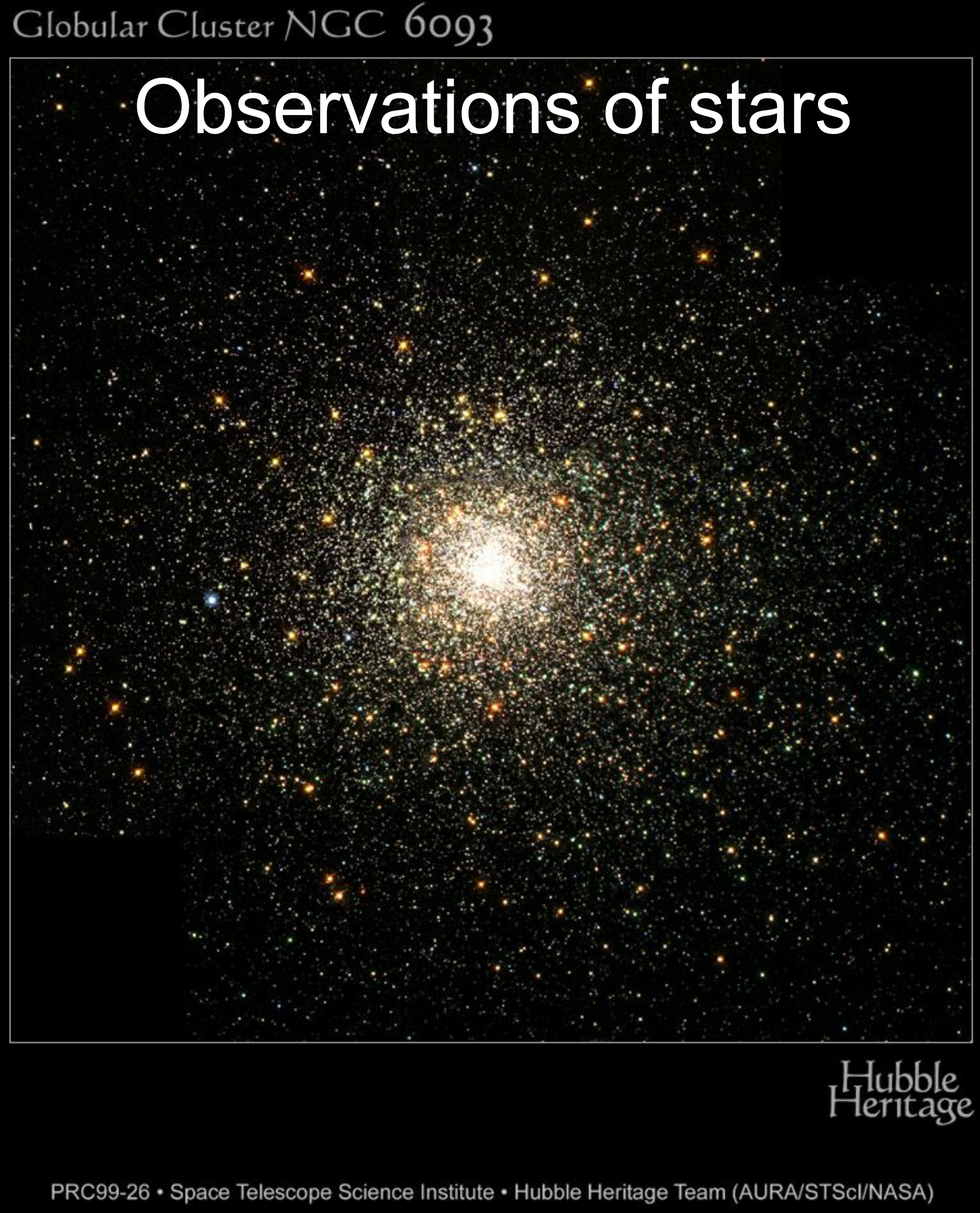
Observations of stars

Hyades open cluster

Observations of stars



Astronomers count photons!

We can measure three things about a photon:

- What direction did it come from?
- When did it arrive?
- What was its energy (wavelength/color)?

Different types of observing modes

1. Count photons in a fixed region of the sky (aperture), a fixed window of time (exposure time), and a fixed wavelength range (filter or band).

   what we call "*photometry*"

2. Count photons as a function of direction in a fixed window of time (exposure time), and a fixed wavelength range (filter or band).

   what we call "*imaging*"

Different types of observing modes

3. Count photons as a function of wavelength in a fixed region of the sky (aperture), and a fixed window of time (exposure time).

   what we call "*spectroscopy*"

4. Count photons as a function of time in a fixed region of the sky (aperture), and a fixed wavelength range (filter or band).

   what we call "*time series photometry*"

Different types of observing modes

5. Count photons as a function of direction AND time in a fixed wavelength range (filter or band).

   what we call "*time series imaging*"

6. Count photons as a function of wavelength AND time in a fixed region of the sky (aperture).

   what we call "*time series spectroscopy*"

Different types of observing modes

7. Count photons as a function of direction AND wavelength in a fixed window of time (exposure time).

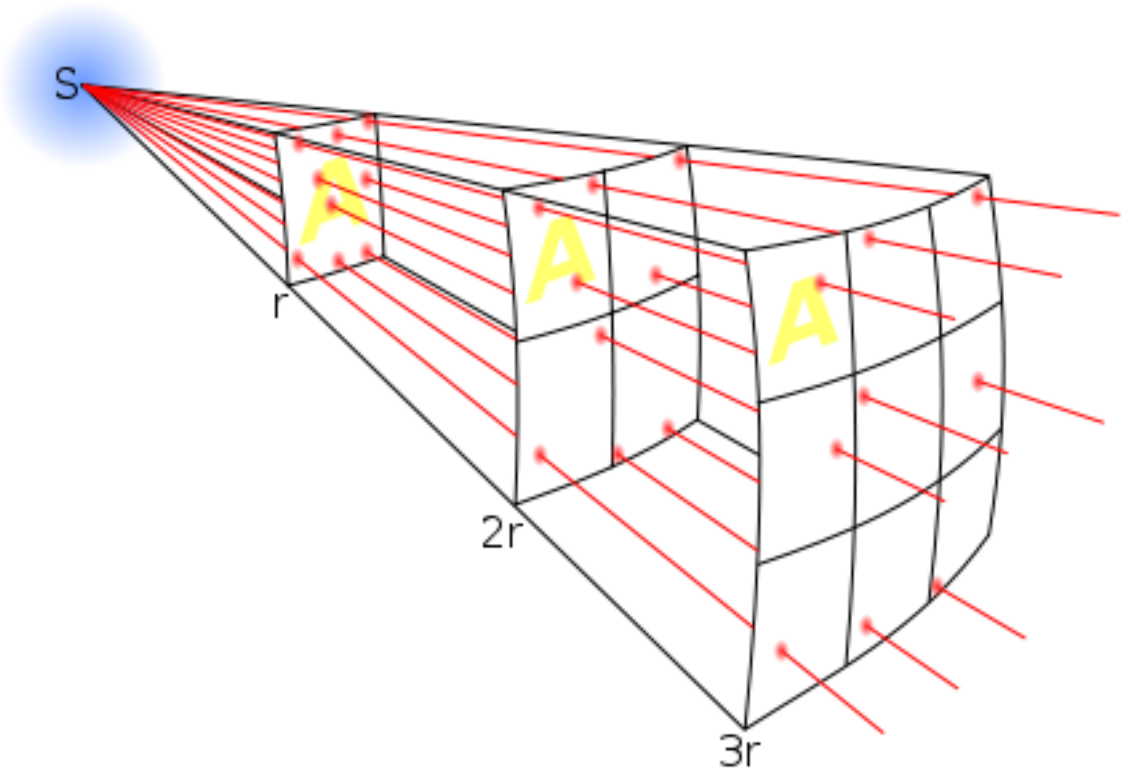
   what we call "*integral field spectroscopy*"

8. Count photons as a function of direction AND time AND wavelength.

   the holy grail of observational astronomy…

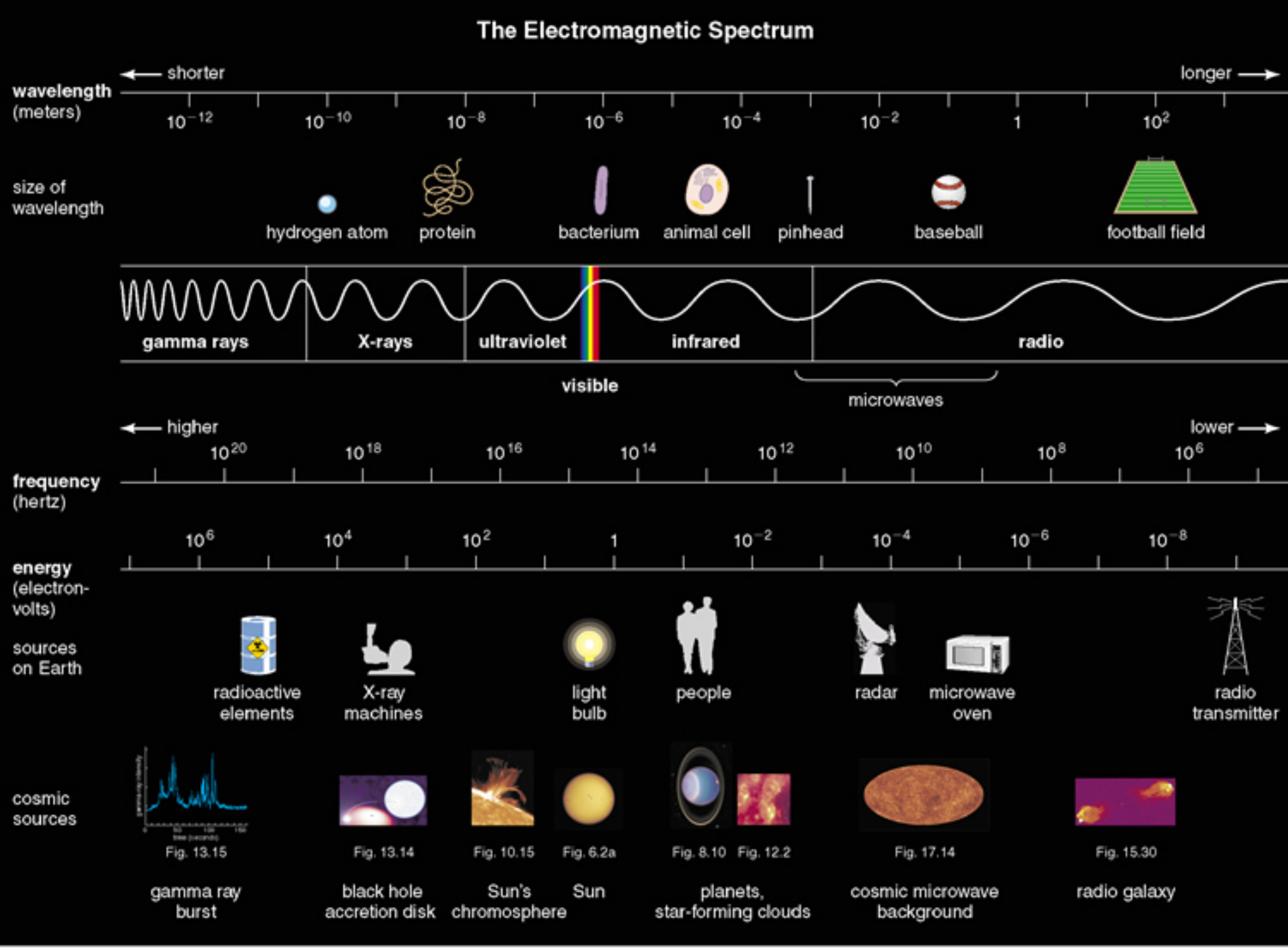
Luminosity and flux

Luminosity L : energy/time (erg/s)
Flux f : luminosity/area (erg/s/cm^2)



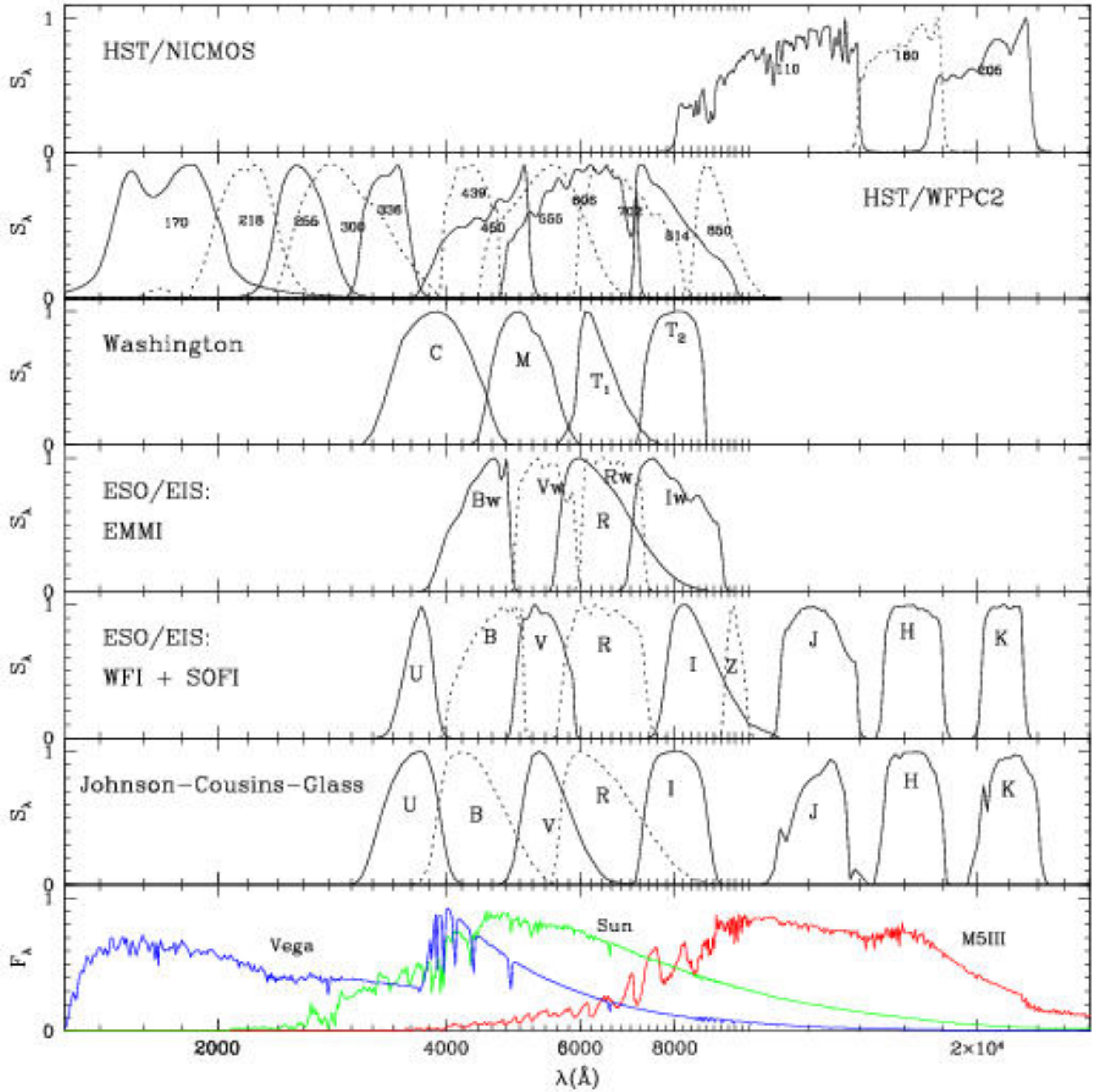
Inverse square law:

$$f = \frac{L}{4\pi d^2}$$

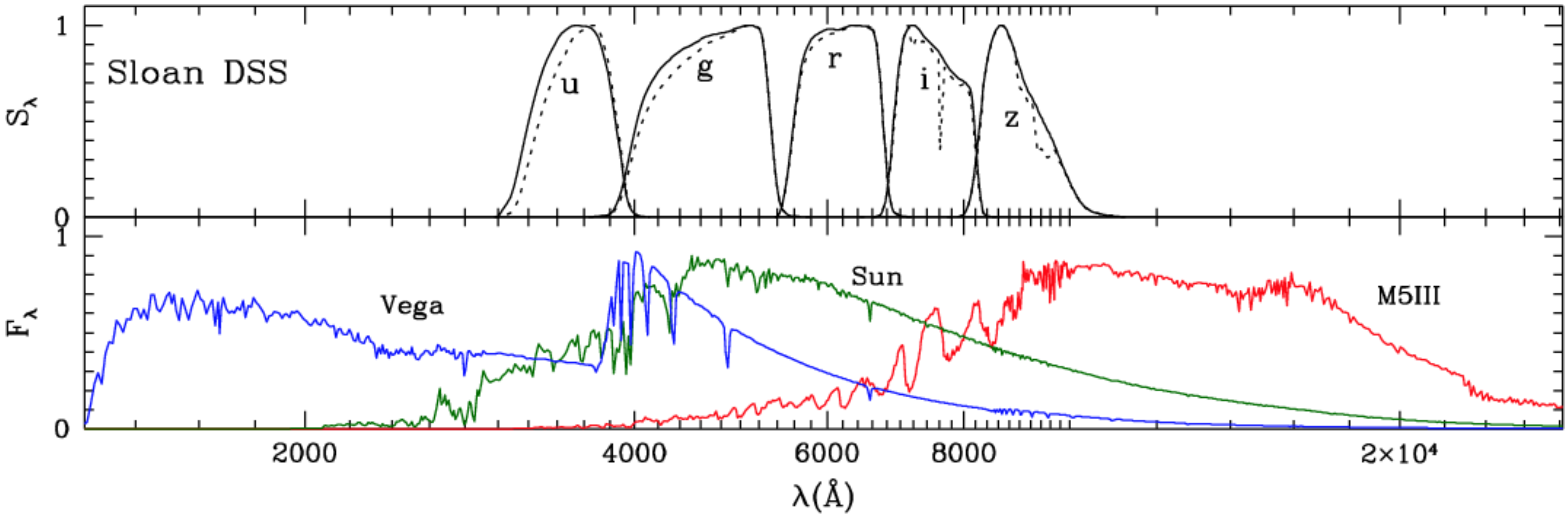


The Electromagnetic Spectrum
shorter
longer
wavelength
(meters)
10^−12
10^−10
10^−8
10^−6
10^−4
10^−2
1
10^2
size of
wavelength
hydrogen atom
protein
bacterium
animal cell
pinhead
baseball
football field
gamma rays
X-rays
ultraviolet
infrared
radio
visible
microwaves
higher
lower
10^20
10^18
10^16
10^14
10^12
10^10
10^8
10^6
frequency
(hertz)
10^6
10^4
10^2
1
10^−2
10^−4
10^−6
10^−8
energy
(electron-
volts)
sources
on Earth
radioactive
elements
X-ray
machines
light
bulb
people
radar
microwave
oven
radio
transmitter
cosmic
sources
Fig. 13.15
Fig. 13.14
Fig. 10.15
Fig. 6.2a
Fig. 8.10
Fig. 12.2
Fig. 17.14
Fig. 15.30
gamma ray
burst
black hole
accretion disk
Sun's
chromosphere
Sun
planets,
star-forming clouds
cosmic microwave
background
radio galaxy

Photometric filters



SDSS filters



Photometric Filters

Astronomical fluxes are usually measured using filters

The flux in the SDSS *g* filter is:

$$f_g = \int_0^{\infty} F(\lambda) S_g(\lambda) d\lambda$$

The flux in the SDSS *r* filter is:

$$f_r = \int_0^{\infty} F(\lambda) S_r(\lambda) d\lambda$$

Apparent magnitude

$$m = -2.5\log f + const$$

A star that is 5 magnitudes brighter (smaller m) has 100x the flux.

$$m_1 - m_2 = -2.5\log\left(f_1/f_2\right)$$

$$\frac{f_1}{f_2} = 10^{(m_2 - m_1)/2.5}$$

Absolute magnitude

M = apparent magnitude the star would have if it were 10pc away.

$$f = \frac{L}{4\pi d^2}$$

$$f_{10} = \frac{L}{4\pi (10\,pc)^2}$$

$$m - M = -2.5 \log\left[\frac{L/4\pi d^2}{L/4\pi (10\,pc)^2}\right] = -2.5 \log\left[\left(\frac{d}{10\,pc}\right)^{-2}\right]$$

$$m - M = 5 \log\left(\frac{d}{10\,pc}\right)$$

distance modulus

Hipparcos Data

Table 3.6.4. The 150 most luminous stars in the Hipparcos Catalogue.

HIP	HD	α	δ	V	M_V	π	σ_π	σ_π/π	$\|\mu\|$	$\mu_{\alpha*}$	μ_δ	V_T	C	Name
24436	34085	78.634	−08.202	0.18	−6.69	4.22	0.81	0.192	1.95	1.87	−0.56	2.19		β Ori
100453	194093	305.557	+40.257	2.23	−6.12	2.14	0.51	0.238	2.60	2.43	−0.93	5.76		γ Cyg
39429	66811	120.896	−40.003	2.21	−5.95	2.33	0.51	0.219	35.09	−30.82	16.77	71.39		ζ Pup
48002	85123	146.776	−65.072	2.92	−5.56	2.01	0.40	0.199	12.57	−11.55	4.97	29.65		υ Car
30438	45348	95.988	−52.696	−0.62	−5.53	10.43	0.53	0.051	30.98	19.99	23.67	14.08		α Car
68702	122451	210.956	−60.373	0.61	−5.42	6.21	0.56	0.090	42.21	−33.96	−25.06	32.22		β Cen
25985	36673	83.183	−17.822	2.58	−5.40	2.54	0.72	0.283	3.61	3.27	1.54	6.75		α Lep
48774	86440	149.216	−54.568	3.52	−5.34	1.69	0.50	0.296	13.43	−13.13	2.83	37.68		φ Vel
39953	68273	122.383	−47.337	1.75	−5.31	3.88	0.53	0.137	11.54	−5.93	9.90	14.10		γ Vel
26727	37742	85.190	−01.943	1.74	−5.26	3.99	0.79	0.198	4.73	3.99	2.54	5.62		ζ Ori
27989	39801	88.793	+07.407	0.45	−5.14	7.63	1.64	0.215	29.41	27.33	10.86	18.27		α Ori
85927	158926	263.402	−37.104	1.62	−5.05	4.64	0.90	0.194	31.24	−8.90	−29.95	31.92		λ Sco
25930	36486	83.002	−00.299	2.25	−4.99	3.56	0.83	0.233	1.76	1.67	0.56	2.35		δ Ori
35264	56855	109.286	−37.097	2.71	−4.92	2.98	0.55	0.185	12.68	−10.57	7.00	20.17		π Pup
46974	83183	143.611	−59.230	4.08	−4.83	1.65	0.49	0.297	12.74	−11.23	6.02	36.61		h Car
27366	38771	86.939	−09.670	2.07	−4.65	4.52	0.77	0.170	1.96	1.55	−1.20	2.06		κ Ori
38518	64760	118.326	−48.103	4.22	−4.65	1.68	0.50	0.298	7.66	−4.90	5.89	21.62		J Pup
47854	84810	146.312	−62.508	3.69	−4.64	2.16	0.47	0.218	15.31	−12.88	8.28	33.60		l Car
41037	71129	125.629	−59.510	1.86	−4.58	5.16	0.49	0.095	34.03	−25.34	22.72	31.27		ϵ Car
18246	24398	58.533	+31.884	2.84	−4.55	3.32	0.75	0.226	10.16	4.41	−9.15	14.50		ζ Per
37819	63032	116.314	−37.969	3.62	−4.52	2.35	0.55	0.234	12.31	−10.77	5.97	24.84		c Pup
43023	75063	131.507	−46.042	3.87	−4.52	2.10	0.53	0.252	13.15	−12.23	4.82	29.67		a Vel
15863	20902	51.081	+49.861	1.79	−4.50	5.51	0.66	0.120	35.47	24.11	−26.01	30.51		α Per
45556	80404	139.273	−59.275	2.21	−4.42	4.71	0.46	0.098	23.11	−19.03	13.11	23.26		ι Car
85267	157246	261.349	−56.378	3.31	−4.40	2.87	0.75	0.261	15.87	−0.77	−15.85	26.21		γ Ara

Bolometric magnitudes

M is measured in a band. To get the light from all wavelengths, we must add a correction.

Bolometric correction:

$$M_{bol} = M_V + BC$$
$$m_{bol} = m_V + BC$$

BC depends on band and star spectrum. By definition, BC=0 for V-band and T=6600K

Color

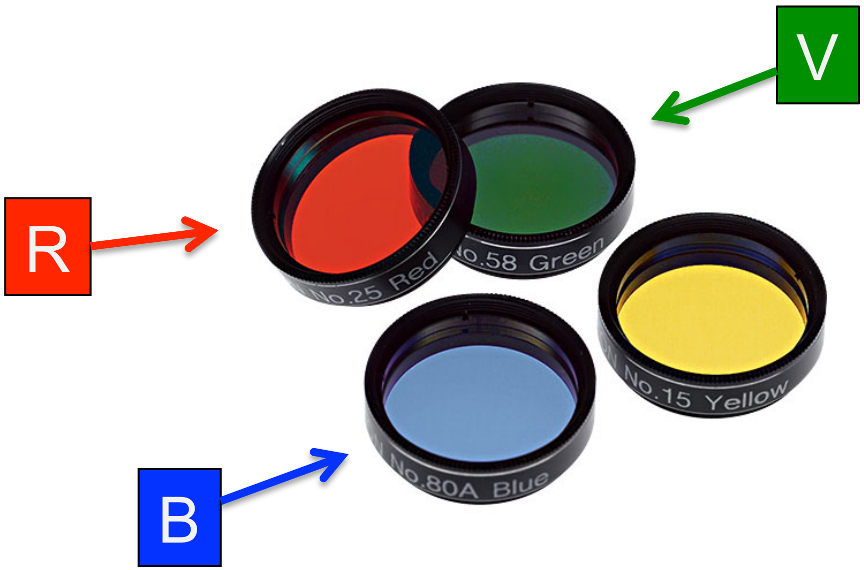
Color = crude, low resolution, estimate of spectral shape

$$B - V = m_B - m_V = M_B - M_V = -2.5\log\left(\frac{f_B}{f_V}\right)$$

- distance independent
- indicator of surface temperature
- by definition, *(B-V)*=0 for Vega (T~9500K)

Color

- Measure a star's brightness through two different filters



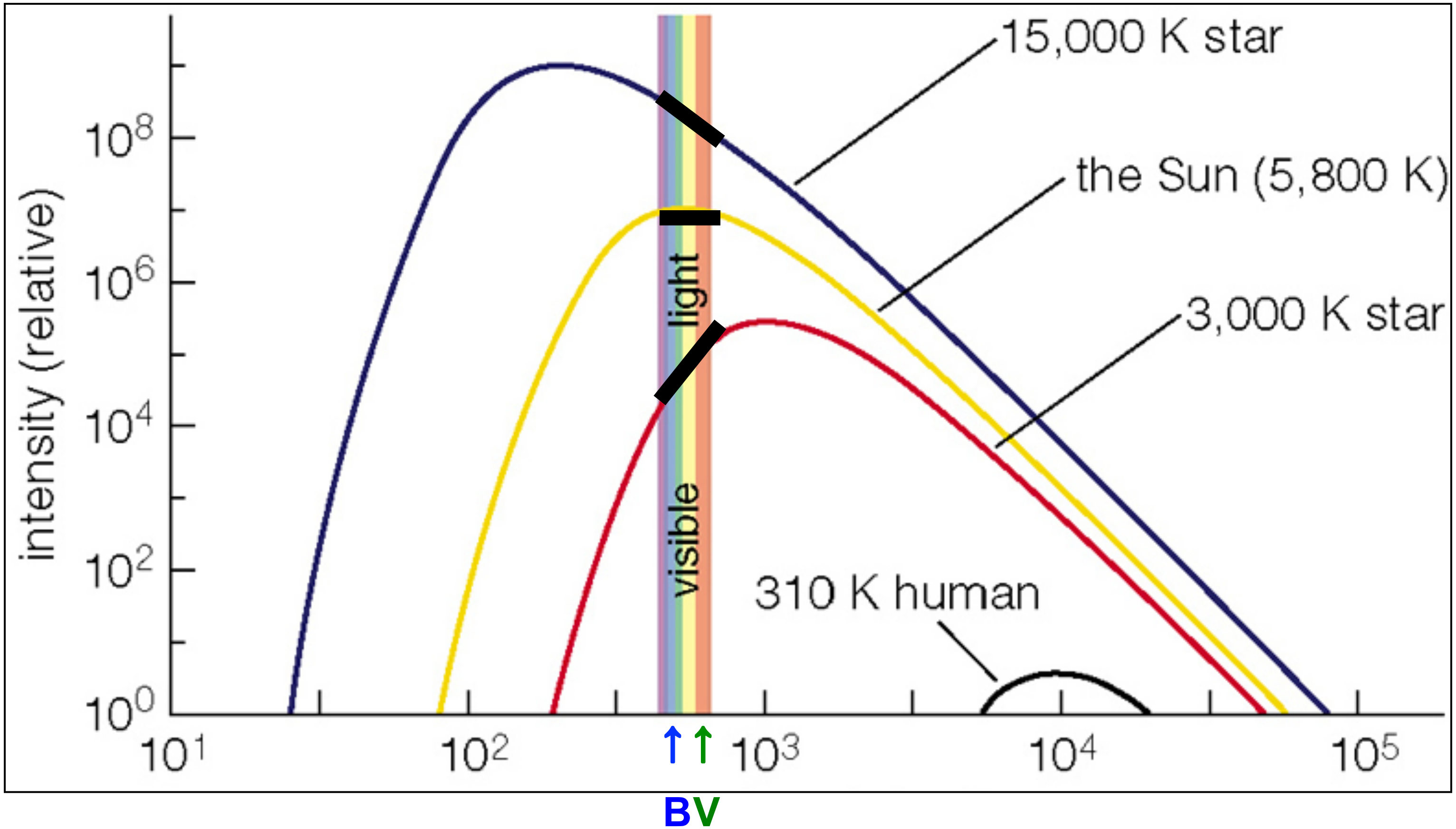
- Take the ratio of brightness: (redder filter)/(bluer filter)

  if ratio is large → red star

  if ratio is small → blue star

e.g., **V**/**B**

Color



wavelength (nm)

The color of a star measured like this tells us its temperature!

Stellar spectra

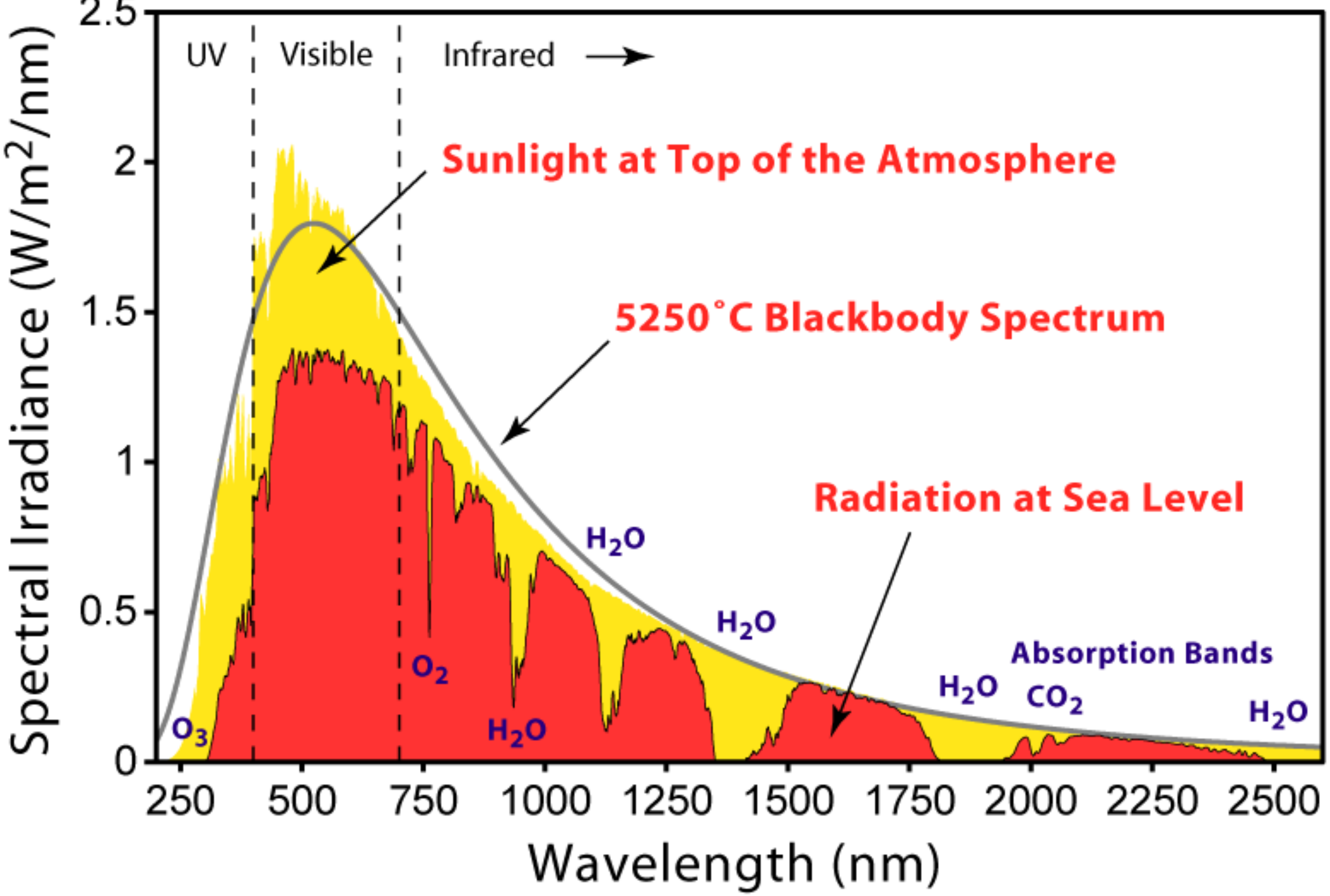
The solar spectrum can be approximated as

- a blackbody

    +

- absorption lines (looking at hotter layers through cooler outer layers)

Solar Radiation Spectrum



Blackbody radiation

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$ erg s^{-1} cm^{-2} Hz^{-1} st^{-1}

$$h\nu_{\max} \sim 2.8kT$$

- Effective temperature of a star = T of a blackbody that gives the same Luminosity per unit surface area of the star.

$$L = 4\pi R^2 \sigma T_e^4$$ Stefan–Boltzmann law

For sun: T_e = 5,778 K

Blackbody Spectrum or thermal spectrum

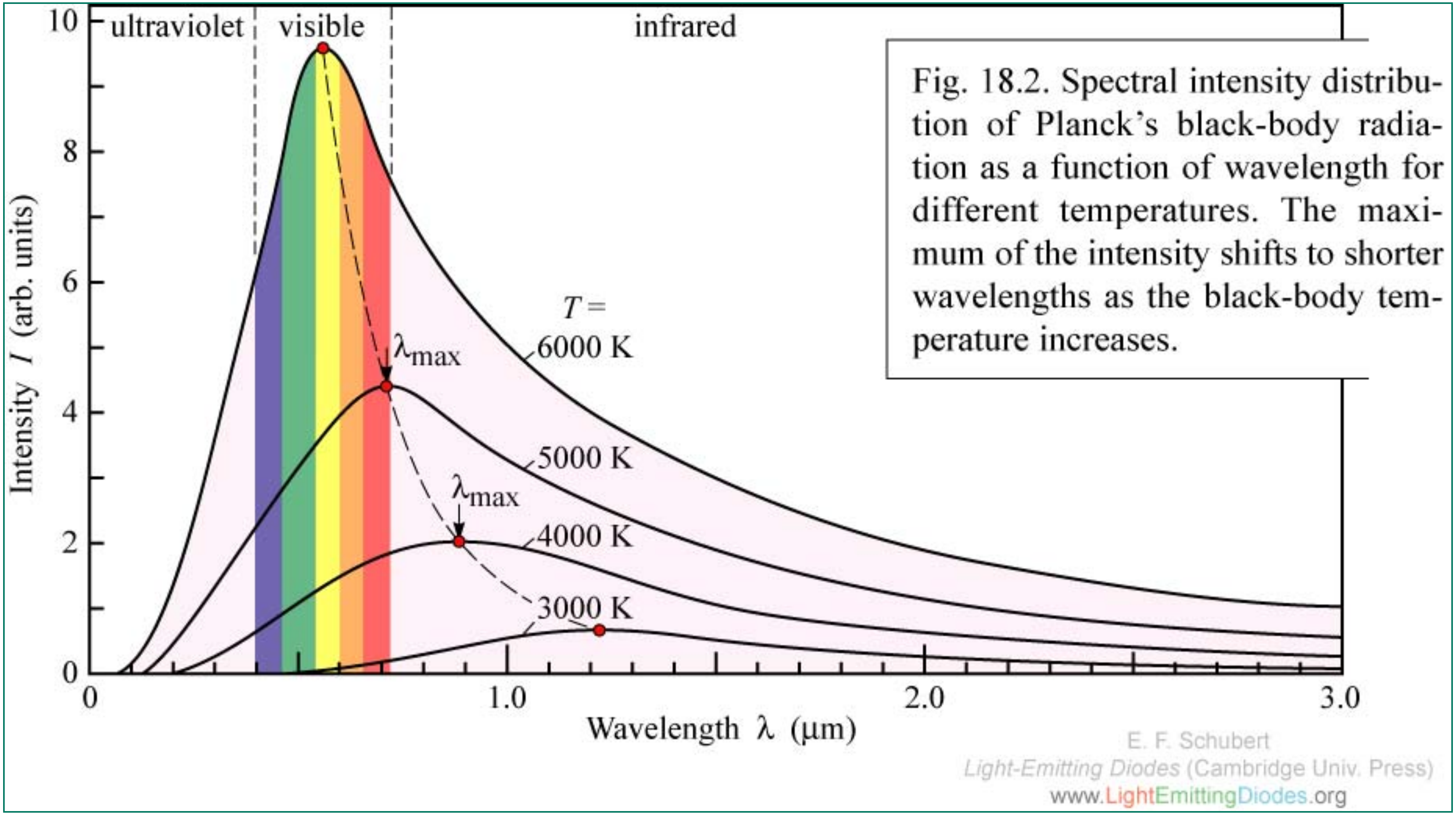
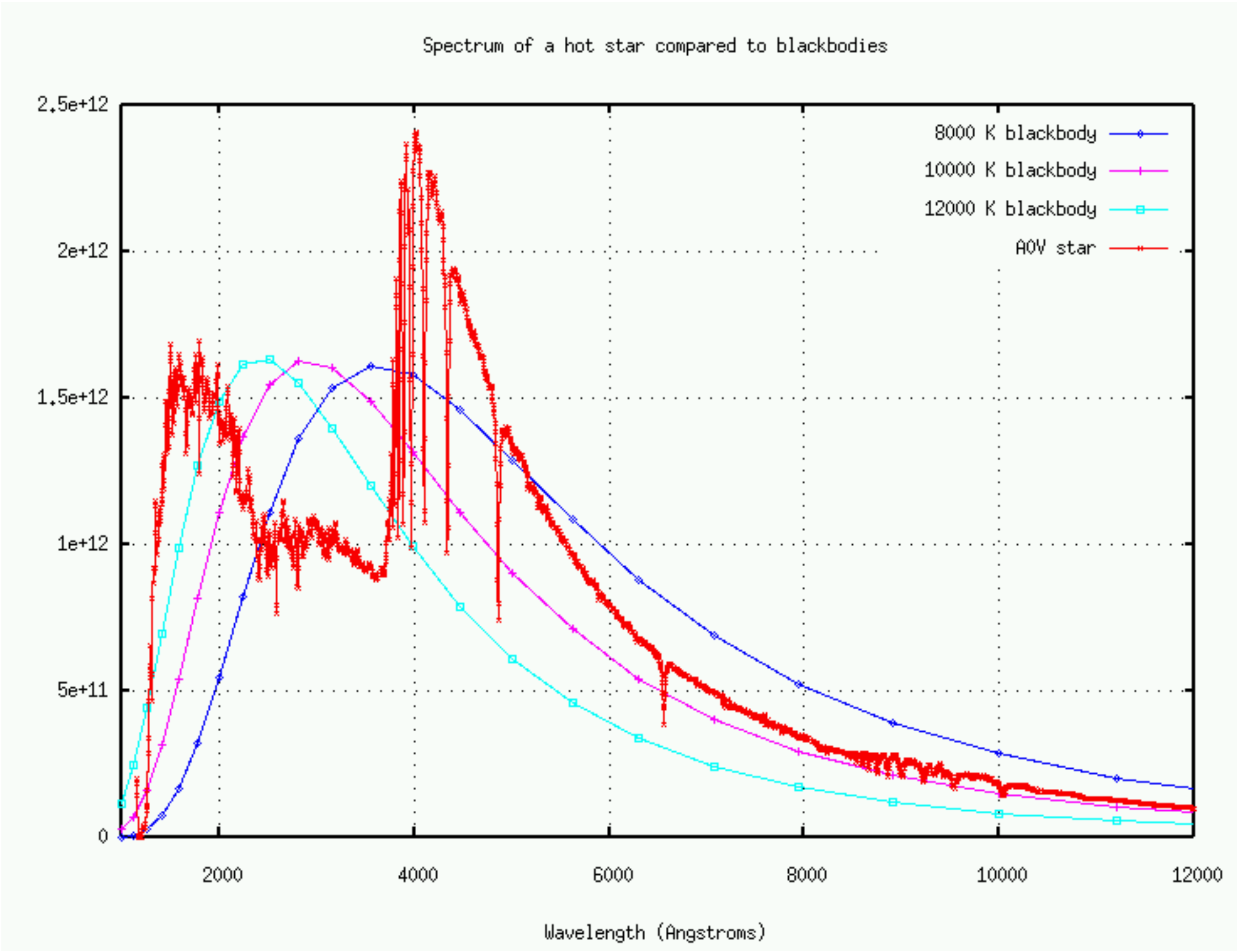
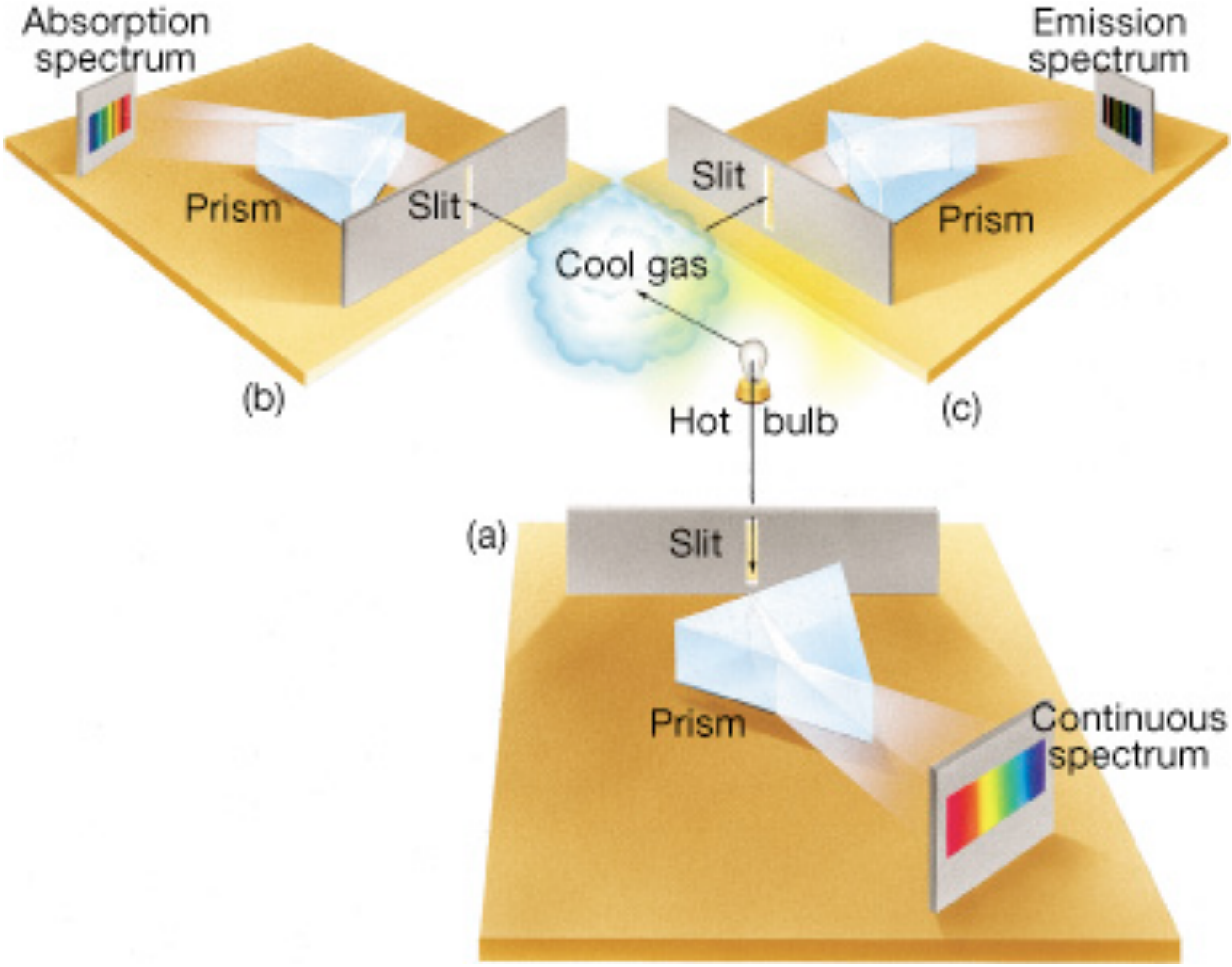


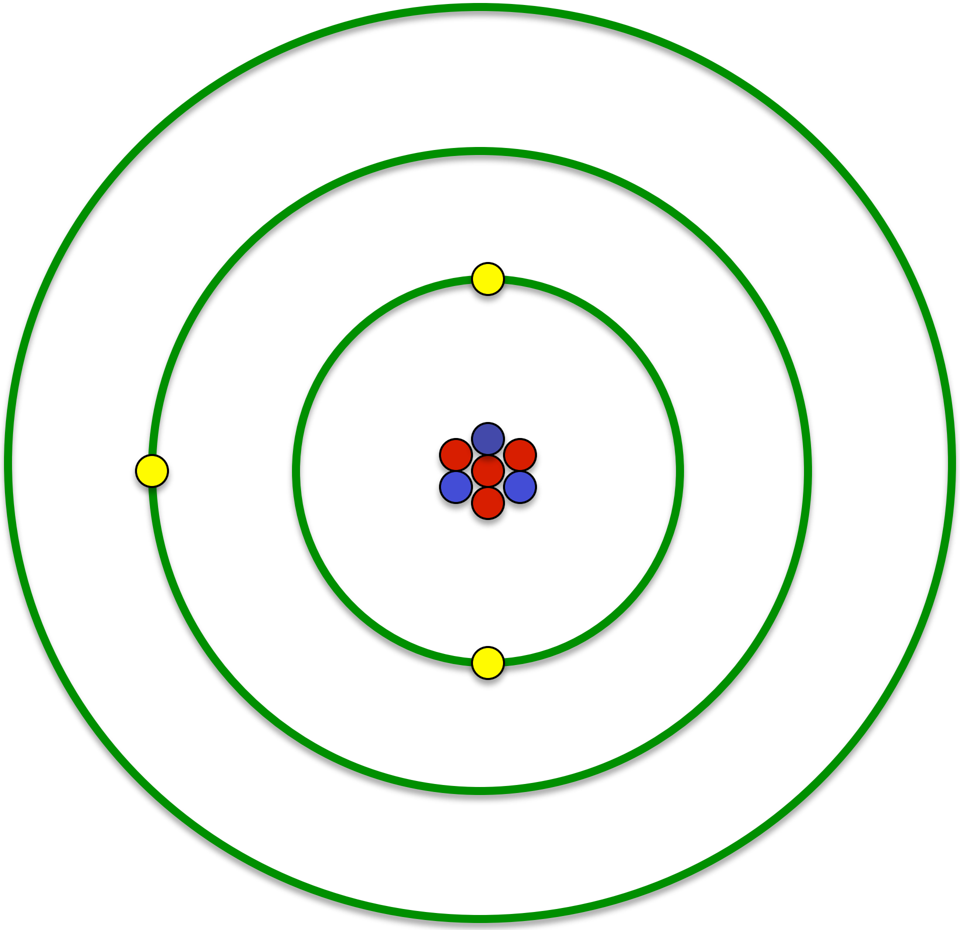
Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

Stellar spectra are not perfect blackbodies



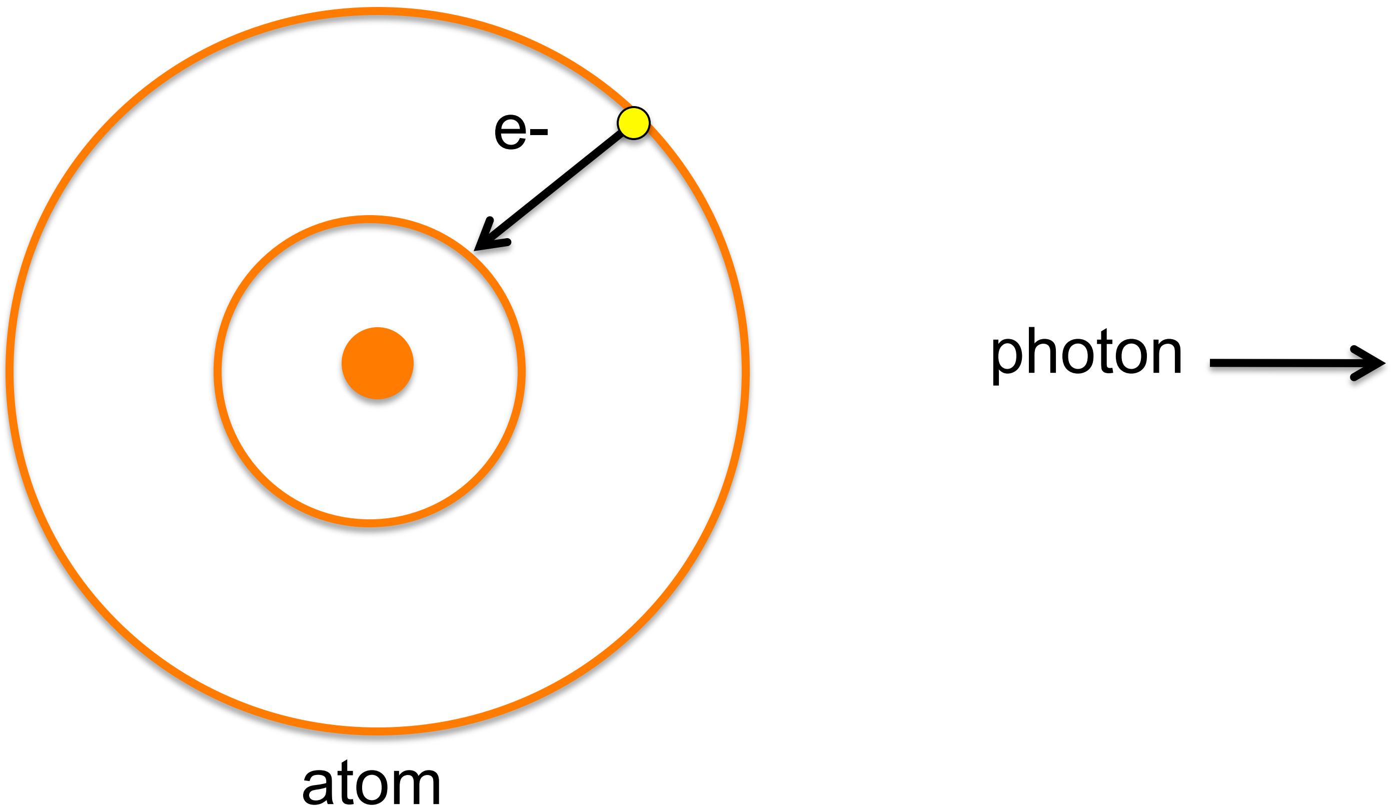

Absorption spectrum
Emission spectrum
Slit
Prism
Slit
Prism
Cool gas
(b)
Hot bulb
(c)
(a)
Slit
Prism
Continuous spectrum

Atomic energy levels

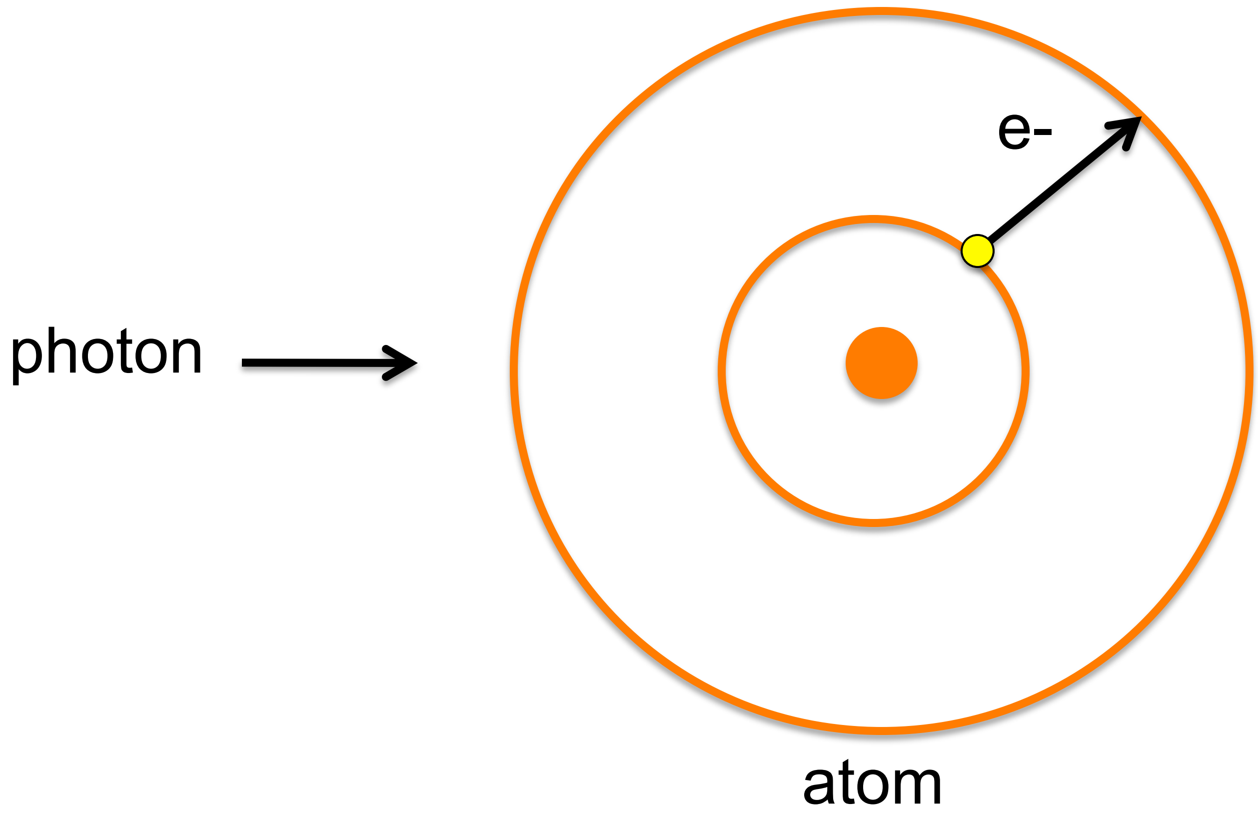


- electrons orbit the nucleus in specific energy levels
- electrons can jump between energy levels given the right energy

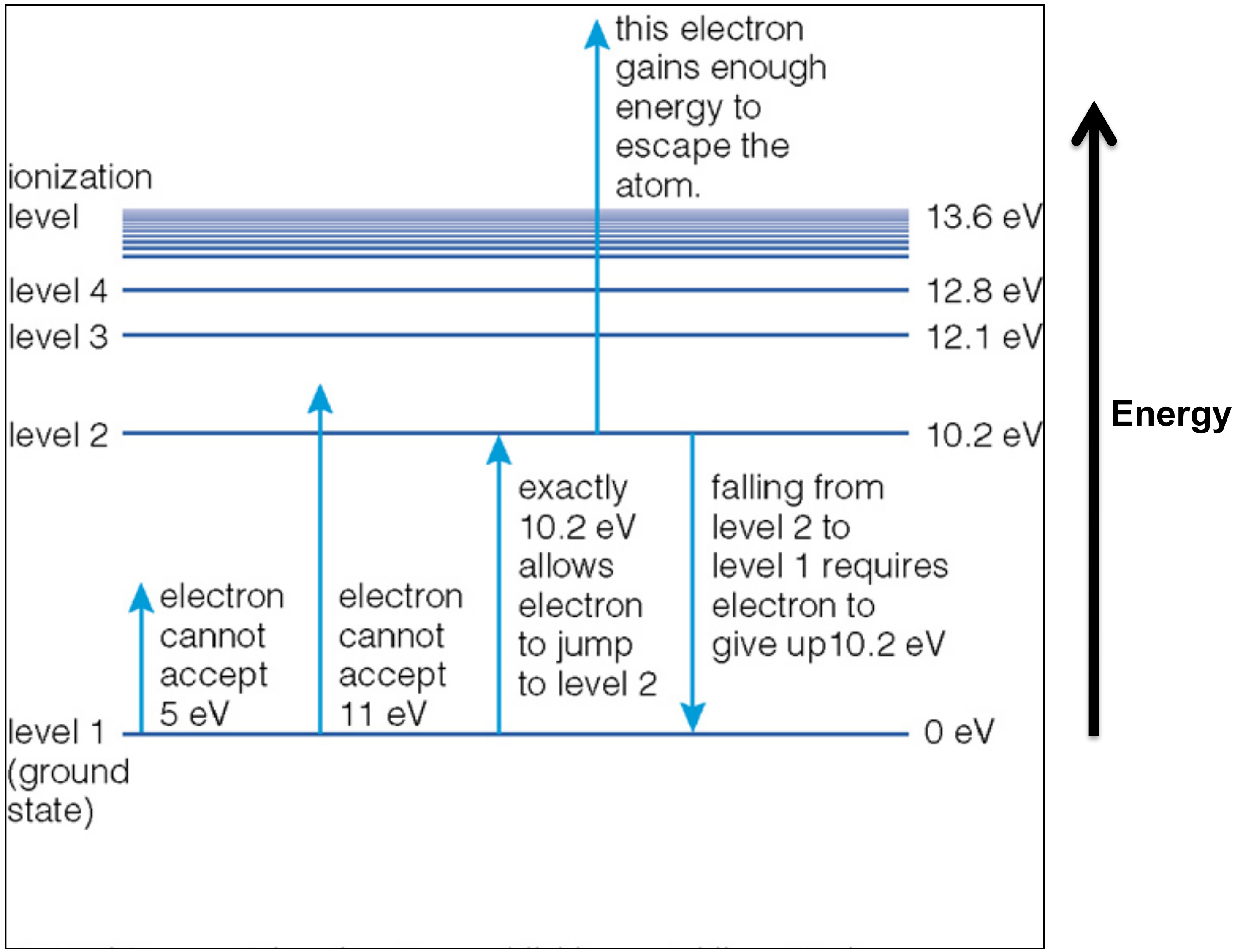
Emission of light

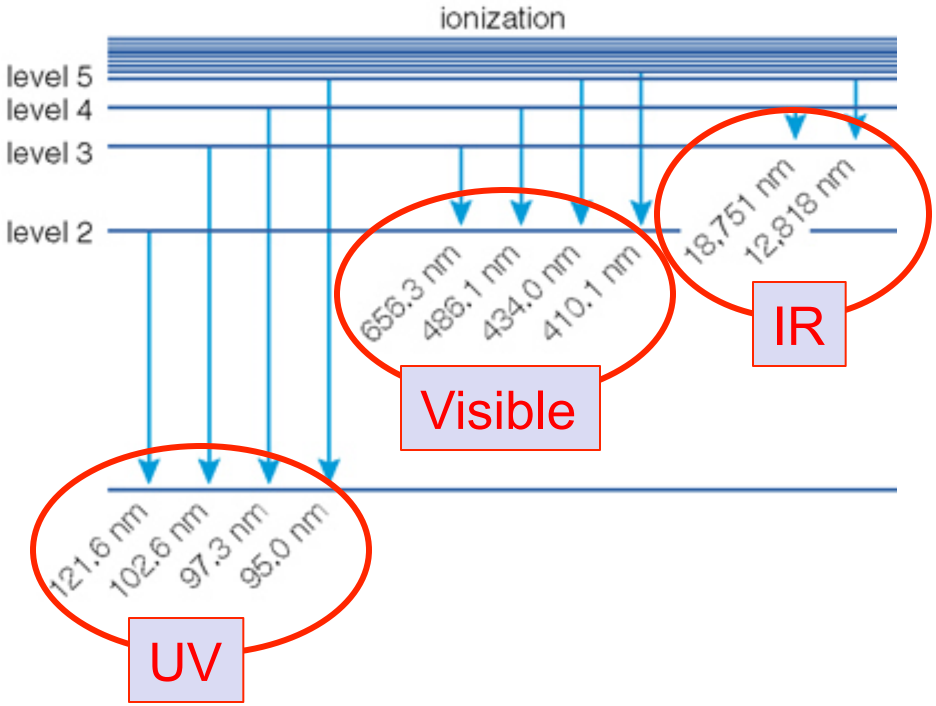


Absorption of light



Energy levels for Hydrogen



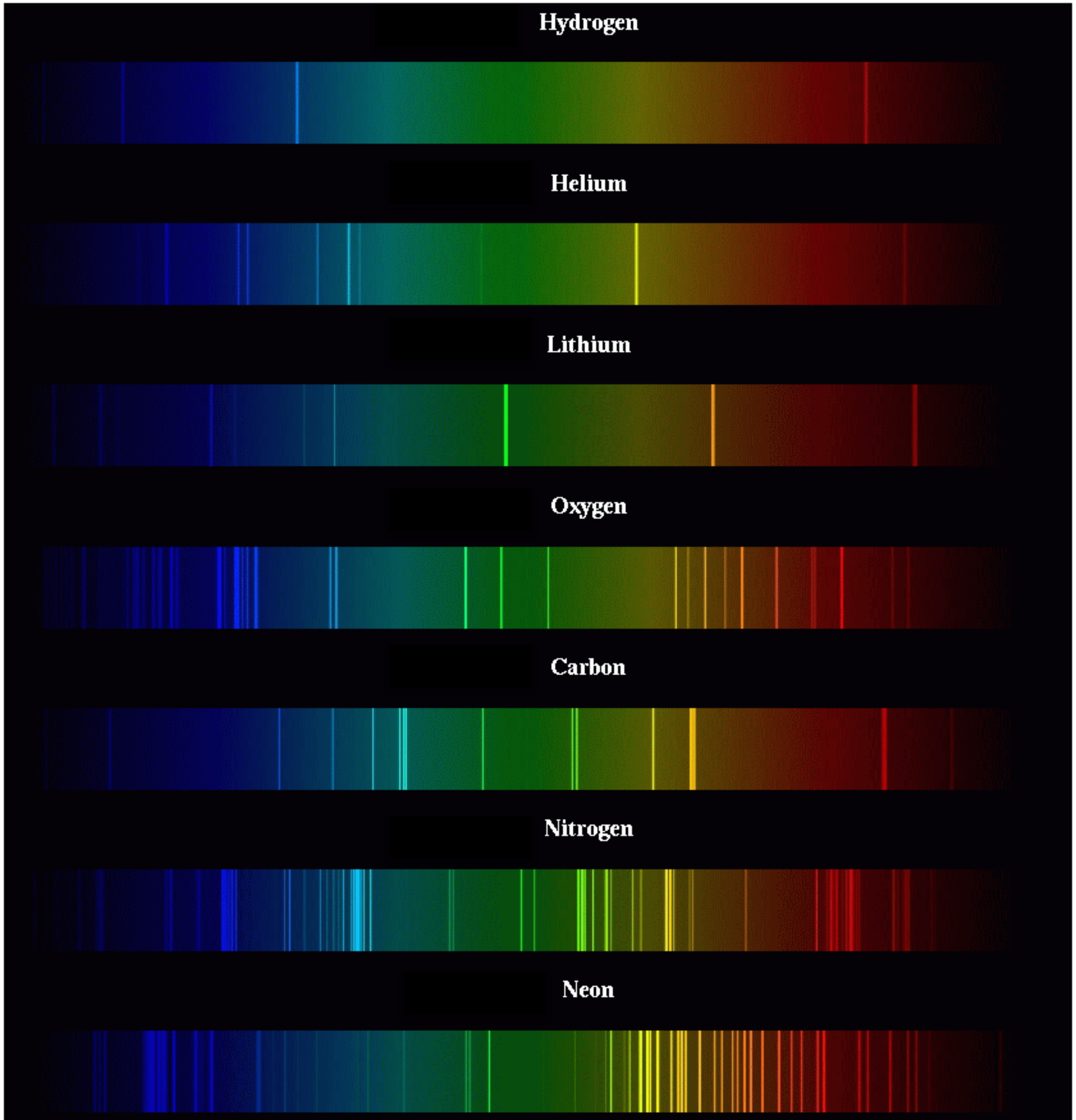


Visible spectrum shows signature of hydrogen atoms

$$E = h\nu = \frac{hc}{\lambda}$$

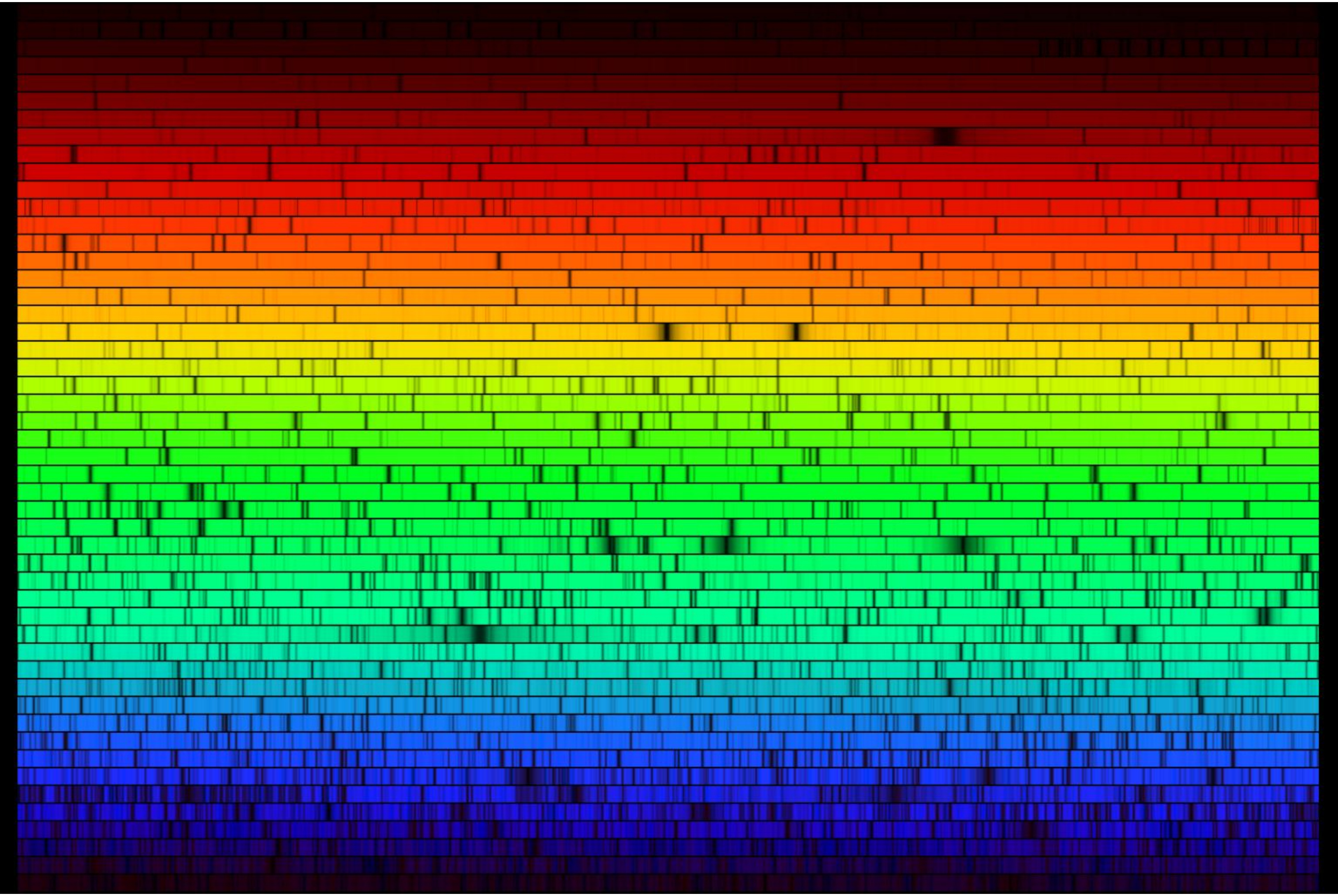
Emission line spectrum

Absorption line spectrum



Wavelength of light

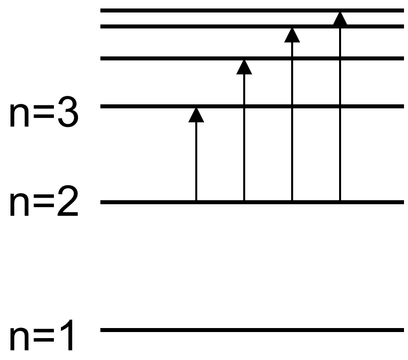
Spectrum of Sun



Spectral lines

Strength of lines depends on temperature.

e.g., Balmer lines:
transitions from n=2 to higher states



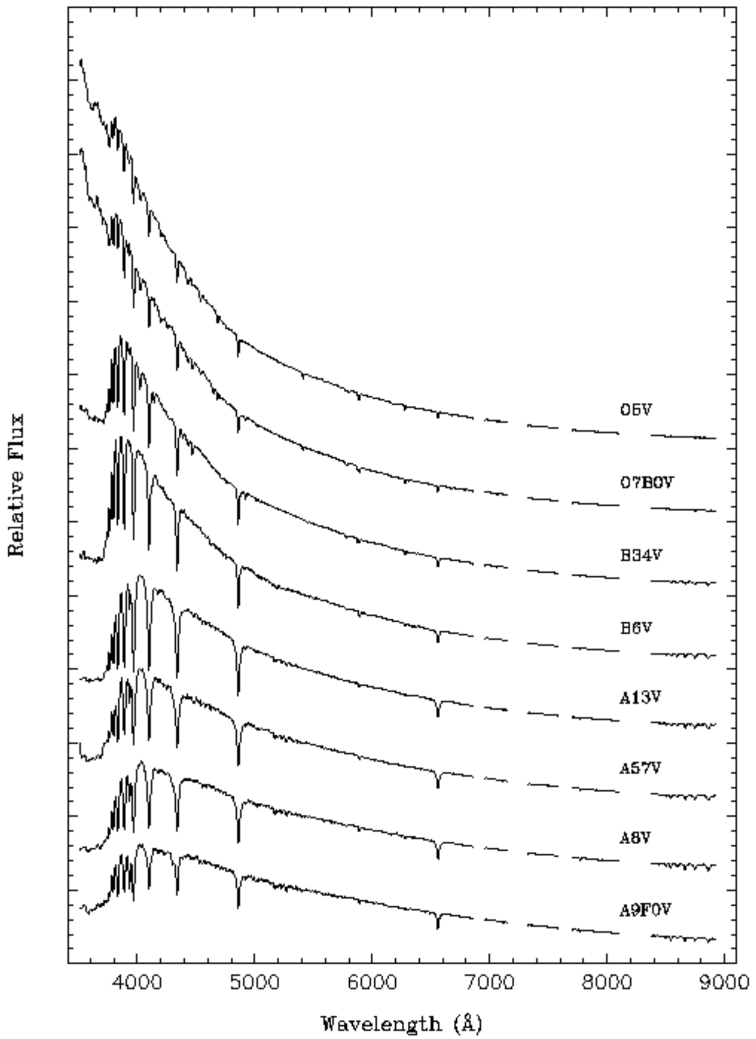
T < 5,000K: all Hydrogen is in ground (n=1) state ➔ no lines

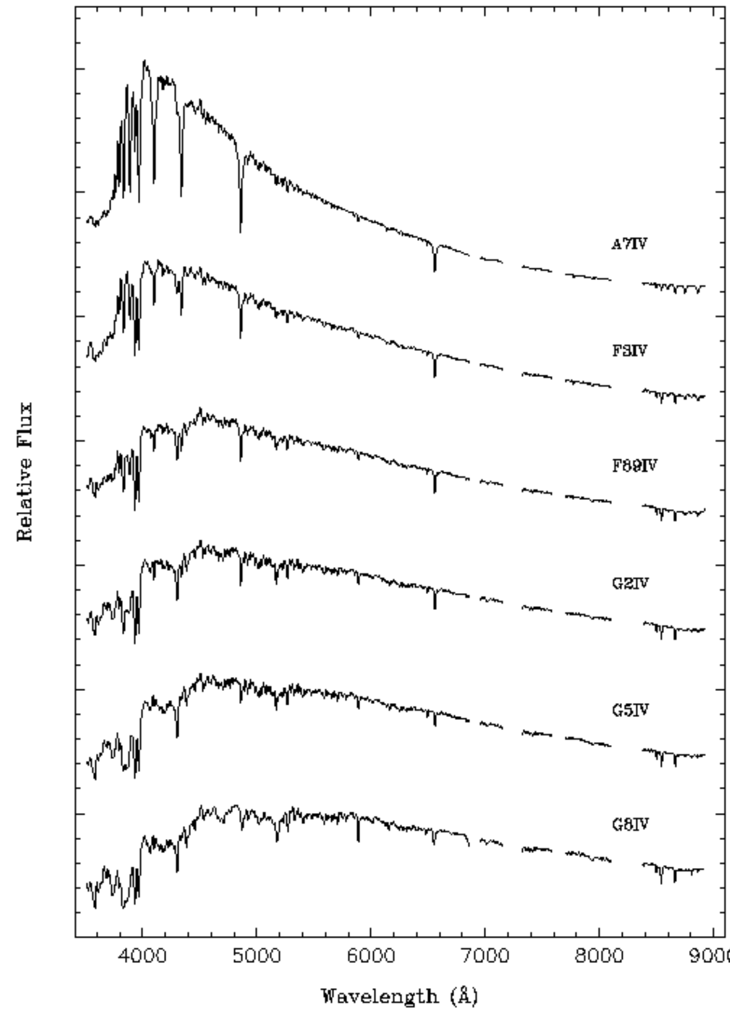
T > 20,000K: all Hydrogen is ionized ➔ no lines

T ~ 10,000K: some Hydrogen is in n=2 state ➔ strong lines

- Spectral lines are observational indicators of T_e

Stellar spectra





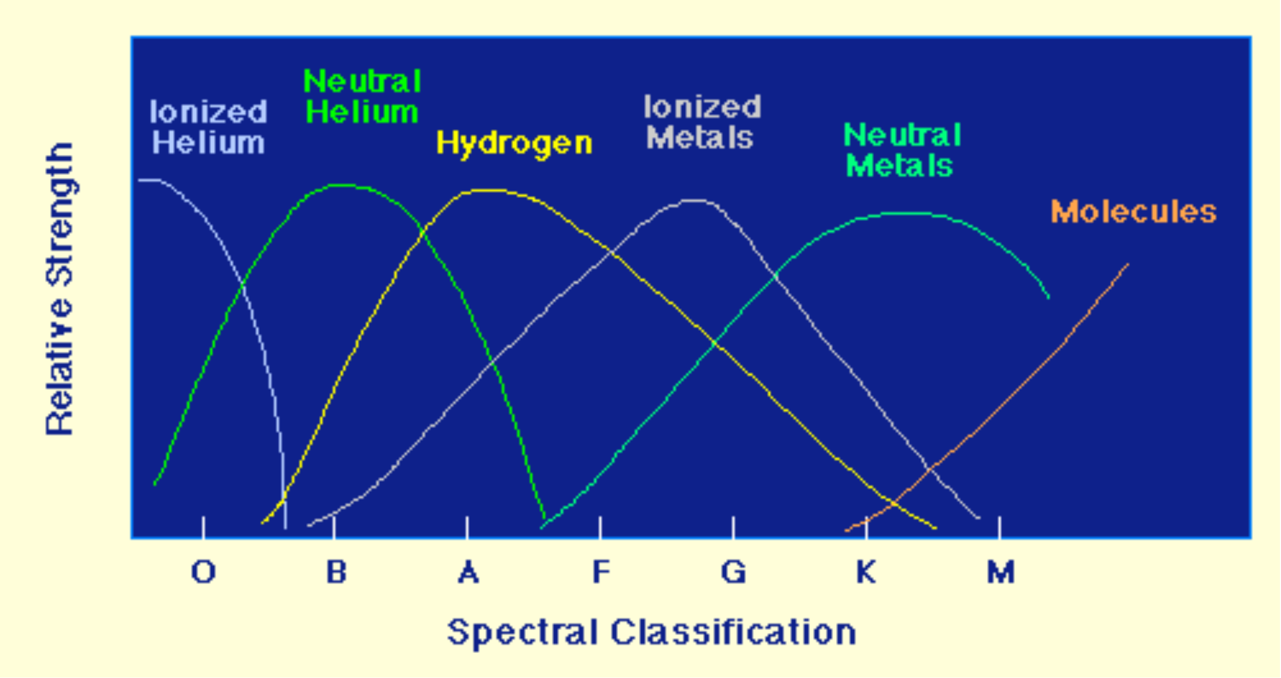
Spectral lines

Lines depend on temperature in stellar atmosphere
+
ionization potentials for relevant species

e.g.,	H	HeI	HeII	CaI	CaII	FeI
	13.6eV	24.6eV	54.5eV	6.1eV	11.9eV	7.9eV

Ionization occurs when kT ~ ionization potential/10

Spectral classification

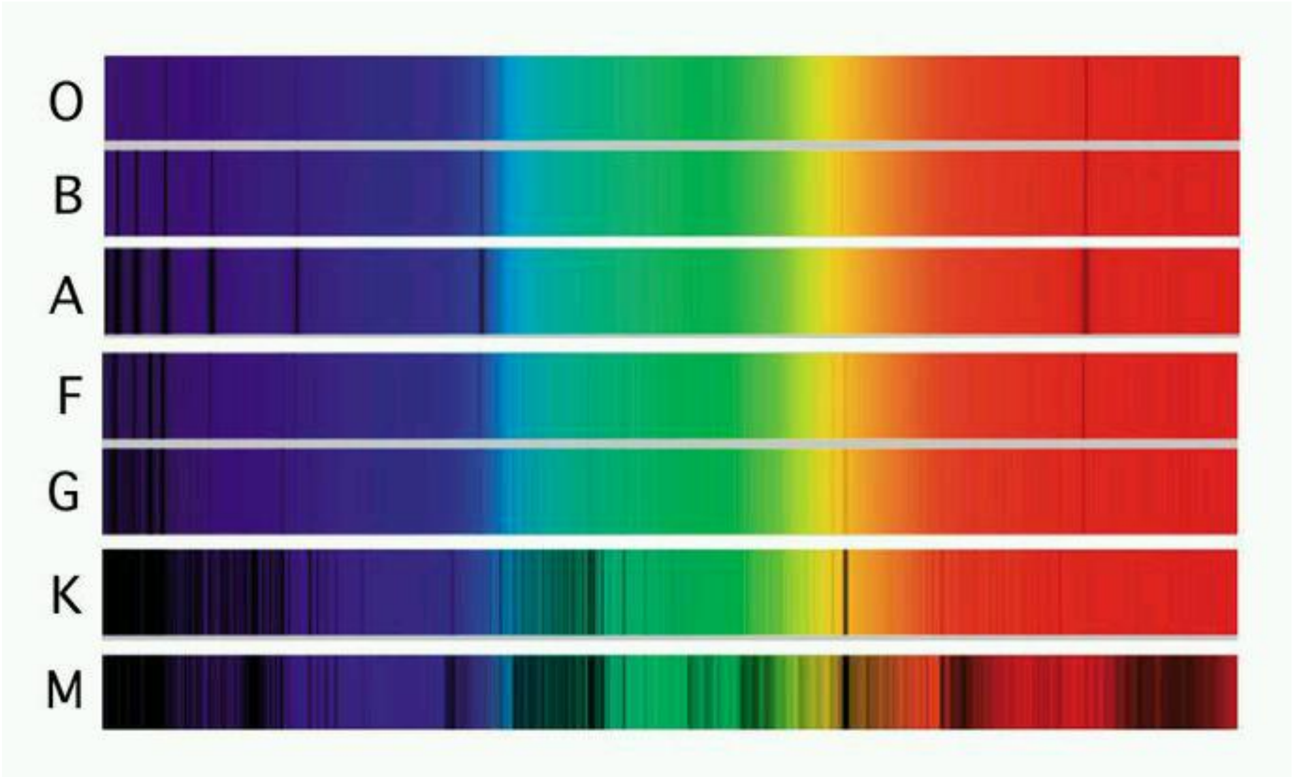


T_e: 40K 20K 10K 6.7K 5.5K 4.5K 3.5K

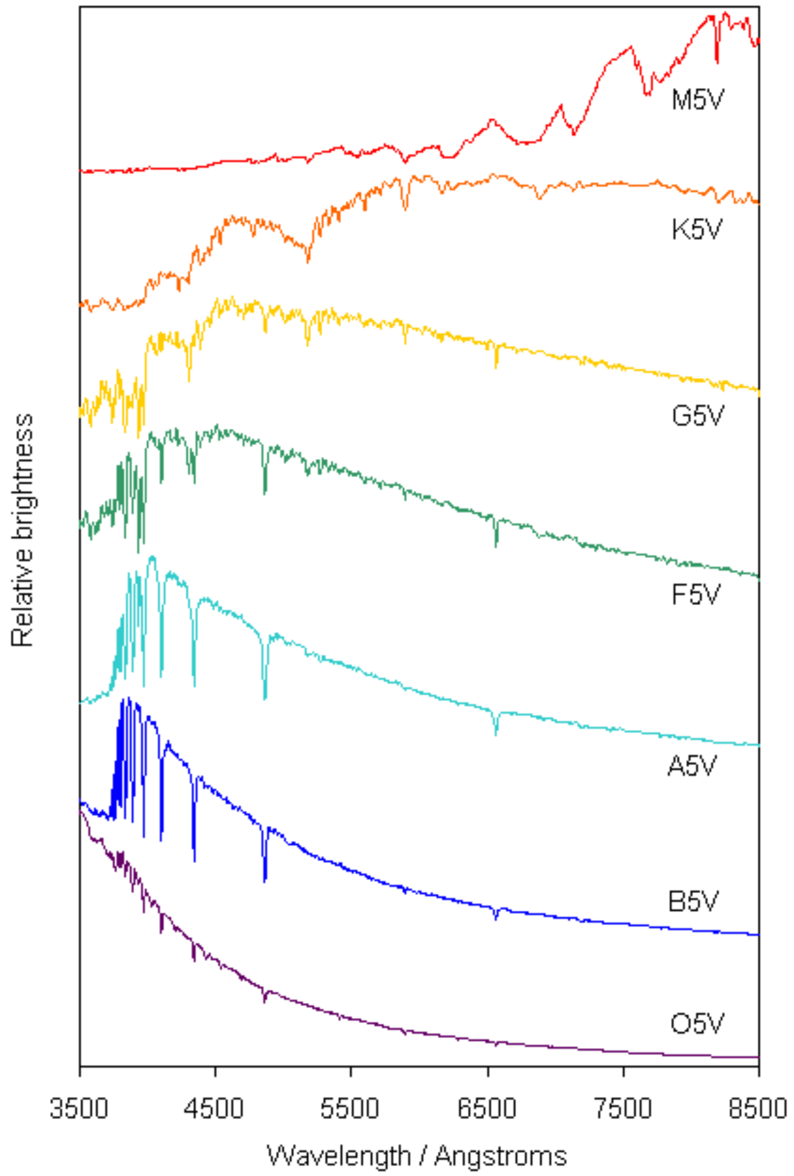
early type

late type

Spectral classification



Spectral classification



Spectral classification

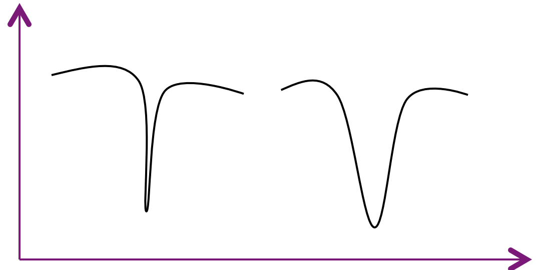
Class	Effective temperature[1][2][3]	Vega-relative "color label"[4][nb 1]	Chromaticity[5][6][7][nb 2]	Main-sequence mass[1][8] (solar masses)	Main-sequence radius[1][8] (solar radii)	Main-sequence luminosity[1][8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[9]
O	≥ 30,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–30,000 K	blue white	deep blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	orange	pale yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,400–3,700 K	red	light orange red	0.08–0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Oh Be A Fine Girl/Guy Kiss Me

Omnivorous Butchers Always Find Good Kangaroo Meat

Only Bored Astronomers Find Gratification Knowing Mnemonics

Luminosity class



Stars of same type have different line widths

Same *T*, different *R* → different surface gravity *g* → → different surface pressure *P*

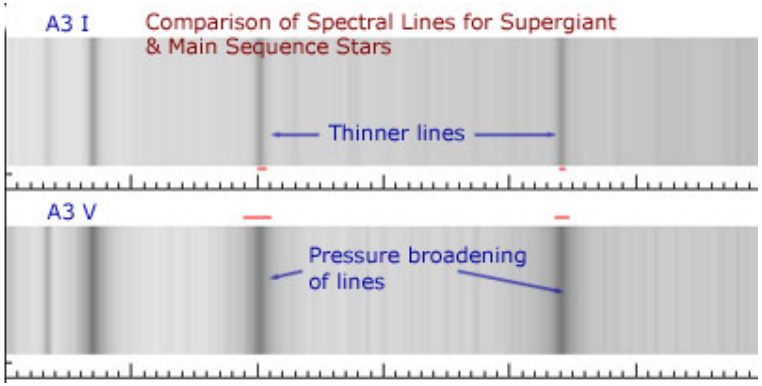
Pressure broadening: orbitals of atoms are perturbed due to collisions → broadening of spectral lines.

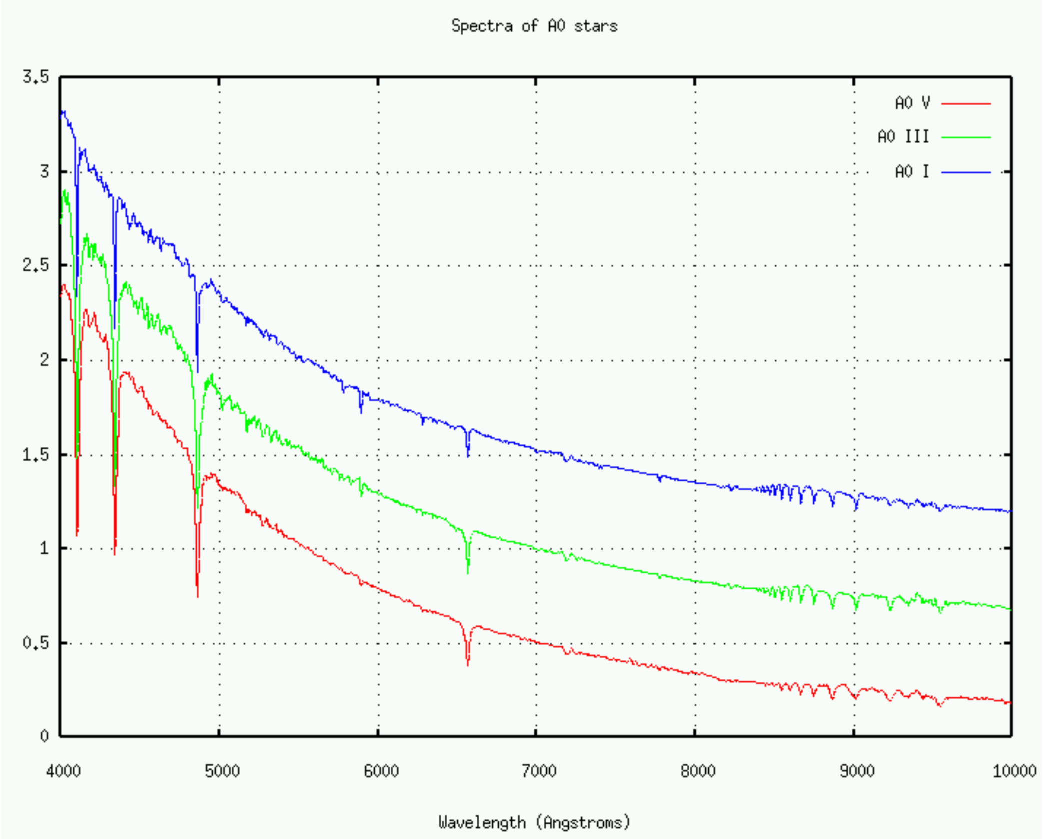
Since $L = 4\pi R^2 \sigma_T T^4$, changes in *R* at fixed *T* are changes in *L*

Spectral line widths → luminosity classification

I_a	I_b	II	III	IV	V	VI	VII
Supergiants		Luminous giants	Giants	Subgiants	Dwarfs	Subdwarfs	White dwarfs

Luminosity class





Special stars

C: carbon stars - same T_{eff} as K, M stars, but higher abundance of C than O → all O goes to form CO. Remaining C forms C2, CN.

S: same T_{eff} as K, M stars, but have extra heavy elements

W: Wolf-Rayet - He in atmosphere instead of H, strong winds

L: cooler than M stars. Some do not have fusion.

T: cool brown dwarfs (700-1,000K). Methane lines are prominent.

The Sun is a G2V star

The first Hertzsprung-Russell (H-R) diagram

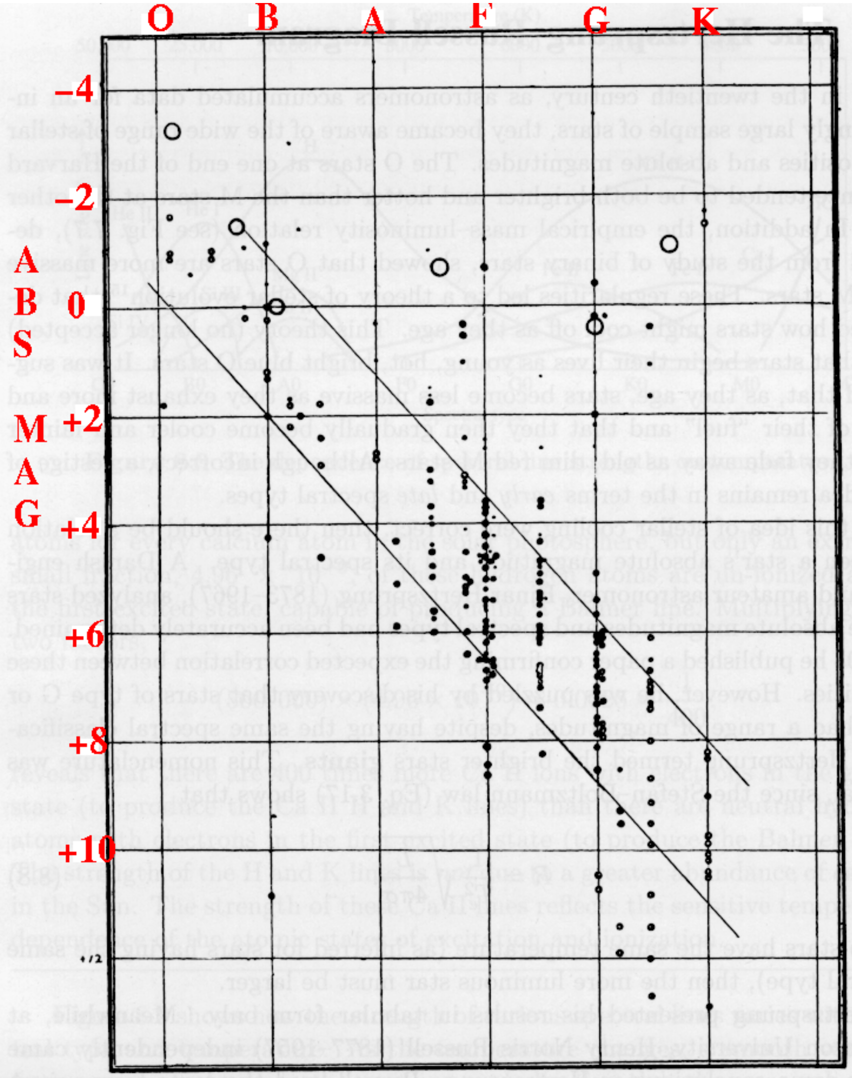
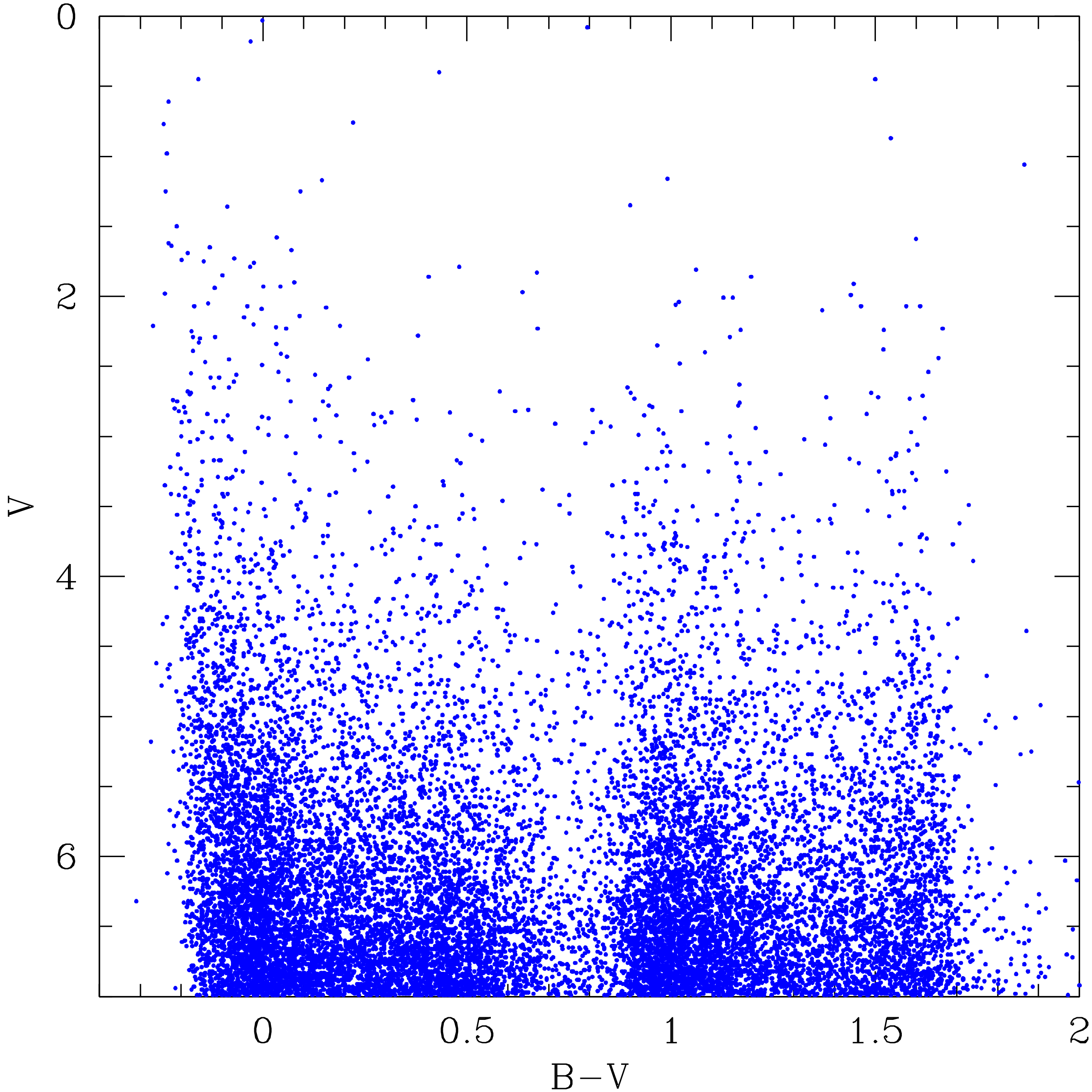
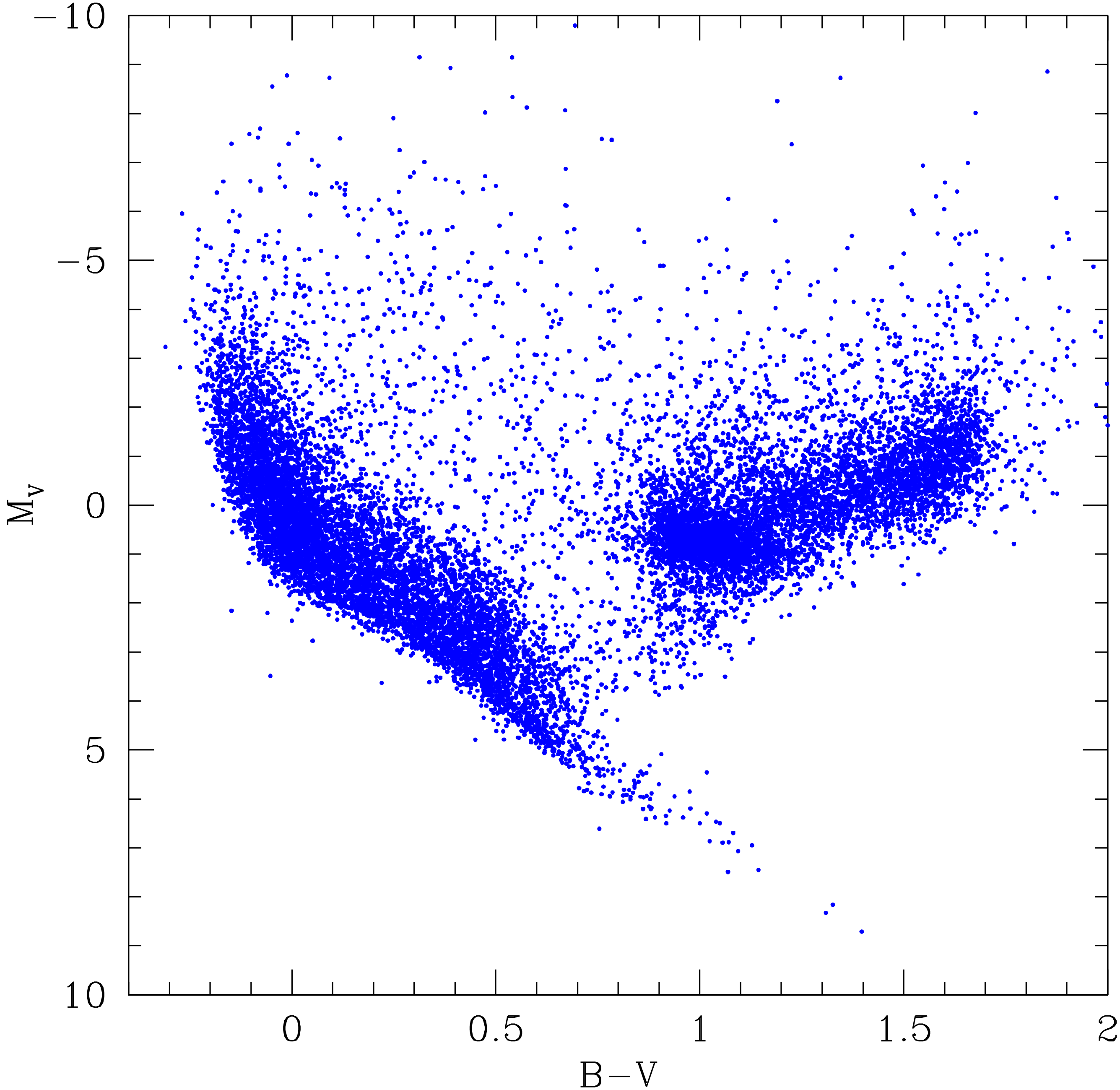


Figure 8.10 Henry Norris Russell's first diagram, with spectral types listed along the top and absolute magnitudes on the left-hand side. (Figure from Russell, *Nature*, *93*, 252, 1914.)

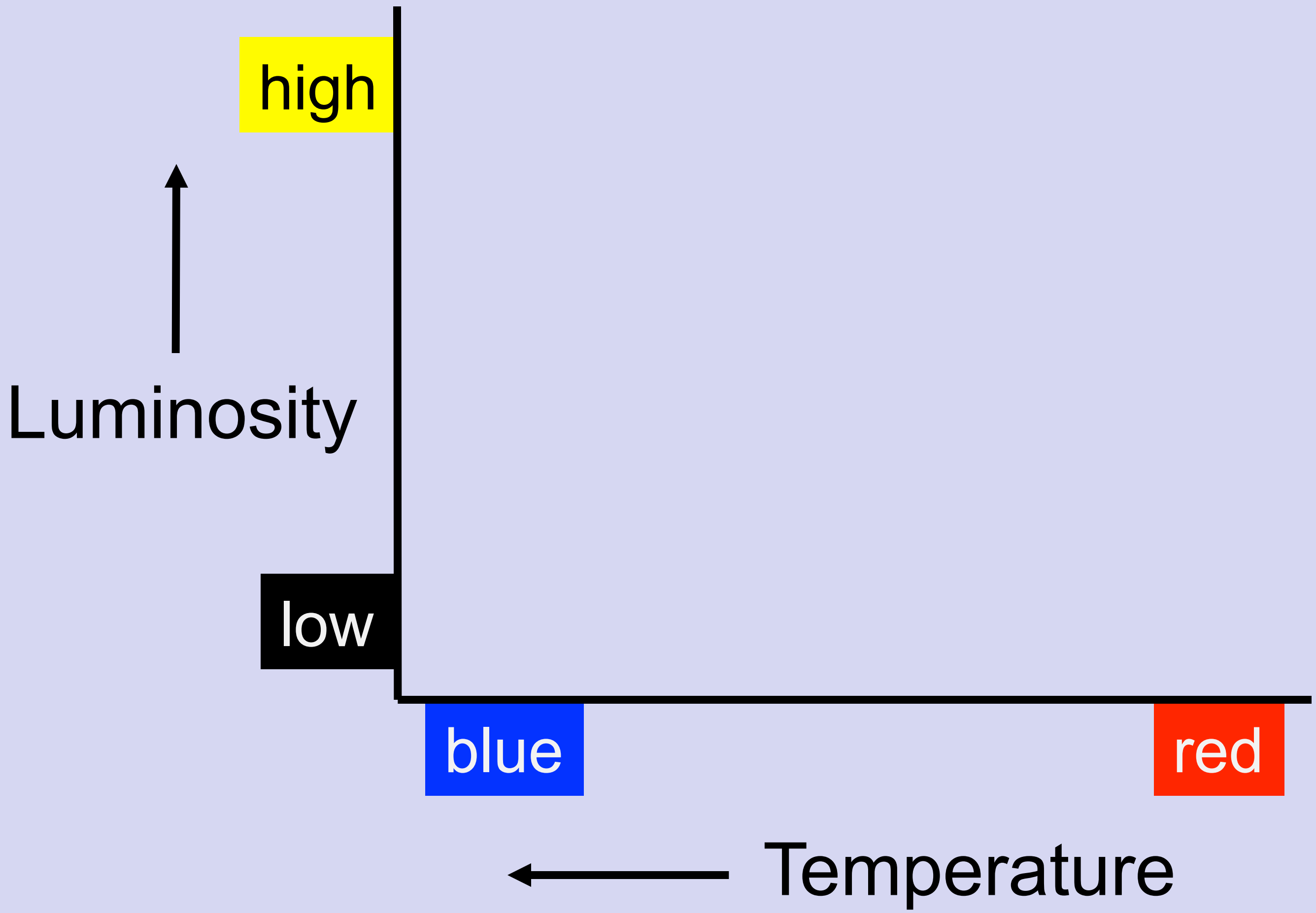
Hipparcos Color-Magnitude Diagram



Hipparcos Color-Magnitude Diagram

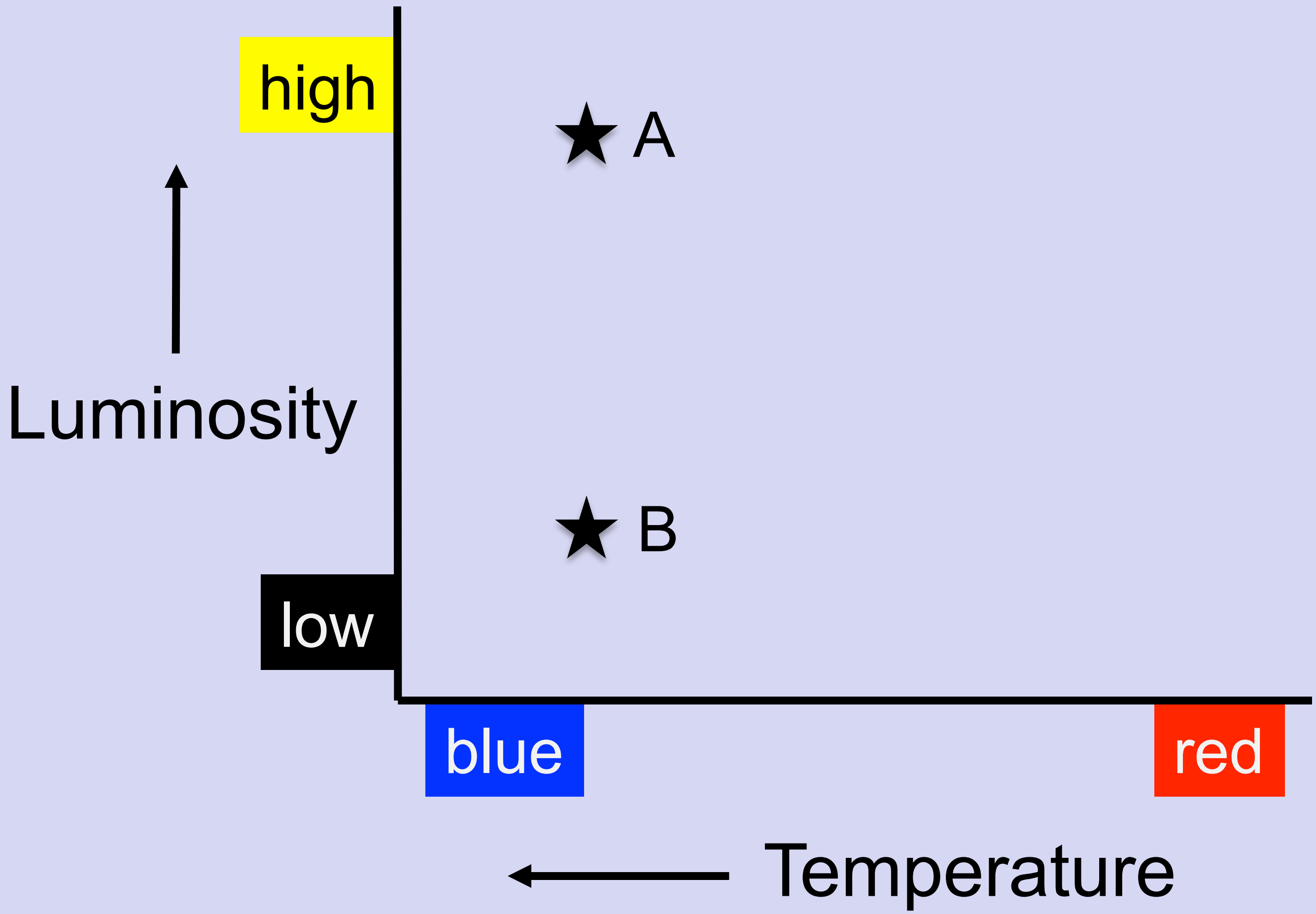


Plot luminosity vs. temperature



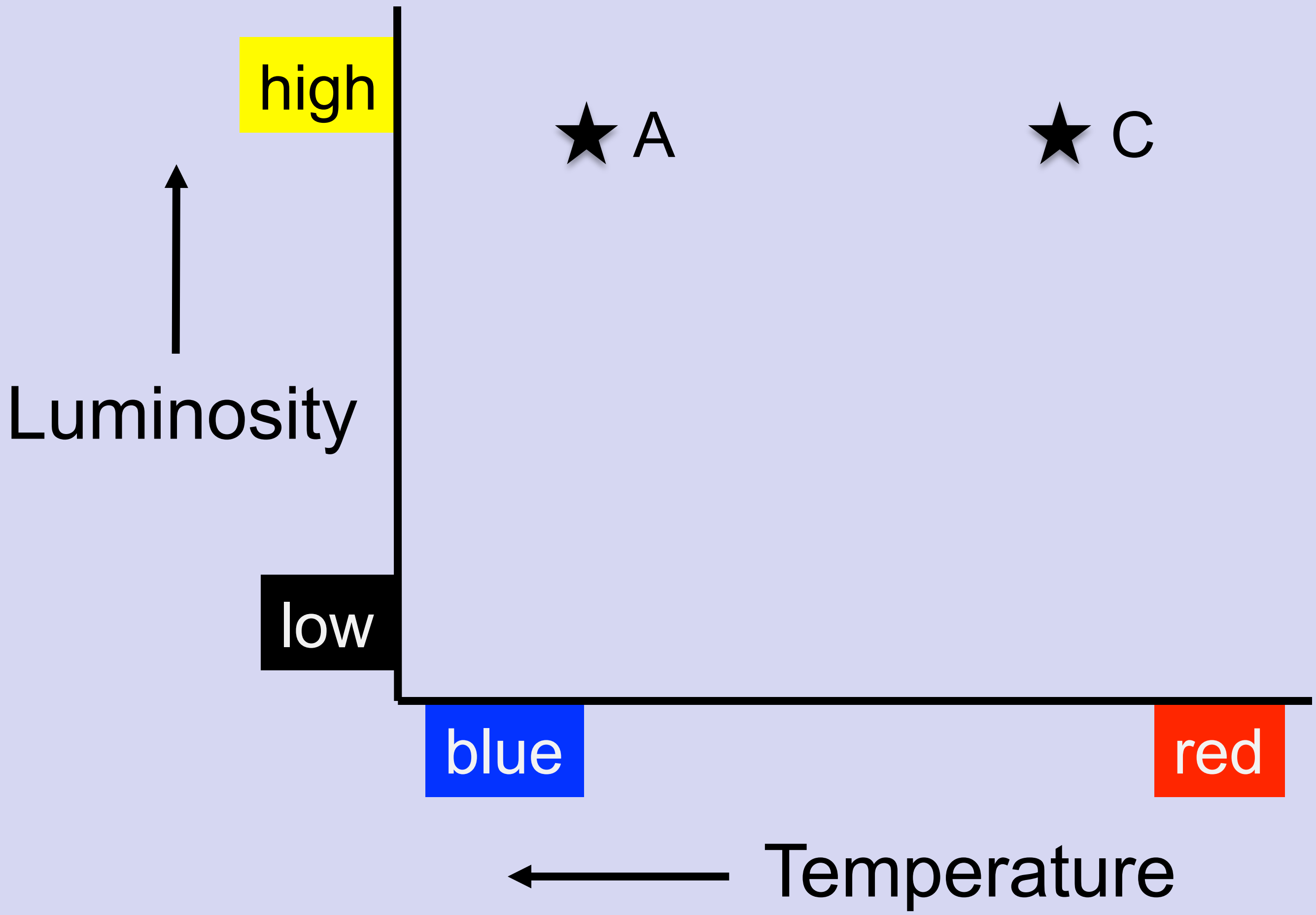
Understanding the H-R diagram

$$L = 4\pi R^2 \sigma T^4$$



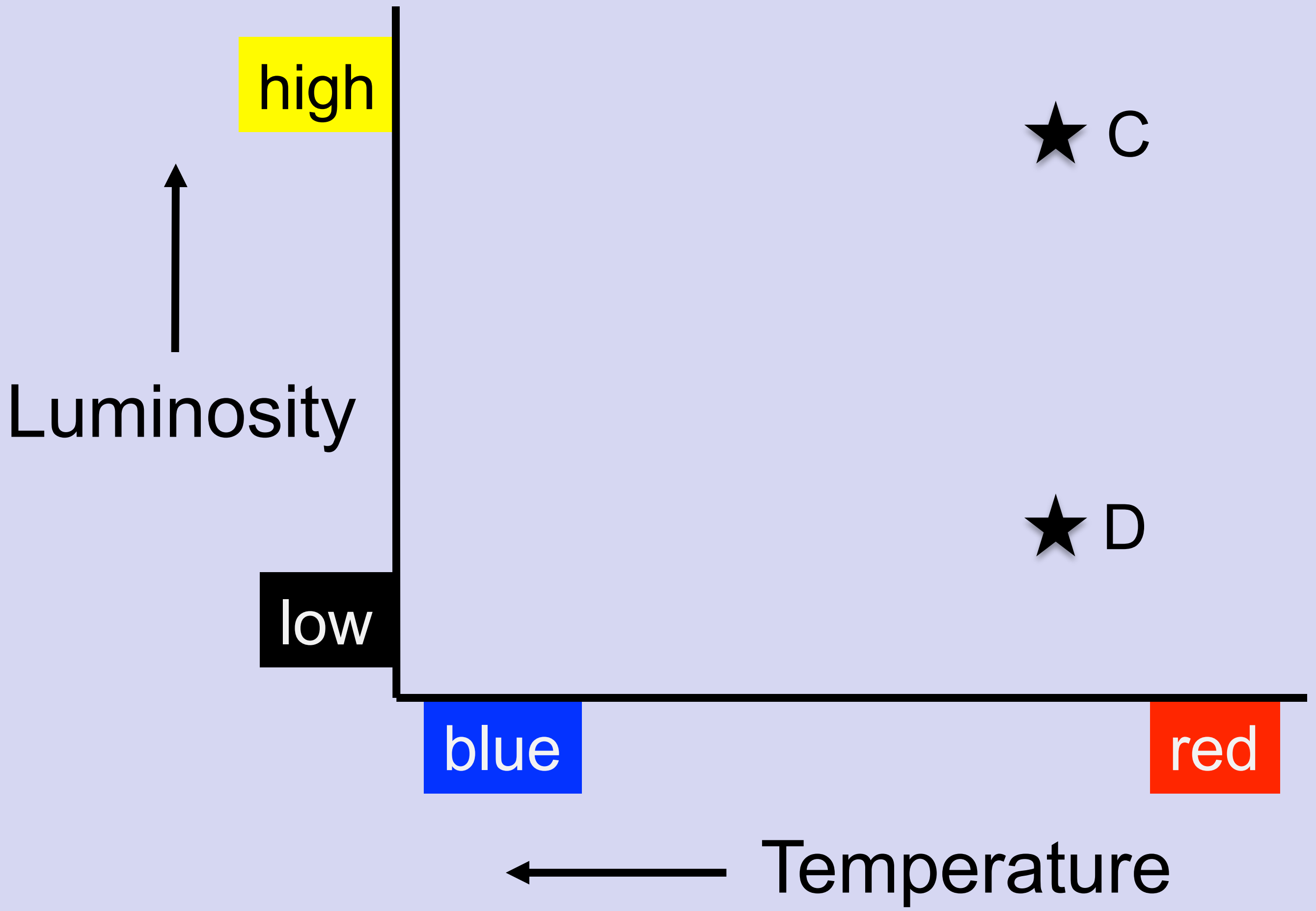
Understanding the H-R diagram

$$L = 4\pi R^2 \sigma T^4$$



Understanding the H-R diagram

$$L = 4\pi R^2 \sigma T^4$$



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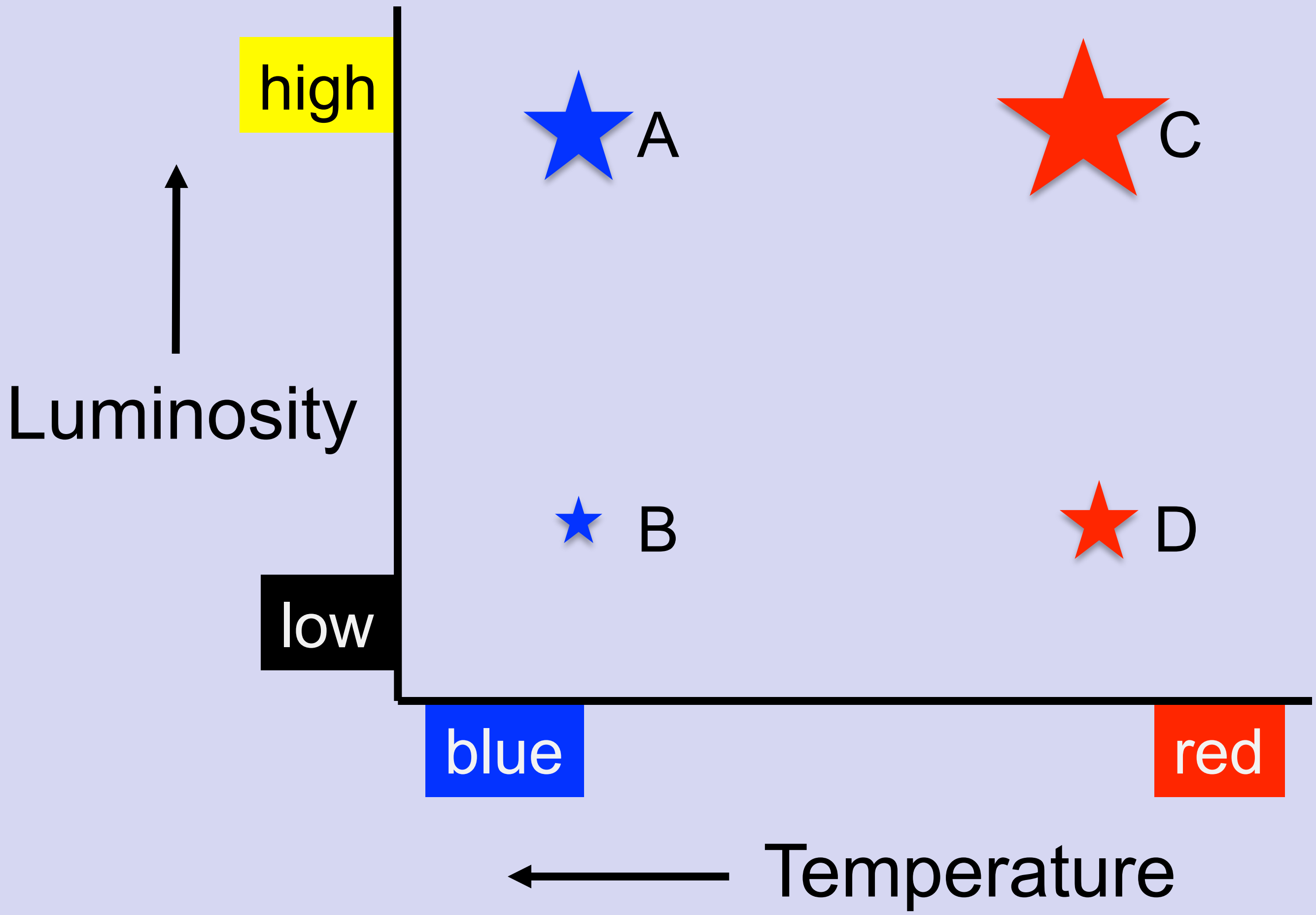

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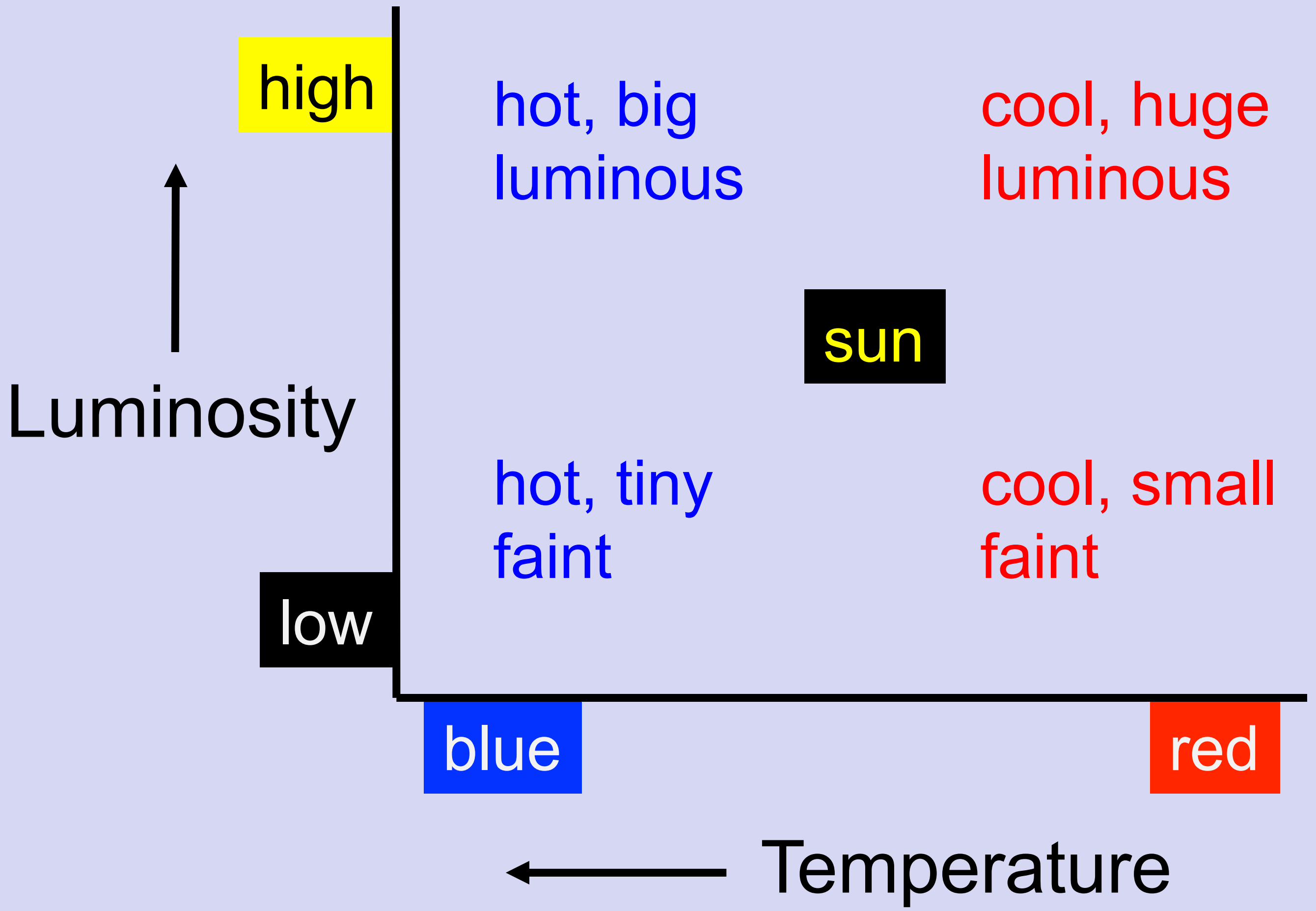
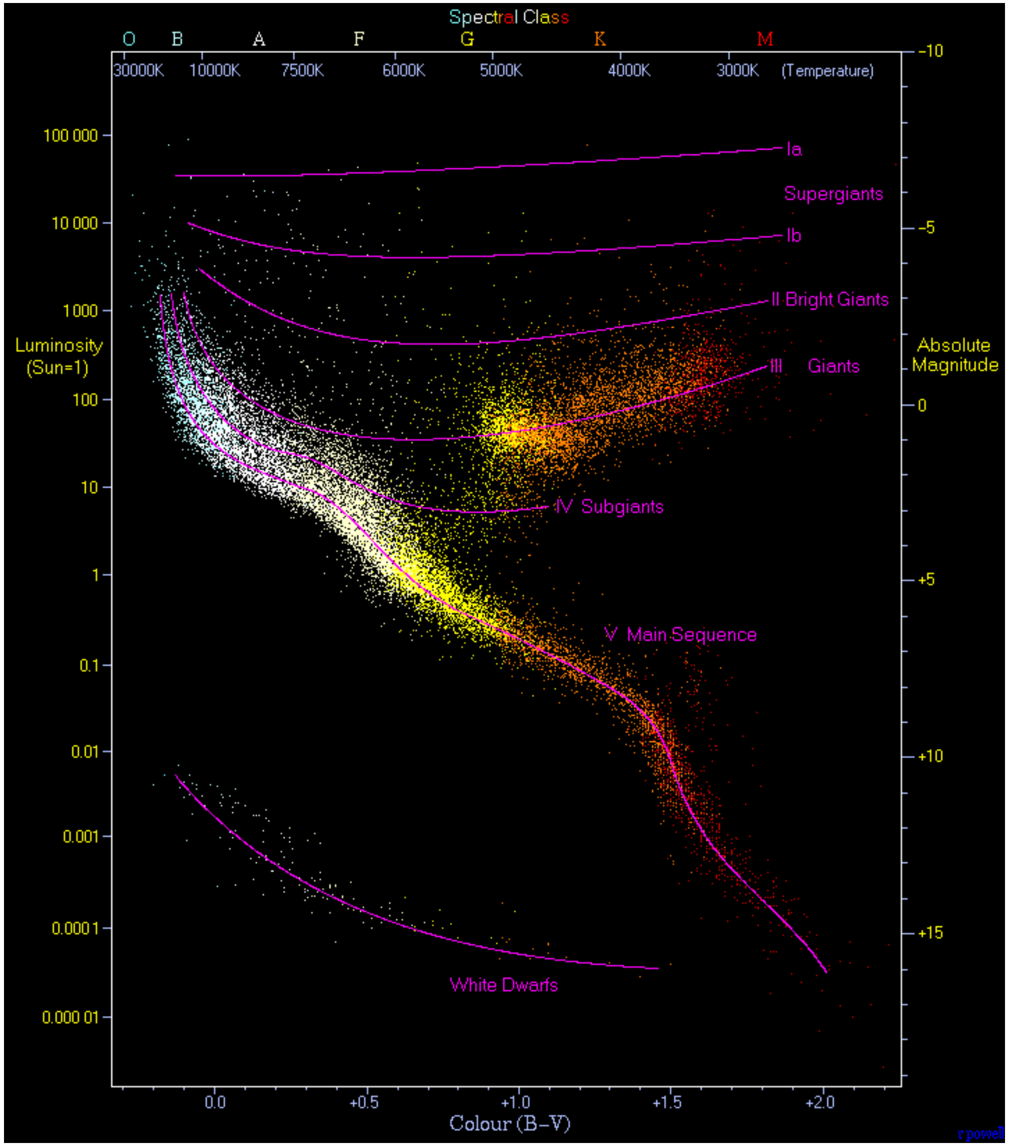
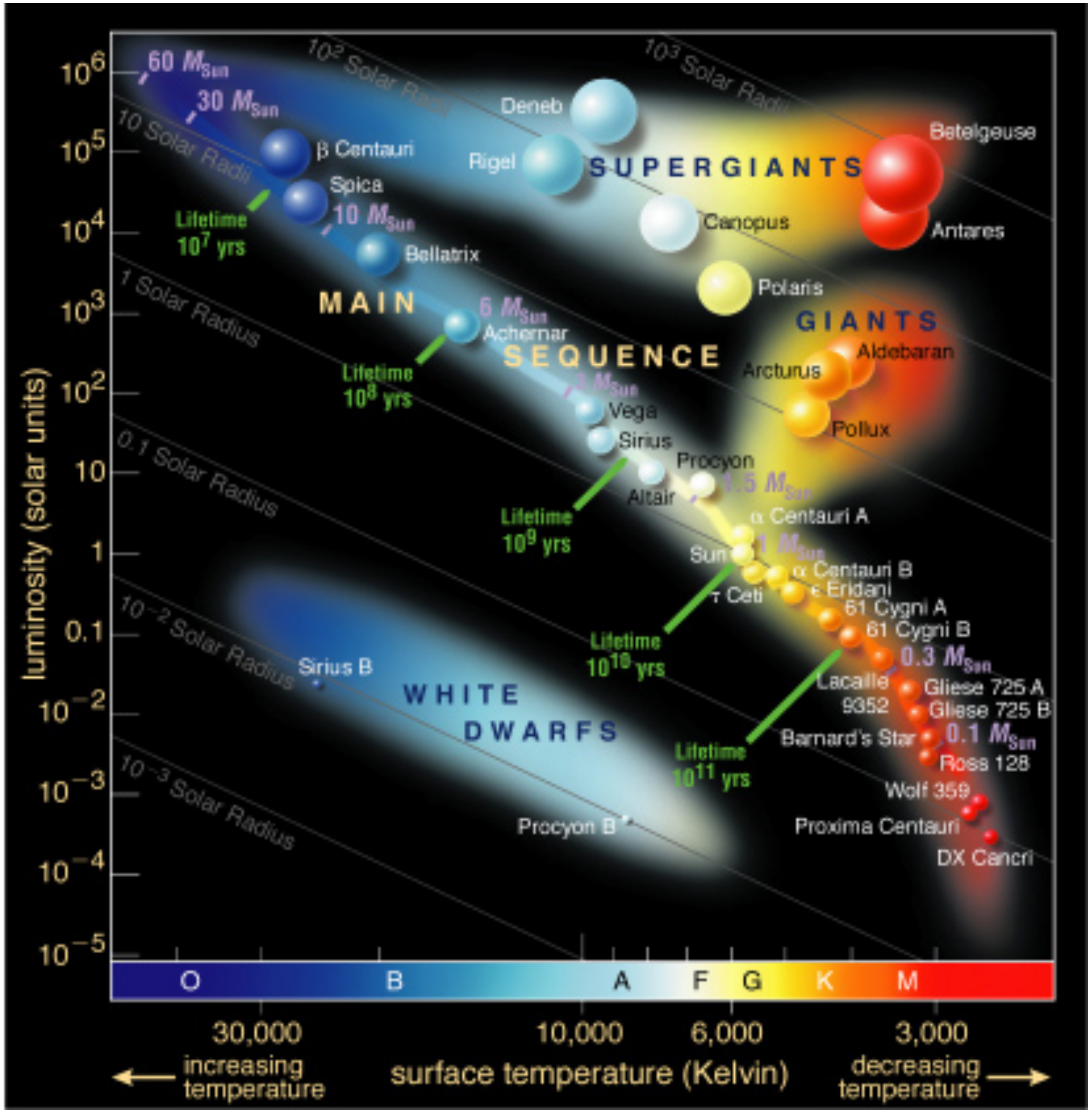


Hipparcos H-R diagram



Theoretical H-R diagram



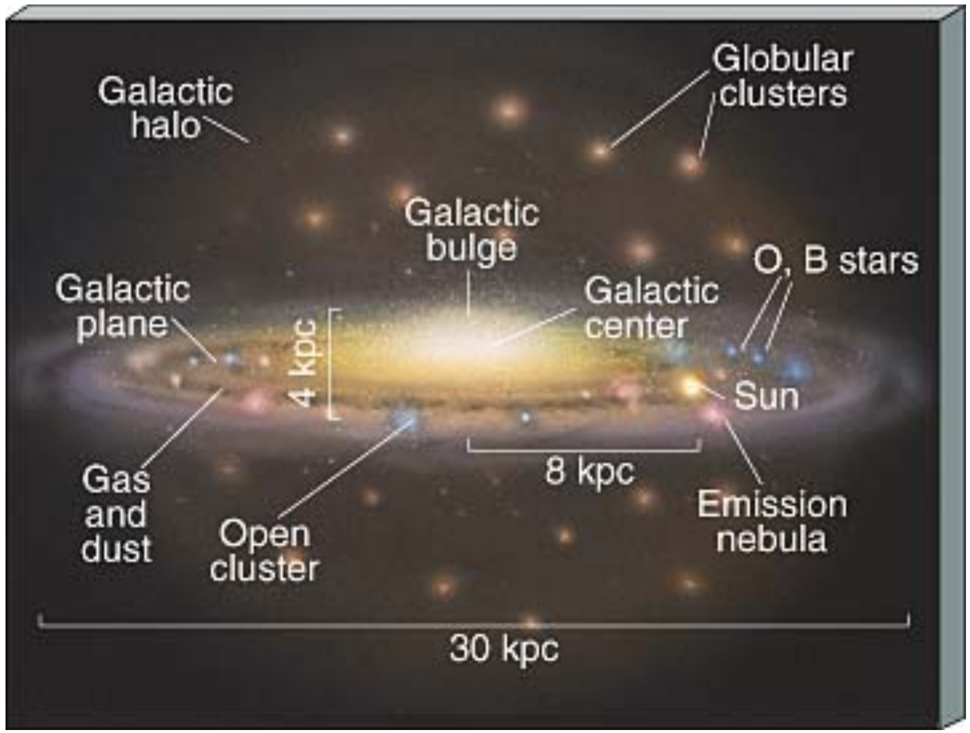
Chemical composition

Primordial (Big Bang) nucleosynthesis: protons fuse to form He and heavier elements 3 minutes after the Big Bang. Ends 20 minutes later.
Alpher, Bethe & Gammow, Physical Review L, 1948

75% H 25% He 0.01% D

Subsequent fusion inside massive stars and enrichment of the inter-stellar medium via supernovae, leads to future generations of stars with more heavy elements.

Stellar populations in the Milky Way



Stellar populations in the Milky Way

	Pop I	Pop II	Pop III
Spatial Distribution	Disk, $\vert z \vert<200$pc	Halo/spheroid	Have not been found
Kinematics (coherent)	Disk rotation (220 km/s)	No rotation	
Kinematics (dispersion)	~30 km/s	large	
Metallicity	$Z\sim0.02$	$Z<0.01$	$Z\sim0$
Age	Young	Old	Primordial