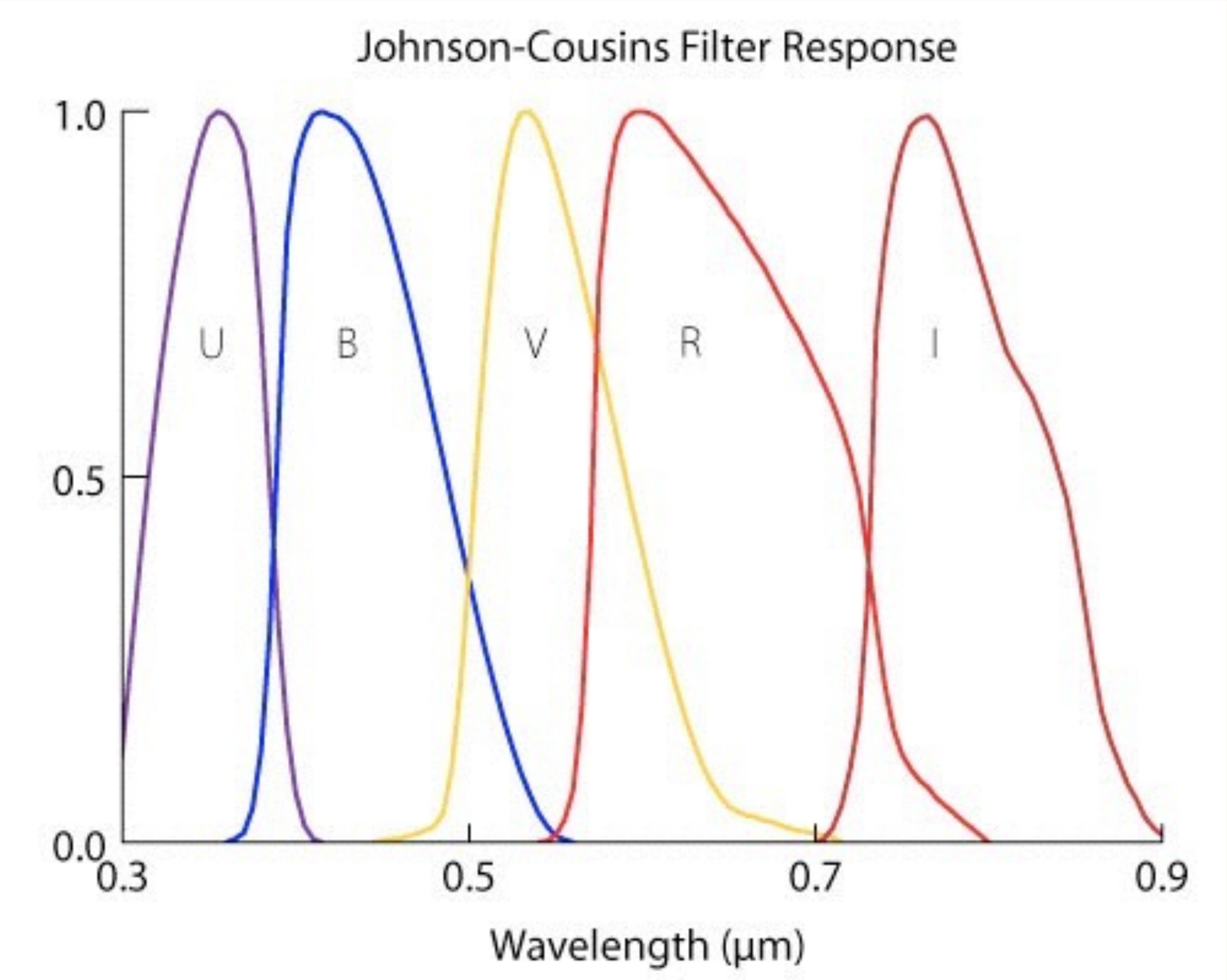
From: http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-transmission-spectra

Atmospheric transmission in the infrared 2700-5600 nm



From: http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-transmission-spectra

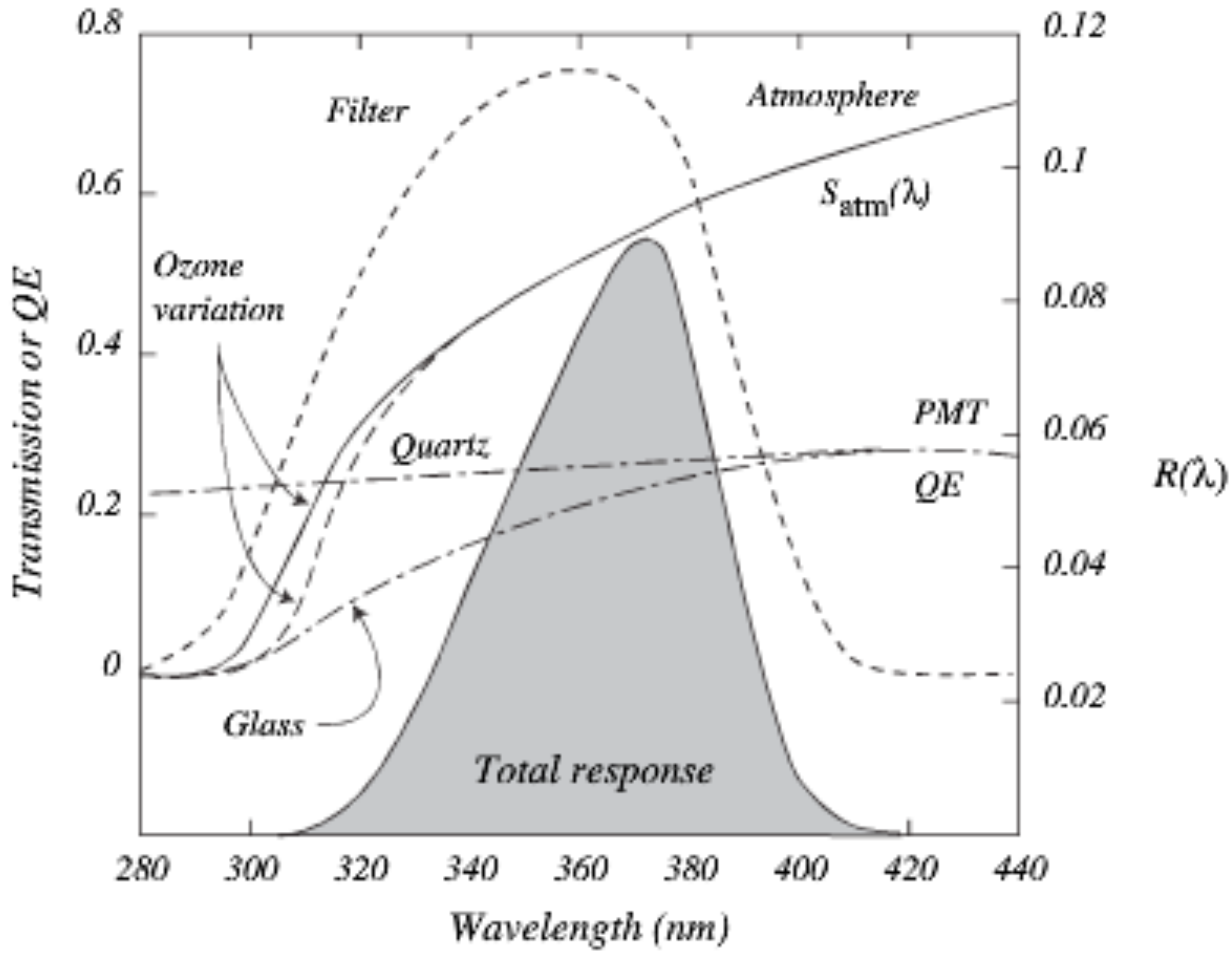
The Johnson’s UBVRI filter



Color bands of J-C filter

Wave Band	Center frequency nm	Band width nm	0 magnitude flux $erg/s/cm^2\ 10^{-5}\ \mu m^{-1}$
U	350	70	3.98
B	438	98.5	6.95
V	546.5	870	3.63
R	647	151.5	2.254
I	786.5	109	1.196

1. Filter transmission (Corning glass #9863).
2. QE(λ) of the detector (RCA 1P21). tube walls matter too (fused quartz used later).
3. Atmosphere transmission $S_{atm}(\lambda)$: object at the zenith and ozone partial pressure is 3mm. With quartz the atmosphere sets the cut off.
4. Transmission of the telescope optics.



From Chromey

Response function for the Johnson U band

Response function description

- Many times it suffices to give R_{max} at λ_{peak}
- Also there are only two half max points and they could be used as specs for λ_{low} and λ_{high} :

$$R(\lambda_{peak}) = R_{max}$$

$$R(\lambda_{low}) = R(\lambda_{high}) = R_{max}/2$$

- A measure of the width of the response function could be given then by:

$$FWHM = \lambda_{high} - \lambda_{low}$$

The half max points determine the central wavelength of the band (and it could be more representative of the midpoint than λ_{peak}) :

$$\lambda_{cen} = (\lambda_{low} + \lambda_{high})/2$$

and the bandwidth is a more useful measure in general than the width:

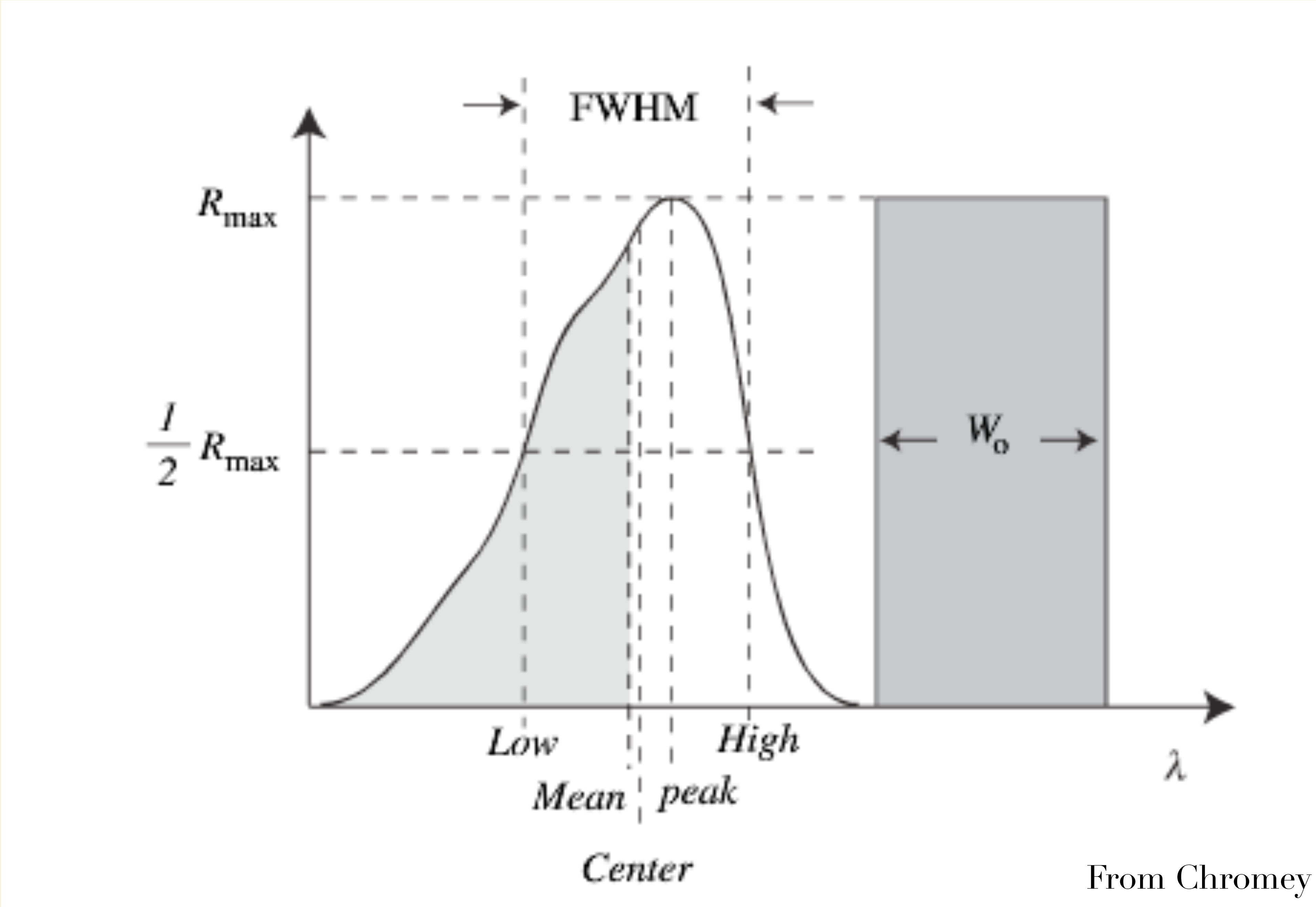
$$W_0 = \frac{1}{R_{max}} \int R(\lambda) d\lambda$$

- Similarly mean wavelength:

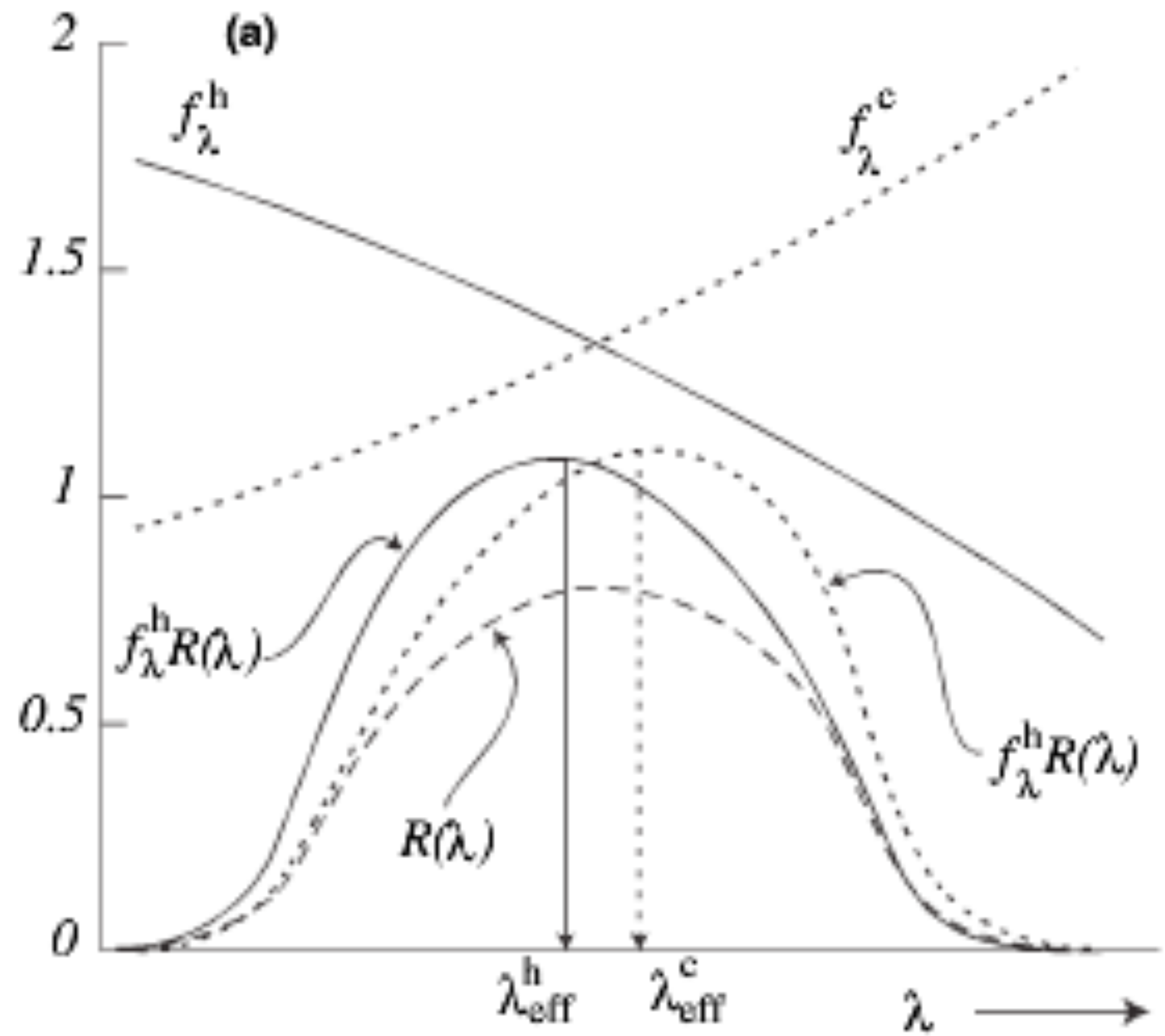
$$\lambda_0 = \frac{\int \lambda R(\lambda) d\lambda}{\int R(\lambda) d\lambda}$$

- For a symmetric function, $\lambda_{peak} = \lambda_{cen} = \lambda_0$
- Effective wavelength of the response to a particular source:

$$\lambda_{eff} = \frac{\int \lambda f_\lambda R(\lambda) d\lambda}{\int f_\lambda R(\lambda) d\lambda}$$



$1/2\ R_{max}$, $FWHM$, λ_{cen}, λ_{peak}, λ_0 and W_0



From Chromey

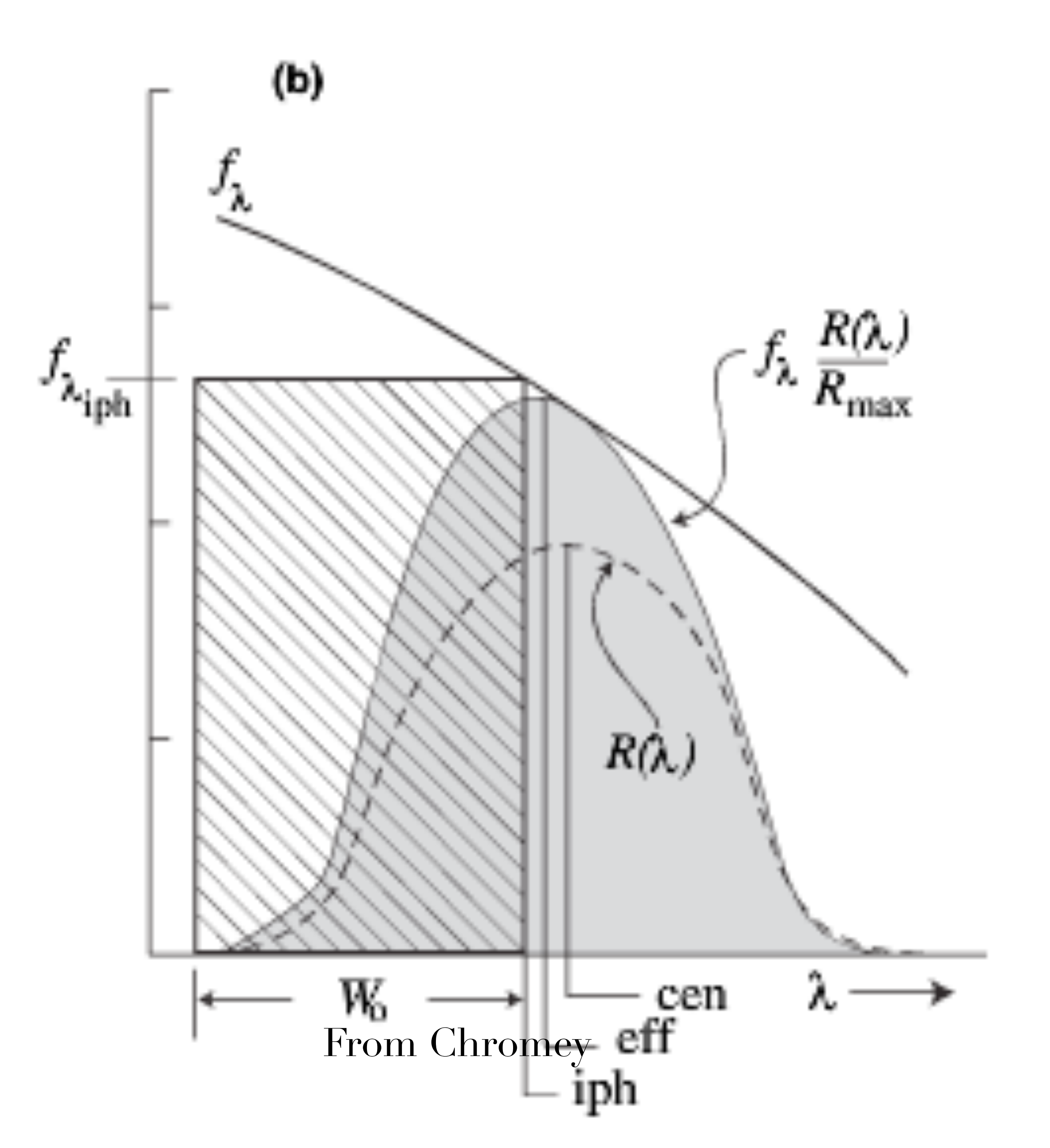
Solid lines represent a hot source and the dashed a cool one. They both have the same magnitude in the band.

A fair approximation to the response function of a band-pass measurement is obtained multiplying the monochromatic flux at λ_{eff} by the bandwidth. The errors when the source has smooth spectra at broadband photometry has low error (1%).

A more correct definition for "middle" of the band is *isophotal wavelength* λ_{iph}, which is obtained through its flux:

$$f_{iph} = \frac{1}{W_0 R_{max}} \int f_\lambda R(\lambda) d\lambda$$

The isophotal wavelength is near λ_0. It reduces to λ_0 when the R is a linear function of λ in the interval covered by the passband.



From Chromey

Dashed curve is the response function.

Recap of black body spectra

- Stefan Boltzman:

  s=σT^4 (σ≃5.7×10^{-8}Wm^{-2}K^{-4})

  The shape is the same regardless of the spectra, such that:

- Wein's displacement law

$$\lambda_{max} = \frac{2.8979 \times 10^{-3}}{T} mK$$

$$\nu_{max} = 0.5766 \times 10^{11} T \quad Hz^{-1} K$$

- Planck distribution, gives the monochromatic flux per unit solid angle

$$B(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\left(exp\left(\frac{h\nu}{kT}\right) - 1\right)}$$

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\left(exp\left(\frac{hc}{\lambda kT}\right) - 1\right)}$$

- At long wavelengths → Rayleigh-Jeans approximation:

$$B(\lambda, T) = \frac{2ckT}{\lambda^4}$$

$$B(\nu, T) = 2kT\frac{\nu^2}{c^2}$$

Color indices

- We can use multi-band photometry to measure the shape of an object's spectrum.
- We can think of the bands as sampling the monochromatic flux of a smoothed spectrum at the isophotal wavelength.
- The next figure shows the spectra of several blackbodies whose temperatures range from 1600K to 12,000K. Remember

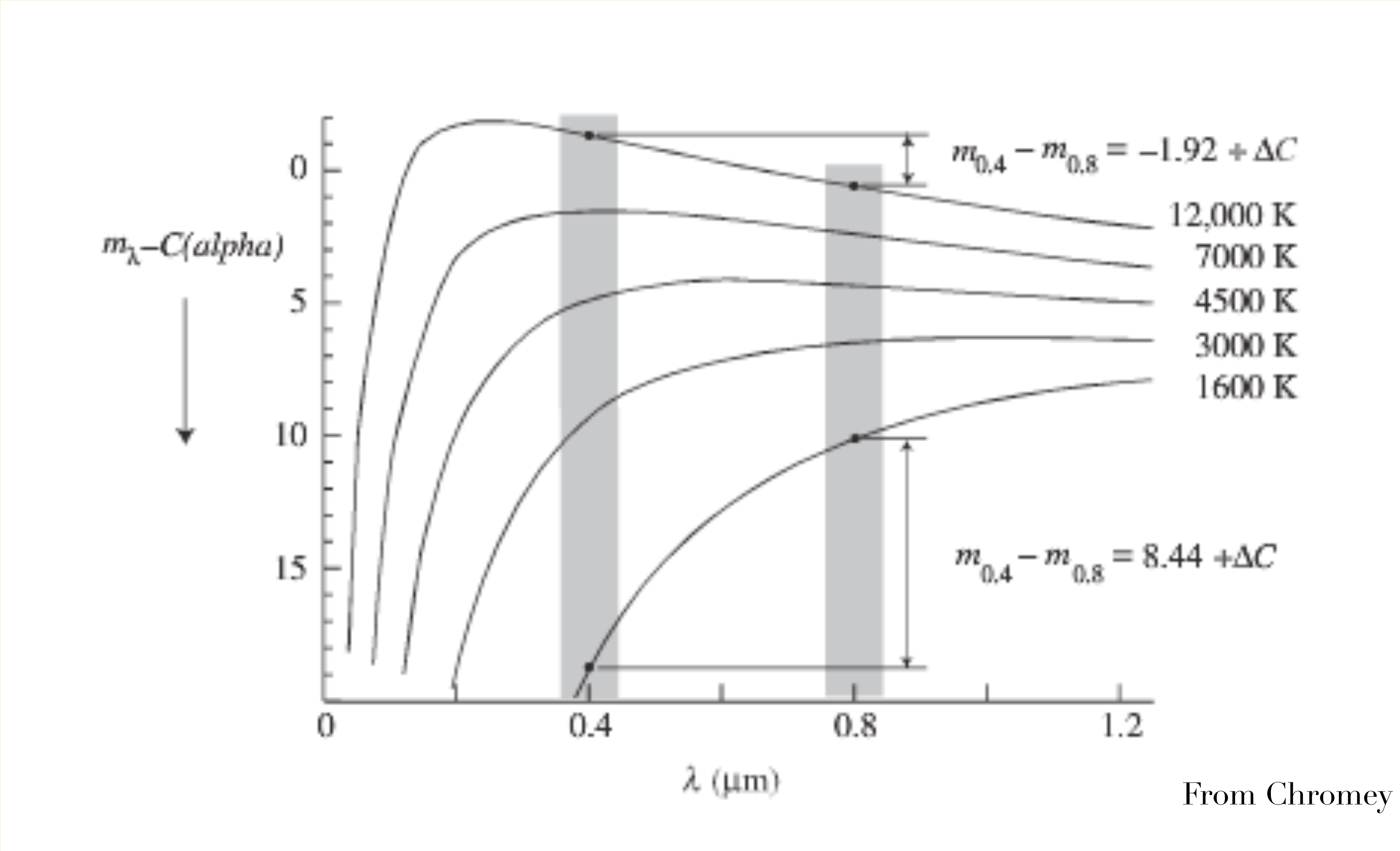
$$m_\lambda = -2.5 log(f_\lambda) + C'(\lambda) = -2.5\ log\{hc\phi(\lambda)/\lambda\} + C'(\lambda)$$

- The difference between any two bandpass magnitudes sampling the spectrum's slope is called the color index.

$$\text{index} = m(shorter\ \lambda) - m\ (longer\ \lambda)$$

$m_{0.4} - m_{0.8}$ in the figure.

R-I i.e. for the Johnson-Cousins red and infrared bands



Color indices for blackbodies $(log\, B(\lambda, T))$, arrow show increase magnitudes

Color indices at the longer and shorter wavelengths

- At long wavelengths ($\lambda kT \gg hc$) the Planck function can be substituted by the Rayleigh Jeans:

$$m_{\lambda}=log(T)+C(\lambda)$$

- So we get

$$m_{\lambda 1} - m_{\lambda 2} = C(\lambda_1) - C(\lambda_2)$$

- Johnson broadband system, a bb of inf T has

$U-B=-1.33$ $B-V=-0.46$

- At short wavelengths, we can use the Wien approximation for the surface brightness of a bb.

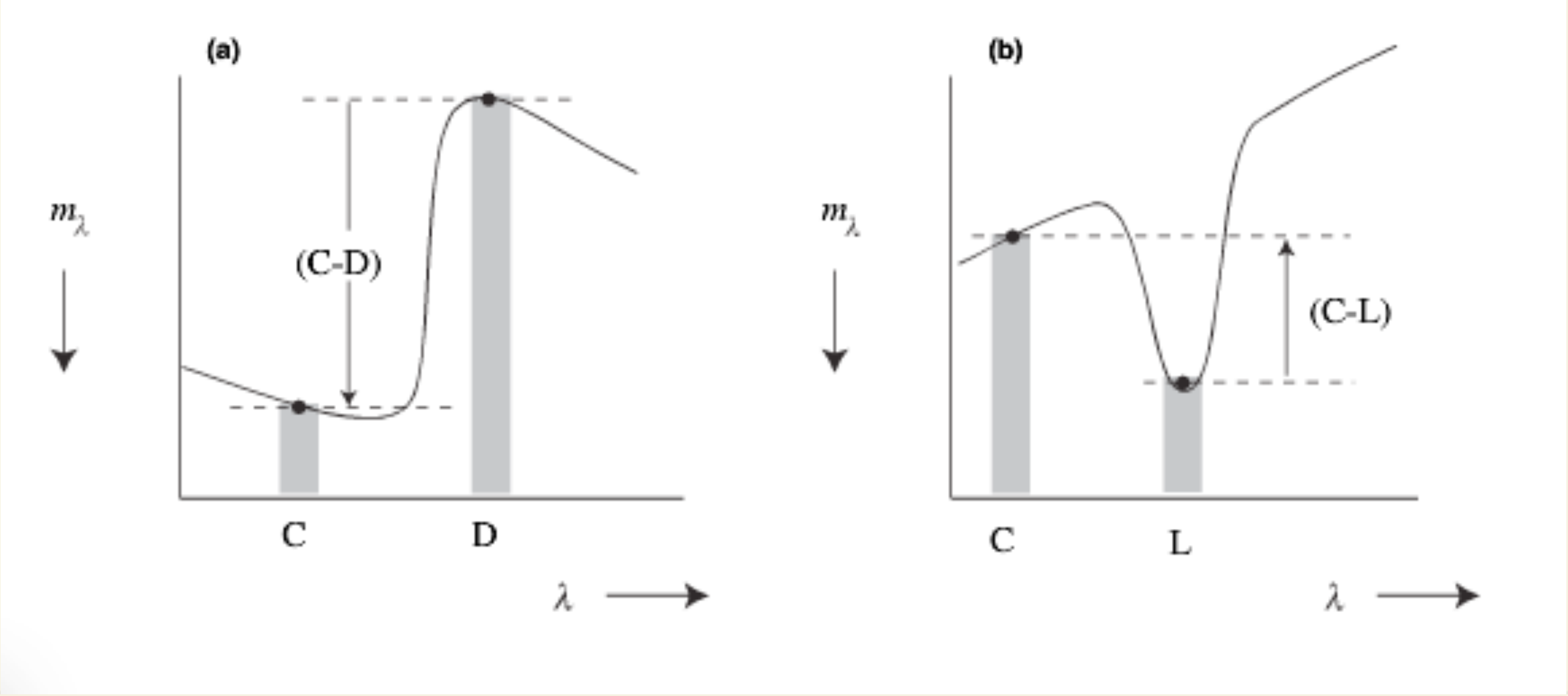
$$B(\lambda, T) \approx \frac{2hc^2}{\lambda^5} \exp\left(-\frac{hc}{\lambda kT}\right)$$

- so the color index is:

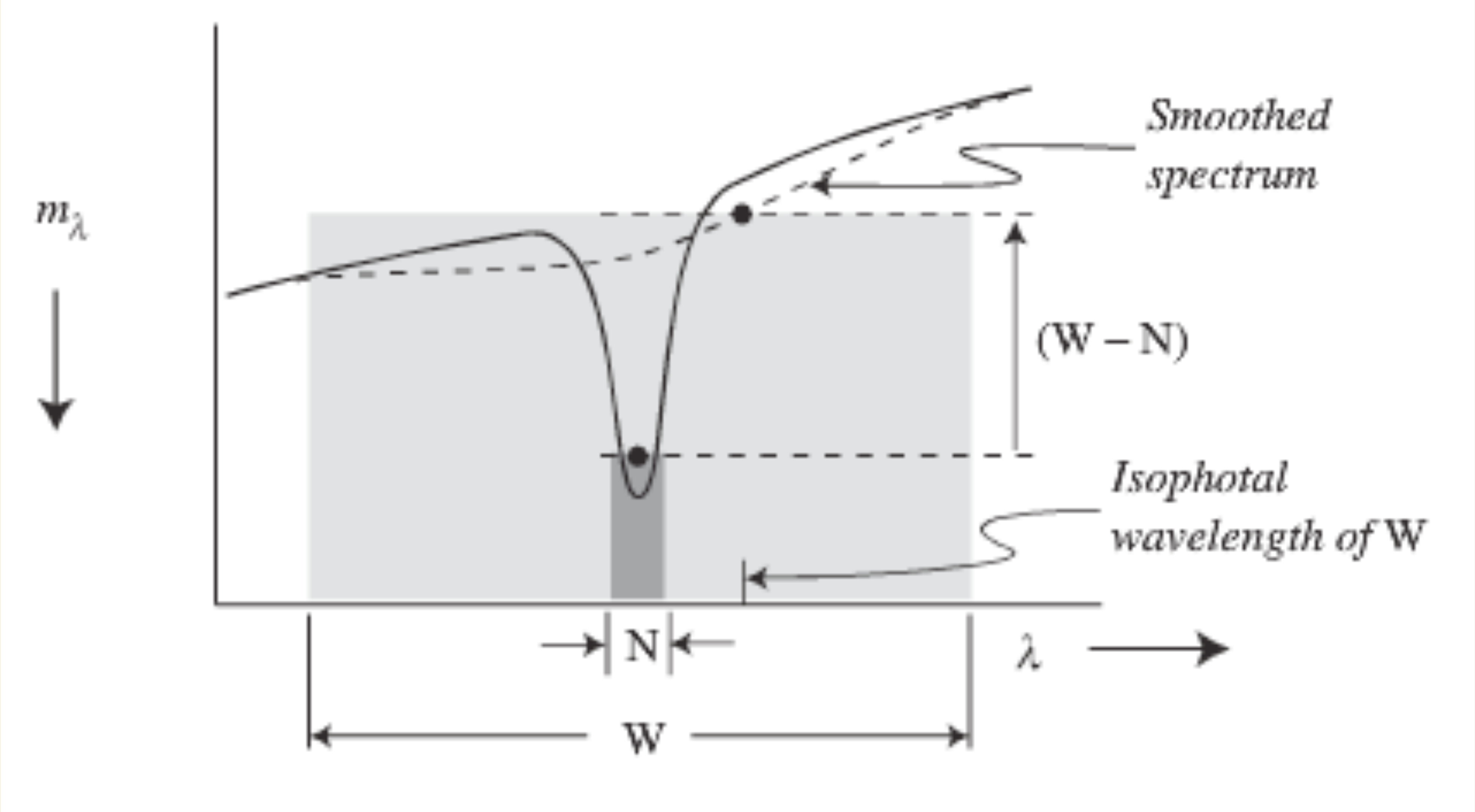
$$m_{\lambda_1} - m_{\lambda_2} = \frac{\alpha}{T}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) + C(\lambda_1) - C(\lambda_2)$$

Lines and features

- Multiband photometry can measure complicated features in complex spectra;

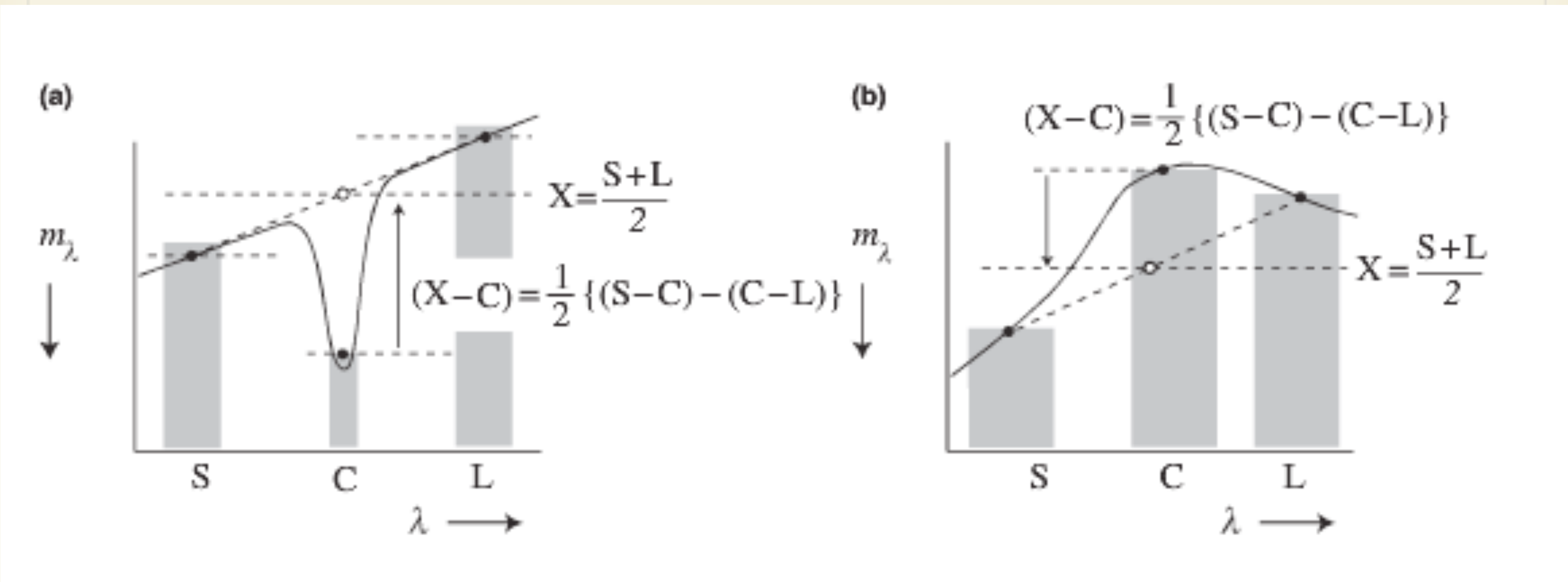


- Alternate strategy: two bands, one broad, one narrow. The index is $m_{narrow} - m_{wide}$
- The β index is one example



- Three bands can measure the curvature.
- i.e. in the one in the left:

curvature index= $m_S - m_C - (m_C - m_L) = S + L - 2C$



Photometric system

$R_P(\lambda)$ is encoded in the magnitude via:

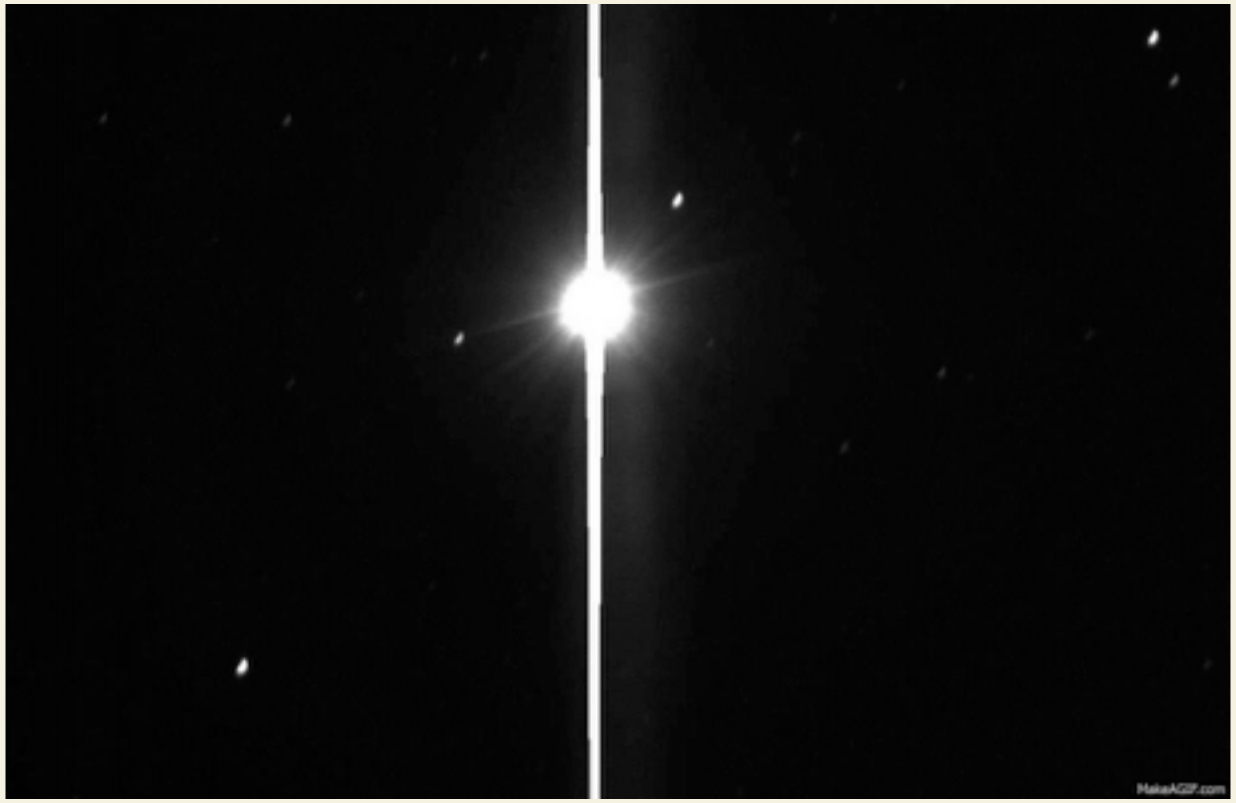
$$m_p = -2.5\log(F_p) + C_p = -2.5\log\int_0^\infty R_p(\lambda) f_\lambda \, d\lambda + C_p$$

It implies 2 specs:

1. The shape of $R_P(\lambda)$.
2. Some standard way of measuring in given bands (i.e. the value of C) and accounting for instrumental differences (hardware diff).

1) determines the natural system.

1) and 2) combined determine the standard system.



We can use a natural system to inform some properties like period. i.e. values of parameters that are independent of calibration.

- To standardize we could measure calibrated sources in the lab. But a single astronomical object or set is more practical. This requires some coordination in observations and variety of objects.
- Closed photometric systems. i.e. HIPPARCOS, Sloan Digital Sky Survey, GAIA.

Visual

- Stocospic vision determines the visual photometric system. Original measurements have to be consistent with ancient catalogs.

- Modern instrumentation promoted the standard sequences (north polar, 48 Harvard 115 Kapteyn areas).

Historical Bandpasses

Band	Symbol	Definition	λ_{peak} nm	FWHM
Visual	m_{vis}	Mesotopic Human eye	515-550	82-106
International photographic	m_{pg}, IPg	Photographic emulsion+atm	400	170
International visual	m_{pv}, IPv	Orthochromatic emulsion +yellow	500	100

1922: IAU set the zero point of both magnitudes so that 6th magnitude A0 V stars in the north polar sequence would have the same value as on the Harvard system. color index=$m_{pg}-m_{pv}$ should be 0.

UBVRI

	U	B	V	R_C	R_J	I_C	I_J
λ_{eff}, nm	366	436	545	641	685	798	864
FWHM	66	94	88	138	174	149	197
f_λ at λ_{eff} in units of 10^{-12} W m^{-2} nm^{-1} for $V = 0$	41.7	63.2	37.4	22.6	19.2	11.4	9.39

Johnson and Harris defined UBV first in 1954, based on the response of the RCA photomultiplier. $V = m_{pv}$ for the standards in the north polar sequence.

Some features to notice in the next slide:

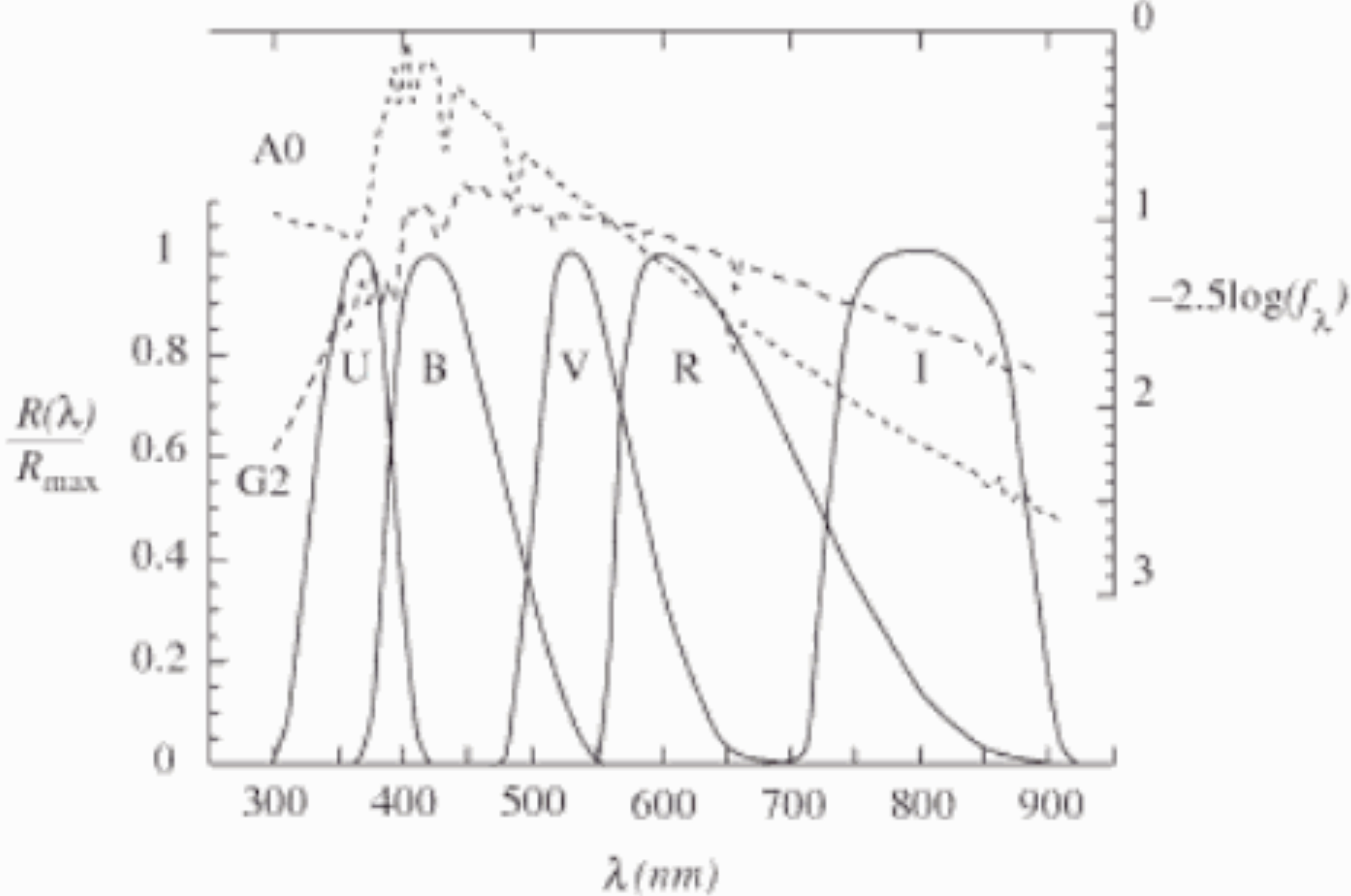
U-B is sensitive to the Balmer discontinuity (370 nm in star A -Vega-). It does depend on luminosity (others on T).

B-V $\rightarrow$ metal abundance

V-I is the most T sensitive

Notice the superimposed monochromatic magnitude for A0 (Vega) and the G2 (Sun) magnitude.

Notice the break due to metal absorption near 400nm in the G2 spectrum.

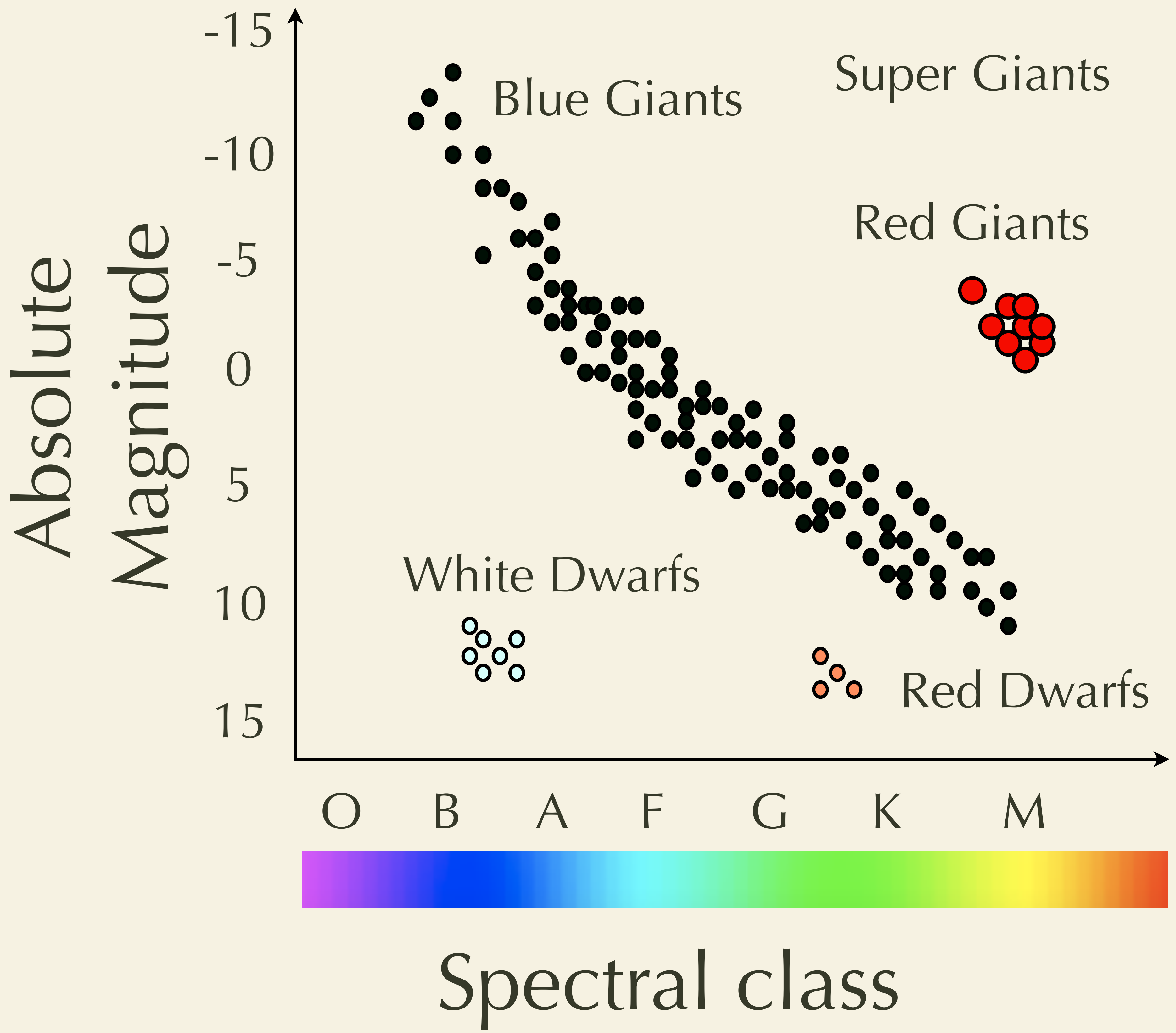


A0
G2
U
B
V
R
I
$\frac{R(\lambda)}{R_{max}}$
$-2.5\log(f_\lambda)$
0
0.2
0.4
0.6
0.8
1
2
3
300
400
500
600
700
800
900
$\lambda\,(nm)$

Spectral classes

Spectral Class	**Approximate Temperature (K)**	**Characteristics**
O	>30,000	few lines; lines of ionized helium
B	10,000-30,000	lines of neutral helium
A	7500-10,000	very strong H lines
F	6,000-7500	strong H lines; ionized Ca lines, many metal lines.
G	5,000-6,000	Strong ionized Ca lines; many strong lines of ionized and neutral iron and other metals
K	3,500-5,000	Strong lines of neutral metals
M	<3,500	bands of Titanium oxide metals.

L (2100-1500), Strong metal hydride mol,neutral Na, K, Ca.
T <1500 Methane bands, neutral K, weak water.


Absolute Magnitude
-15
-10
-5
0
5
10
15
Blue Giants
Super Giants
Red Giants
White Dwarfs
Red Dwarfs
O
B
A
F
G
K
M
Spectral class

Broadband IR system

The broadband IR system has the same zero point as the UBVRI (colors of un-reddened A0V stars are zero).

CCD are not very good detectors in this region.

	J	H	K	L	M	N	Q
λ_{eff}, μm for A0 stars	1.22	1.63	2.19	3.45	4.8	10.6	21
FWHM	0.213	0.307	0.39	0.472	0.46	3–6	6–10
f_λ at λ_{eff} in units of 10^{-11} W m^{-2} μm^{-1} for $V = 0$	315	114	39.6	7.1	2.2	0.96	0.0064

IR depends strongly on particular conditions at ground based observatories. The table below shows the Mauna Kea (MKO) filter characteristics for L' and M' .

	J	H	K	L′	M′
λ_{cen}, µm	1.24	1.65	2.20	3.77	4.67
FWHM	0.16	0.29	0.34	0.70	0.22

IAU in 2000 recommended MKO for JHK (minimizes water vapor optimizing SNR and narrows down the FWHM.

The Strömgren system

classifies stars based on T, L and metal abundance. Works well for spec types B,A,F and G.

	u	v	b	y Yellow	H_β wide	H_β narrow
λ_{eff}, nm A0 stars	349	411	467	547	489	486
FWHM nm	30	19	18	23	15	3

Usually uvby are supplied with a narrow band index β which tracks absorption in the Balmer beta line. All the four intermediate bands are T dependent but u and v are depressed by metal in the stars' atmosphere. Information is typically presented as a y magnitude, b-y color and two curvature indices. b-y is similar to B-V (Johnson)...i.e. $b\text{-}y \approx 0.68(B\text{-}V)$ over many stellar types.

$$c_1 = (u-v)-(v-b)$$

$$m_1 = (v-b)-(b-y)$$

are the two curvature indices.

1. The c_1 measures the strength of the Balmer discontinuity
2. combined with the temperature from (b-y) it provides information about L.
3. m_1 measure metal abundance.
4. The scale has been calibrated for spectral types hotter than K0.

Additional systems

- NICMOS2 camera on HST uses about 30 filters (some correspond to the JKLMN bands).
- HIPPARCOS used 2 filter broadband system similar to B and V.
- Primary CCD for HST (WFPC/WFPC2) has slots for 48 filters.
- SDSS (optimizes CCD sensitivity) -10^8 sources-

	u′	g′	r′	i′	z′
λ_{cen}, nm	354	477	623	762	915
FWHM	57	139	137	153	95