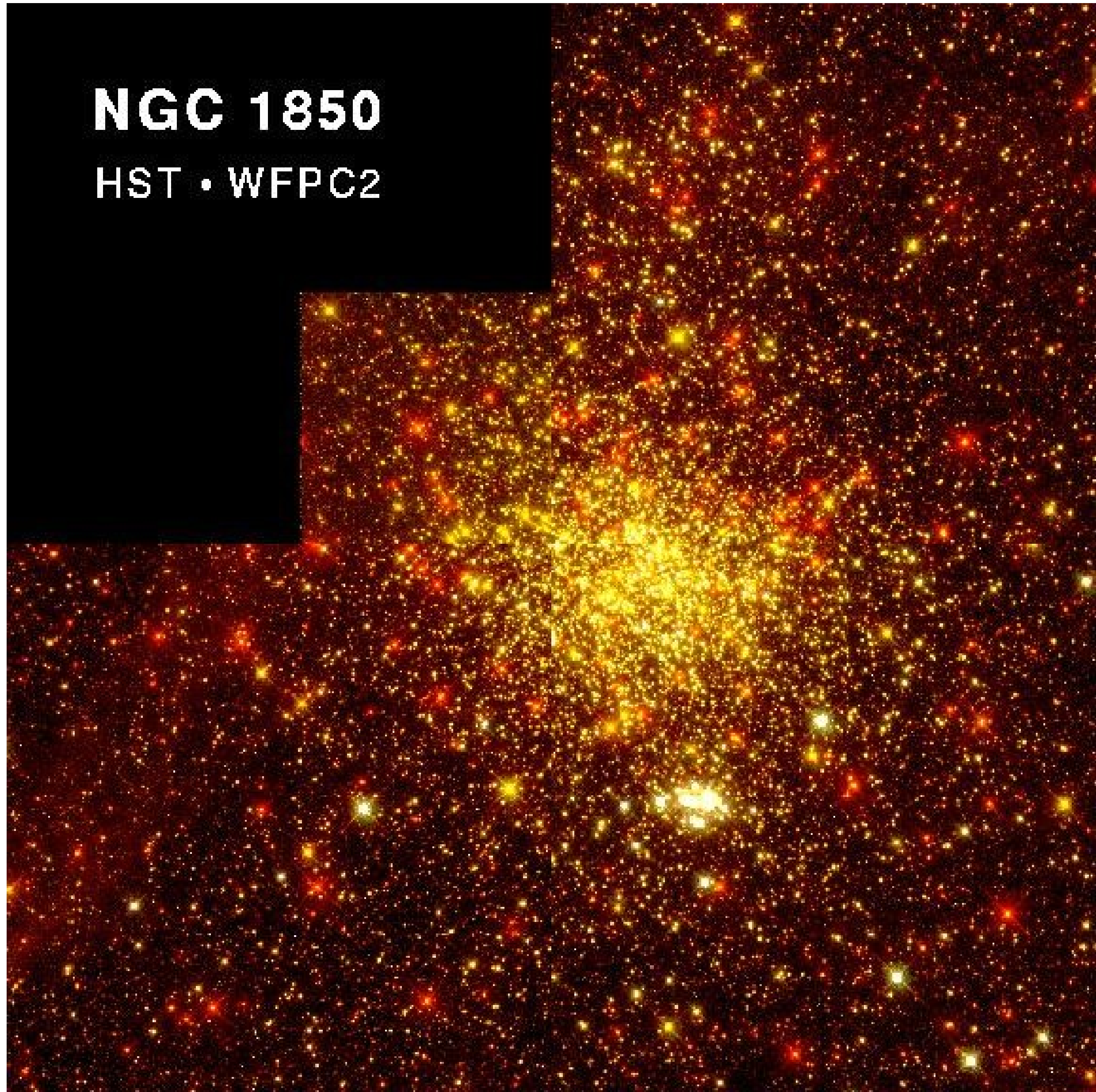
The Classification of Stellar Spectra

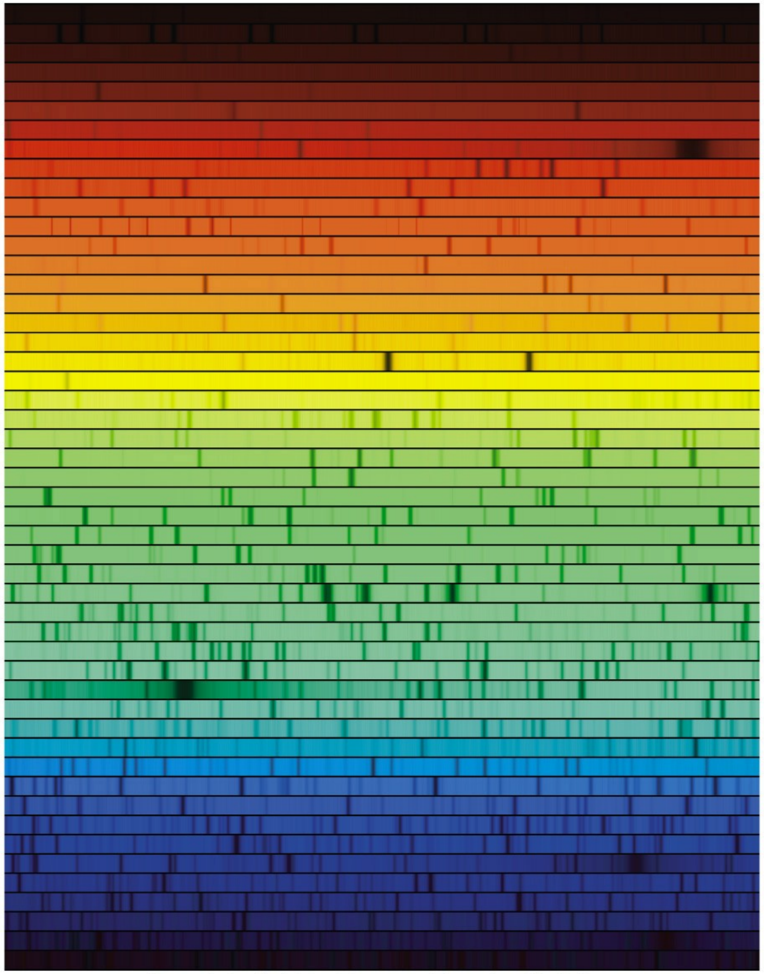
Chapter 8

Star Clusters in the Large Magellanic Cloud



The Classification of Stellar Spectra

Chapter 8



The Classification of Stellar Spectra

- Classification scheme developed before the physics
- Parameters that could be used to classify stars
  - Apparent brightness (bad idea)
  - Luminosity (Intrinsic brightness)
  - Temperature (Color)
  - Spectra (absorption lines)
  - Mass (only for binaries)

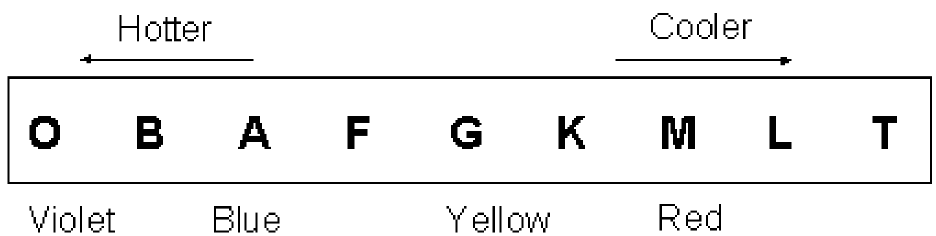
- The Henry Draper Catalogue
  - Contained >100,000 spectral classifications from A.J. Cannon and others from Harvard
  - Used OBAFGKM

The "Computers" of the Harvard College Observatory

http://cannon.sfsu.edu/%7Egmarcy/cswa/history/pick.html

The Classification of Stellar Spectra

- Originally organized by strength of H Balmer lines (A,B,...).
- Atomic physics allowed connection to temperature to be made.
- Spectral Types:



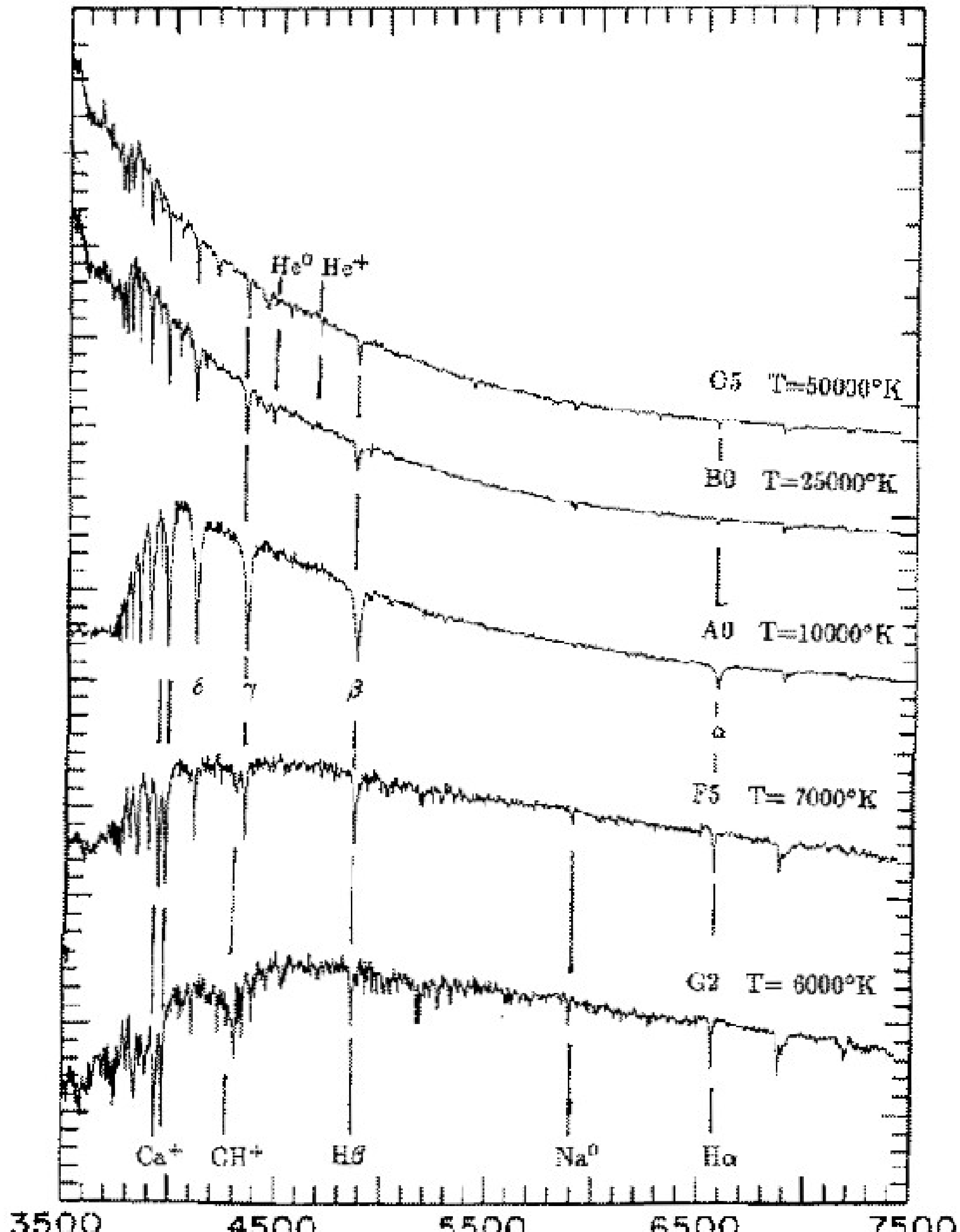
Early type → late type

L and T are more modern additions – Brown Dwarfs. R N S also used after M.

  – Subdivisions in tenths: 0 → 9 (early → late, hot → cool) within a Spectral Type). E.g., A0 is hotter than A5.
  – The Sun is a G2 – an early G-type star
    - G – yellow star (continuum peak in green/yellow)
      – H lines weak
      – Ca II (singly ionized) lines continue becoming stronger
      – Fe I, other *neutrals* metal lines become stronger

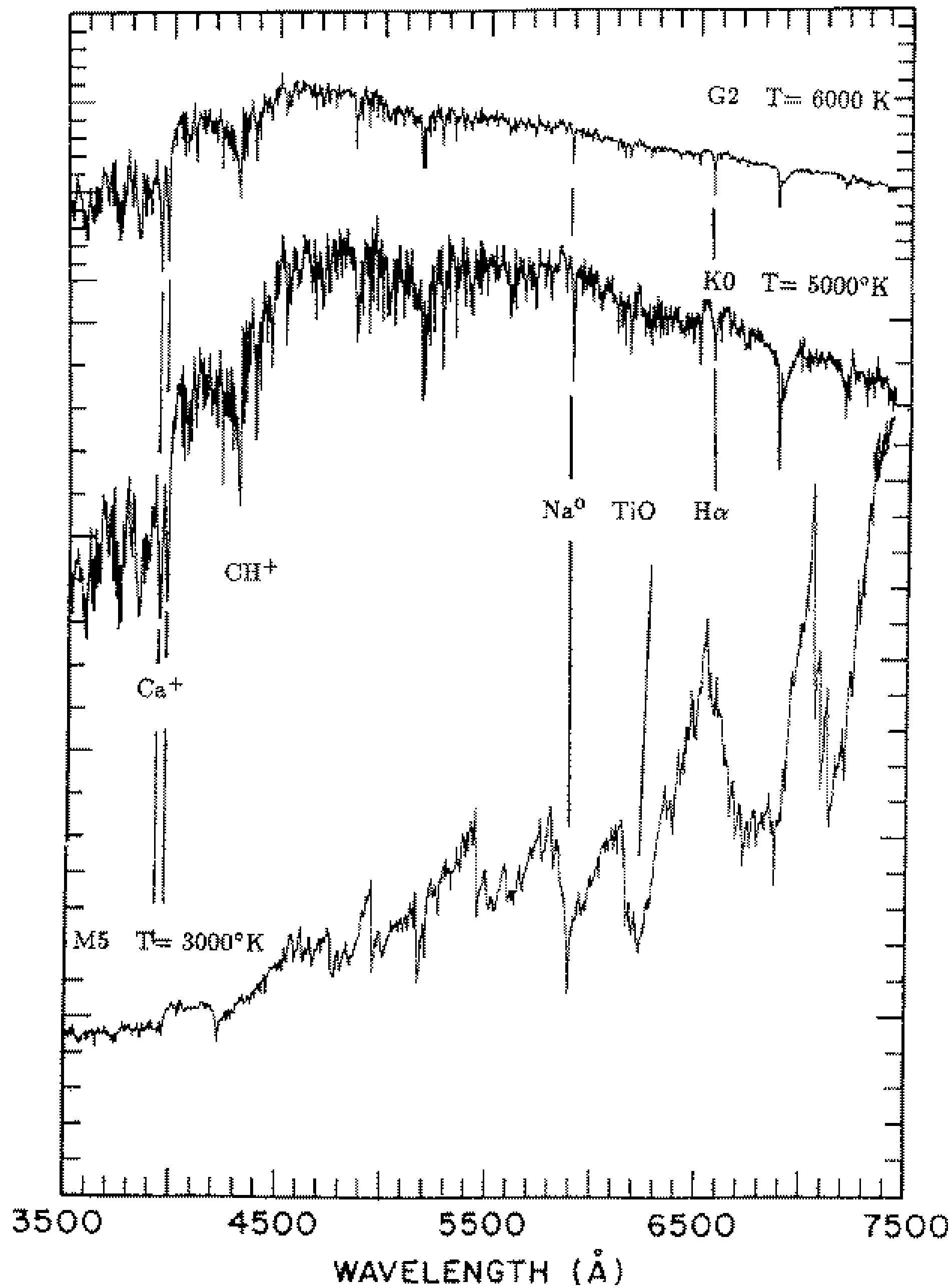
O to G example

O = HeII strongest, HeI increases from O0 to O9
B = HeI strongest at B2, HI (Balmer) strengthen from B0 to B9
A = HI (Balmer) strongest at A0
F = HI weakening, CaII strengthen from F0 to F9. FeI and Cr I present.
G = HI weak while CaII and FeI strengthen
K = CaII peak at K0, lots of neutral metals
M =



G to M example

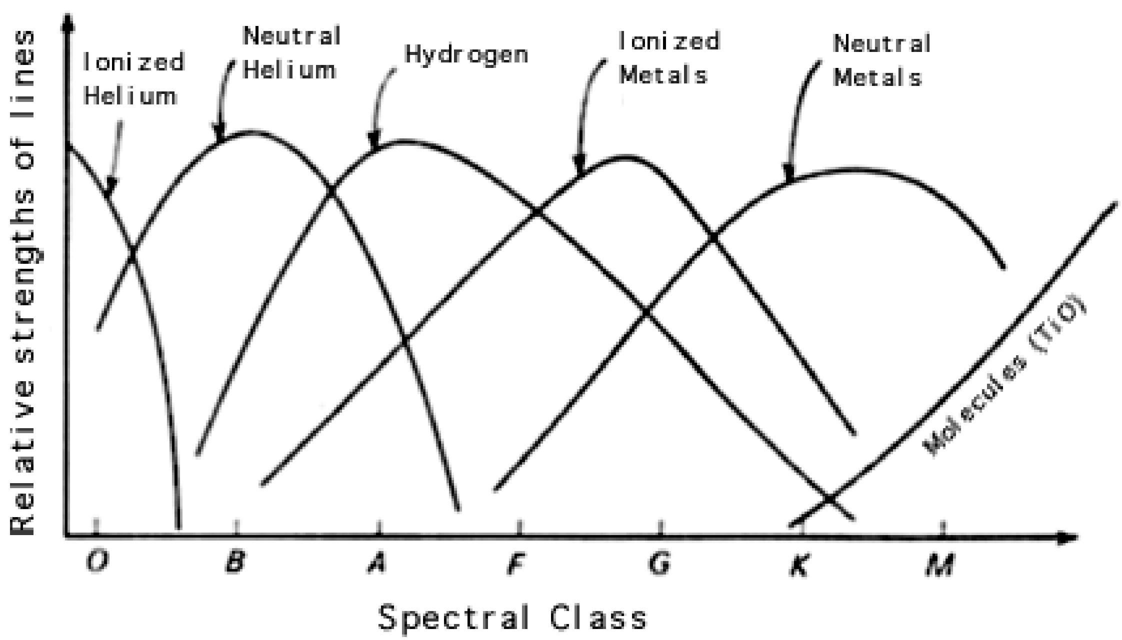
G = HI weak while CaII and FeI strengthen
K = CaII peak at K0, lots of neutral metals
M = TiO, VO and other molecular abs lines dominate. Neutral metals remain.
L = TiO and VO weaker but other molecular bands stronger (CrH, FeH, H2O, CO). Also Alkali metals Na, K, Rb, Cs. Temp = 1300-2500 K.
T = Strong methane (CH4) weakening CO. Temp<1300 K.



The Formation of Spectral Lines

- Question: What causes the differences in the observed spectra??
  - [Absorption by intervening material. Earth's atmos., ISM.]
  - Composition
  - Temperature
  - Surface gravity / pressure
- Answer:
  - Temperature is the main factor

Balmer Thermometer



The Formation of Spectral Lines

- Big Question of Ch.8: Why are the H balmer lines strongest for A stars, which seem to have T_surf = 10,000K?
- To find answer:

Need Ch.5's info about the Bohr atom … energy levels (n) and states l, m_l, m_s.

  - Need Kirchoff's laws → our gas is the upper “atmosphere” of the star.
  - Need statistical mechanics – to find probability that particles are in a given state. Large numbers of particles involved!

The Formation of Spectral Lines

- Distribution of electrons in different atomic orbitals depends on temperature
- Electrons can jump up in energy by absorption of a photon OR collision with a particle! So KE of surrounding particles important.

- Maxwell-Boltzmann velocity distribution
  - Tells us what fraction of particles are in a velocity range
  - Assumes thermal equilibrium
  - Number of gas particles per unit volume have a speed between v and v+dv

$$n_v\, dv = n\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} e^{-\frac{1}{2}mv^2/kT}\, 4\pi\, v^2 dv$$

Maxwell-Boltzmann Distribution

$$n_v\,dv = n\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} e^{-\frac{1}{2}mv^2/kT}\,4\pi\,v^2\,dv$$

- Most probable speed

$$v_{mp} = \sqrt{\frac{2kT}{m}} = 1.4\sqrt{kT/m}$$

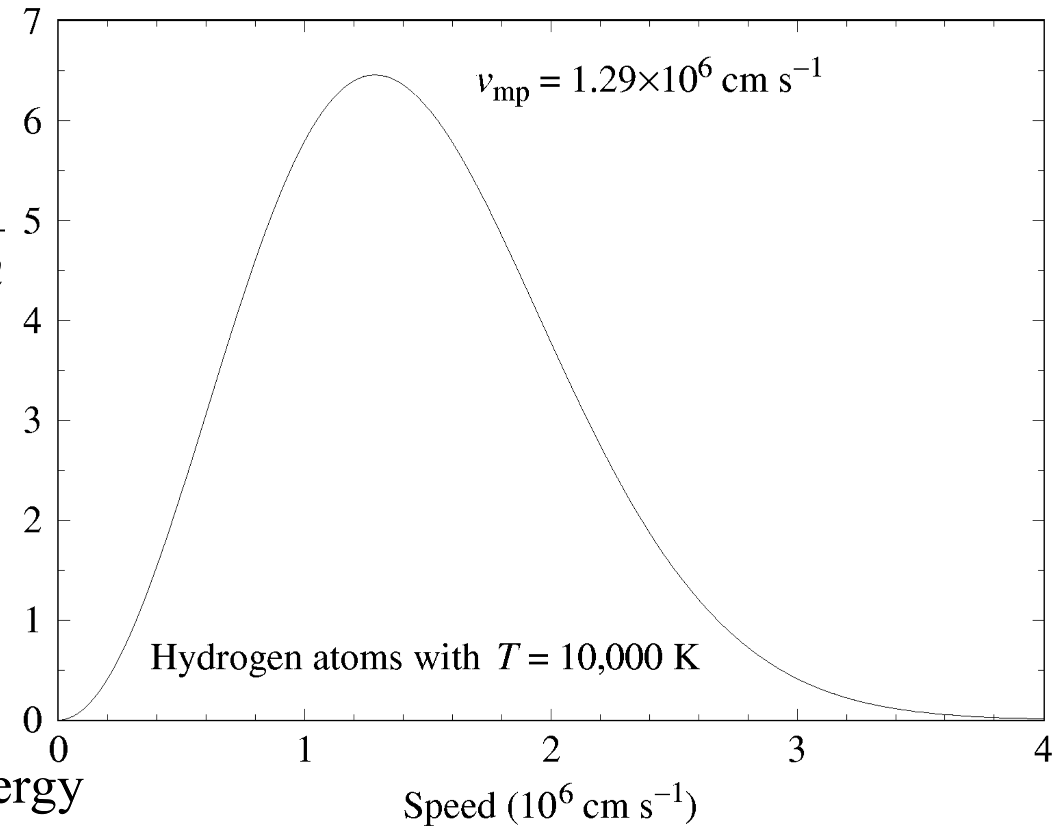
- Root-mean-square

$$v_{rms} = \sqrt{\frac{3kT}{m}} = 1.73\sqrt{kT/m}$$

- Average

$$v_{avg} = \sqrt{\frac{8kT}{\pi m}} = 1.6\sqrt{kT/m}$$

- Collisional energy causes a distribution of electrons among the atomic orbitals (Kinetic Energy → Potential Energy



Boltzmann Factor

- The higher the energy of a state, the less likely it will be occupied

$$P_a \propto e^{\frac{-E_a}{kT}}$$

  - For the Maxwell-Boltzmann distribution, the energy is Kinetic Energy

$$P_v \propto e^{-\frac{1}{2}mv^2/kT}$$

- The "kT" term is associated with the thermal energy of the "gas" as a whole
- Ratio of Probabilities for two different states (and energies)

$$\frac{P_b}{P_a} = \frac{e^{\frac{-E_b}{kT}}}{e^{\frac{-E_a}{kT}}} = e^{\frac{-\left(E_b - E_a\right)}{kT}}$$

Degeneracy Factor

- An energy (eigenvalue) is associated with each set of quantum numbers (eigenstate or eigenfunction)
- *Degenerate States* have different quantum numbers but the same energy

- Modify the Boltzmann factor

$$P_a \propto g_a e^{\frac{-E_a}{kT}}$$

  - The probability of being in any of the g_a degenerate states with energy E_a
    - g_a is the *degeneracy* or *statistical weight* of state a

- Ratio of probabilities between states with two different energies

$$\frac{P_b}{P_a} = \frac{g_b}{g_a} e^{\frac{-(E_b - E_a)}{kT}}$$

Degeneracy Factor

- Details of quantum mechanics determines the energies and quantum numbers…
- Visit the following site on the next page and browse…
- Quantum numbers for Hydrogen $\{n, l, m_l, m_s\}$
  - Table 8.2

State	n Principal quantum number n	l Orbital quantum number	m_l Magnetic quantum number	m_s Spin quantum number	Maximum number of electrons	
1s	1	0	0	$+\frac{1}{2}, -\frac{1}{2}$	2	
2s	2	0	0	$+\frac{1}{2}, -\frac{1}{2}$	2	8
2p	2	1	-1,0,+1	$+\frac{1}{2}, -\frac{1}{2}$	6	
3s	3	0	0	$+\frac{1}{2}, -\frac{1}{2}$	2	
3p	3	1	-1,0,+1	$+\frac{1}{2}, -\frac{1}{2}$	6	18
3d	3	2	-2,-1,0,1,2	$+\frac{1}{2}, -\frac{1}{2}$	10	$=2n^2$

Boltzmann Equation

- Number of atoms in a particular state *a*

$$N_a = N P_a$$

N = total number of atoms

N_a = number of atoms in state a

P_a = probability of being in state a

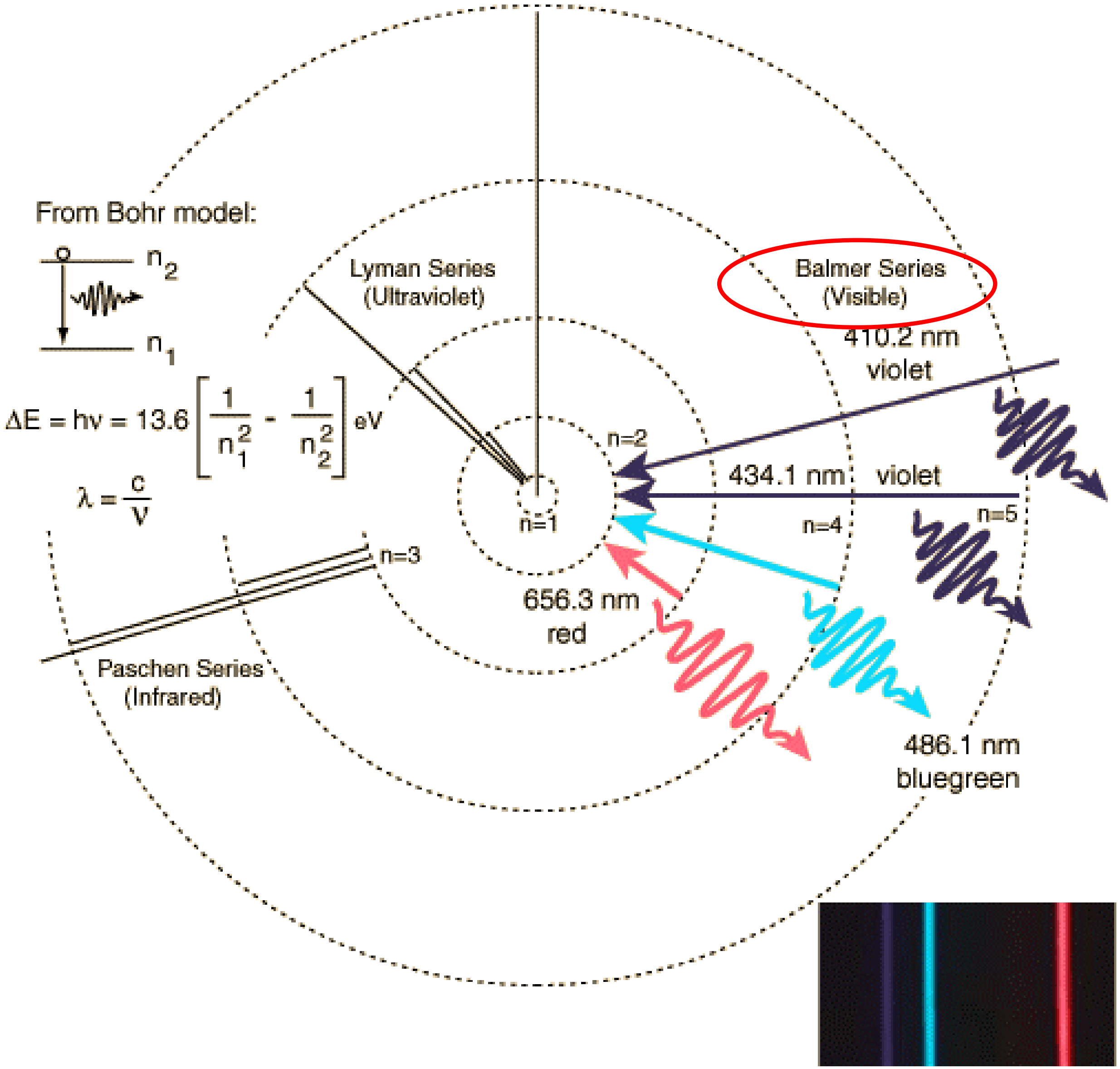
$$\Rightarrow \frac{N_b}{N_a} = \frac{g_b}{g_a} e^{\frac{-\left(E_b - E_a\right)}{kT}}$$

Hydrogen Atom Examples

Hydrogen Atom

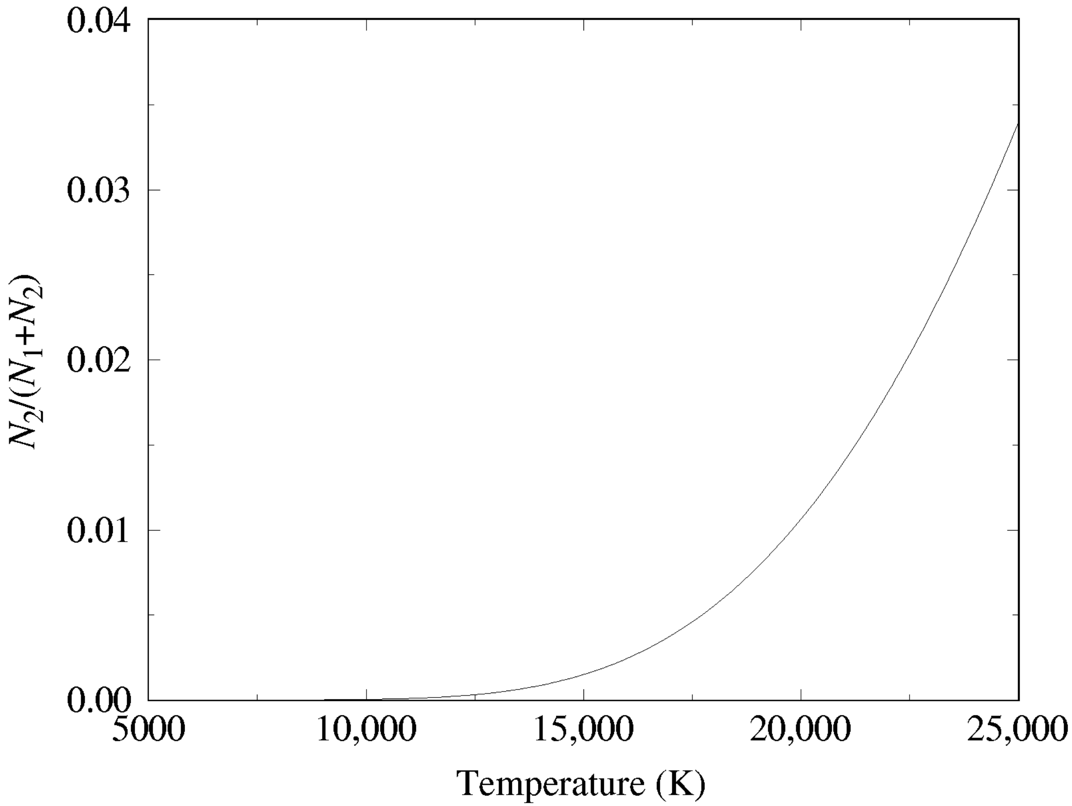
- Balmer series absorption spectra is an upward transition from $n = 2$

- Observation: this series has a peak absorption spectrum at ~9520 K.



Hydrogen Atom Populations

- We just saw that not many Hydrogen atoms are in the $n=1$ state at 9520 K!
  - Shouldn't the intensity keep growing as the temperature increases since there is a higher probability for an H atom to be in the $n=2$ state?!?!



Partition Function

- We also have to figure in all states that have a significant population
- For one state we have: $P_1 \propto g_1 e^{\frac{-E_1}{kT}}$
- Ratio between two states: $\frac{P_2}{P_1} = \frac{g_2 e^{\frac{-E_2}{kT}}}{g_1 e^{\frac{-E_1}{kT}}} = \frac{g_2}{g_1} e^{\frac{-(E_2 - E_1)}{kT}}$
- Ratio of state *2* to *all* other states with reference to the ground state:

$$\frac{P_2}{P_{all}} = \frac{g_b e^{\frac{-(E_2 - E_1)}{kT}}}{g_1 e^{\frac{-(E_1 - E_1)}{kT}} + g_2 e^{\frac{-(E_2 - E_1)}{kT}} + g_3 e^{\frac{-(E_3 - E_1)}{kT}} + \cdots} = \frac{g_2 e^{\frac{-(E_2 - E_1)}{kT}}}{Z}$$

Partition Function

- This tell us how many states are accessible or available at a given temperature (thermal energy)

$$Z = g_1 e^{\frac{-(E_1 - E_1)}{kT}} + g_2 e^{\frac{-(E_2 - E_1)}{kT}} + g_3 e^{\frac{-(E_3 - E_1)}{kT}} + \cdots$$

$$= g_1 + \sum_i g_i e^{\frac{-(E_i - E_1)}{kT}}$$

- The higher the temperature, the more states that are available
- At zero K, everything will be in the ground state
  - Bose-Einstein Condensates

Partition Function and Atoms

- We also have to handle ionization!
- Nomenclature: H I – neutral hydrogen

  H II – singly ionized hydrogen

  He I – neutral Helium

  He II – singly ionized Helium

  He III – doubly ionized Helium

- Ionization Energy for H I to H II

$$\chi_I = 13.6\, eV$$

  – Rather than $N_2/N_1 \rightarrow \infty$, the atom will ionize before this happens

Saha Equation

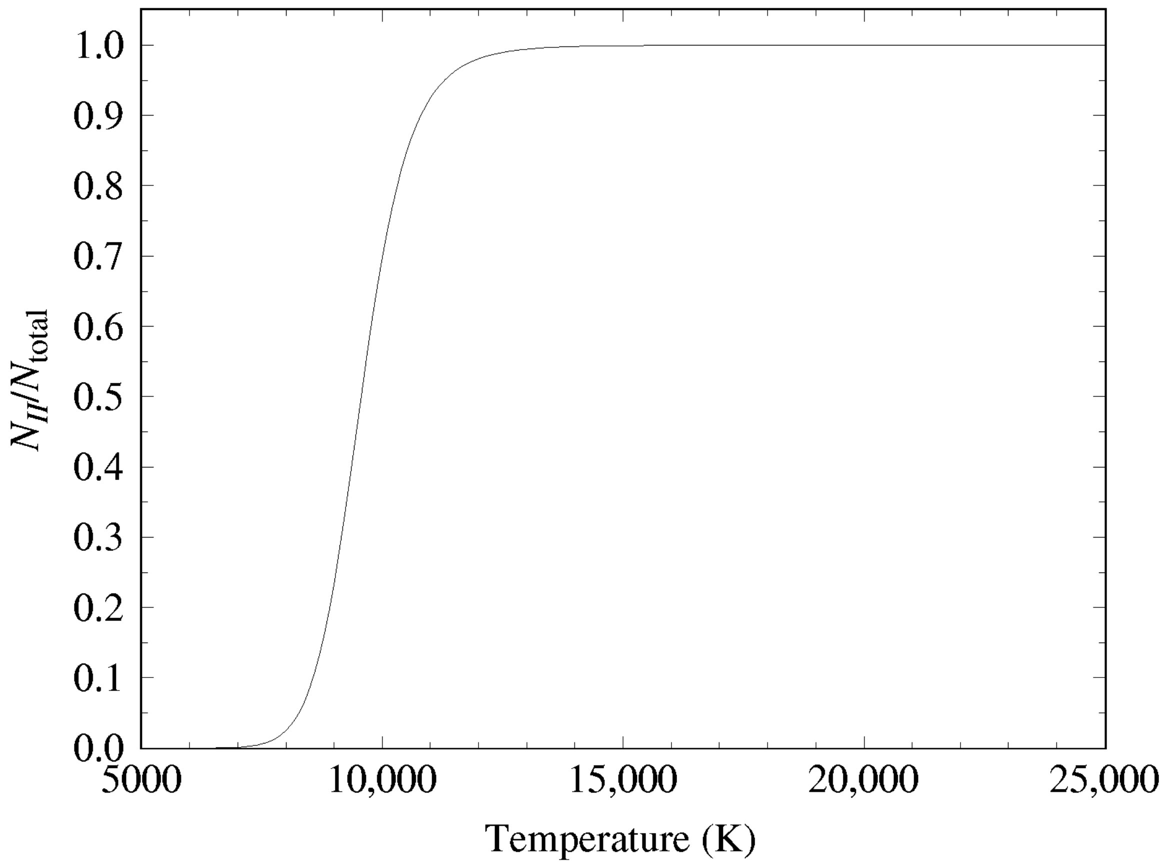
- Determines the ratio of numbers of ionized atoms
- Need distinct partition functions since energy levels of atoms are different for different ionization stages
  - Z_i is the initial stage of ionization
  - Z_{i+1} is the final stage of ionization
- Ratio of the number of atoms in each of these stages

$$\frac{N_{i+1}}{N_i} = \frac{2Z_{i+1}}{n_e Z_i}\left(\frac{2\pi\ m_e kT}{h^2}\right)^{\frac{3}{2}} e^{-\chi_i kT}$$

  - n_e is the electron density (an ideal gas of electrons)
    - Electron pressure $P_e = n_e kT$
    - Electrons recombine with H II to give H I

Ionized Hydrogen Atoms

- Fraction of hydrogen atoms that are ionized
- If we have H II, we can’t have the Balmer series!

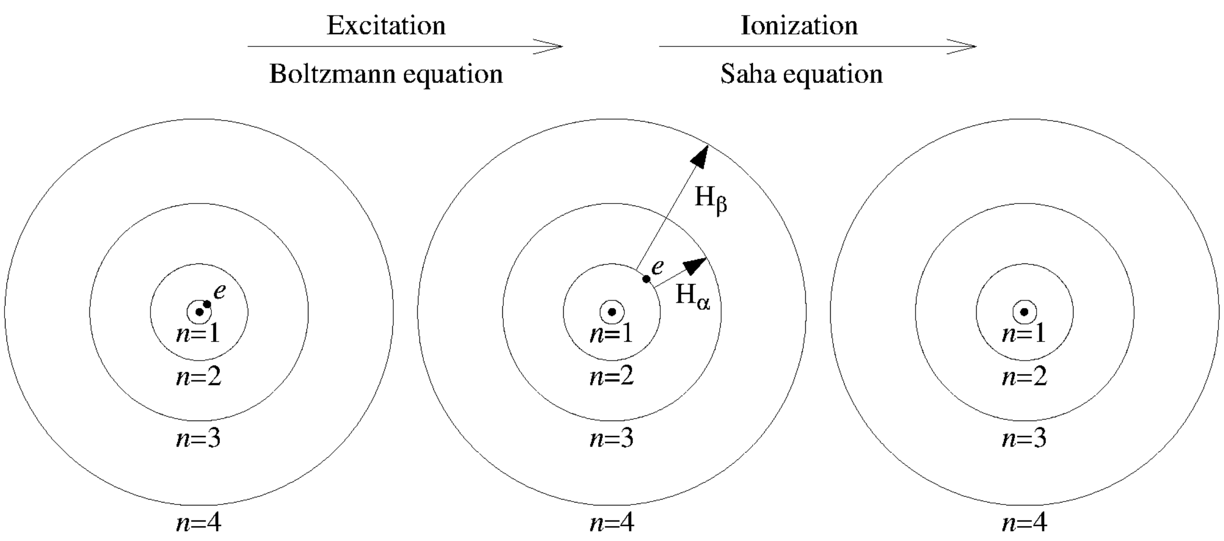


H I $n = 2$ population

$$\frac{N_2}{N_{total}} = \left(\frac{N_2}{N_I + N_2}\right)\left(\frac{N_I}{N_I + N_{II}}\right)$$

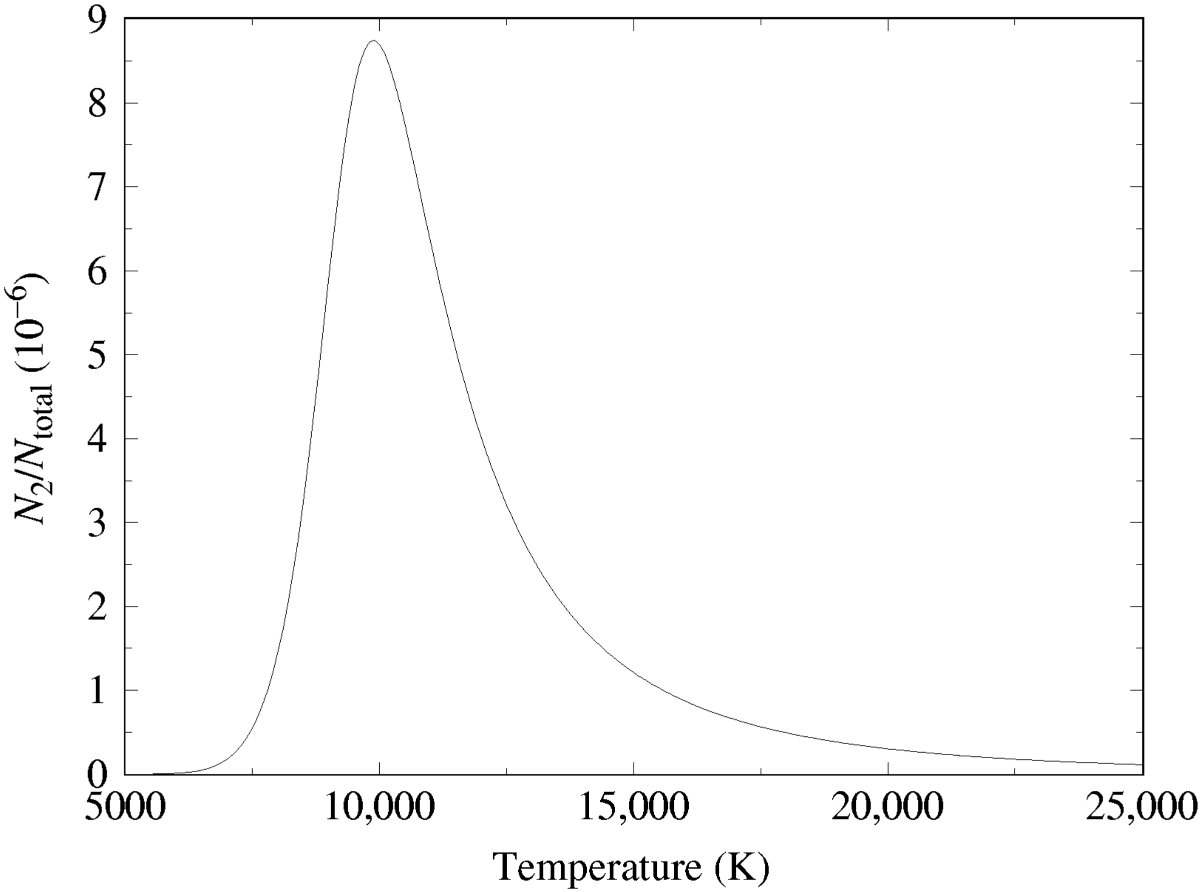
Fraction of non-ionized hydrogen Atoms in the $n = 2$ state

Fraction of non-ionized hydrogen atoms



H I $n = 2$ population

- Includes the Boltzmann factor, partition function and ionization
- Population peak at 9520 K, in agreement with observation of the Balmer series



Example 8.3

- Degree of ionization in a stellar atmosphere of pure hydrogen for the temperature range of 5000-25000 K $\frac{N_{II}}{N_{Total}}$
- Given electron pressure $P_e = 200 \frac{dyne}{cm^2} = 20\ N/m^2$
- Saha equation $$\frac{N_{II}}{N_I} = \frac{2kTZ_{II}}{P_e Z_I}\left(\frac{2\pi\ m_e kT}{h^2}\right)^{\frac{3}{2}} e^{-\chi_i kT}$$
- Must determine the partition functions
  - Hydrogen ion is a proton, so $Z_{II} = 1$
  - Neutral hydrogen over this temp range

$$\Delta E = E_2 - E_1 = 10.2\text{ eV}$$

$\Delta E >> kT$, then $e^{-\Delta E/kT} << 1$

$$\Rightarrow Z_I = g_1 + \sum_i g_i e^{\frac{-(E_i - E_1)}{kT}} \quad g_1 = 2$$

$T := 5000K$

$k \cdot T = 0.43\text{ eV}$

$T := 25000K$

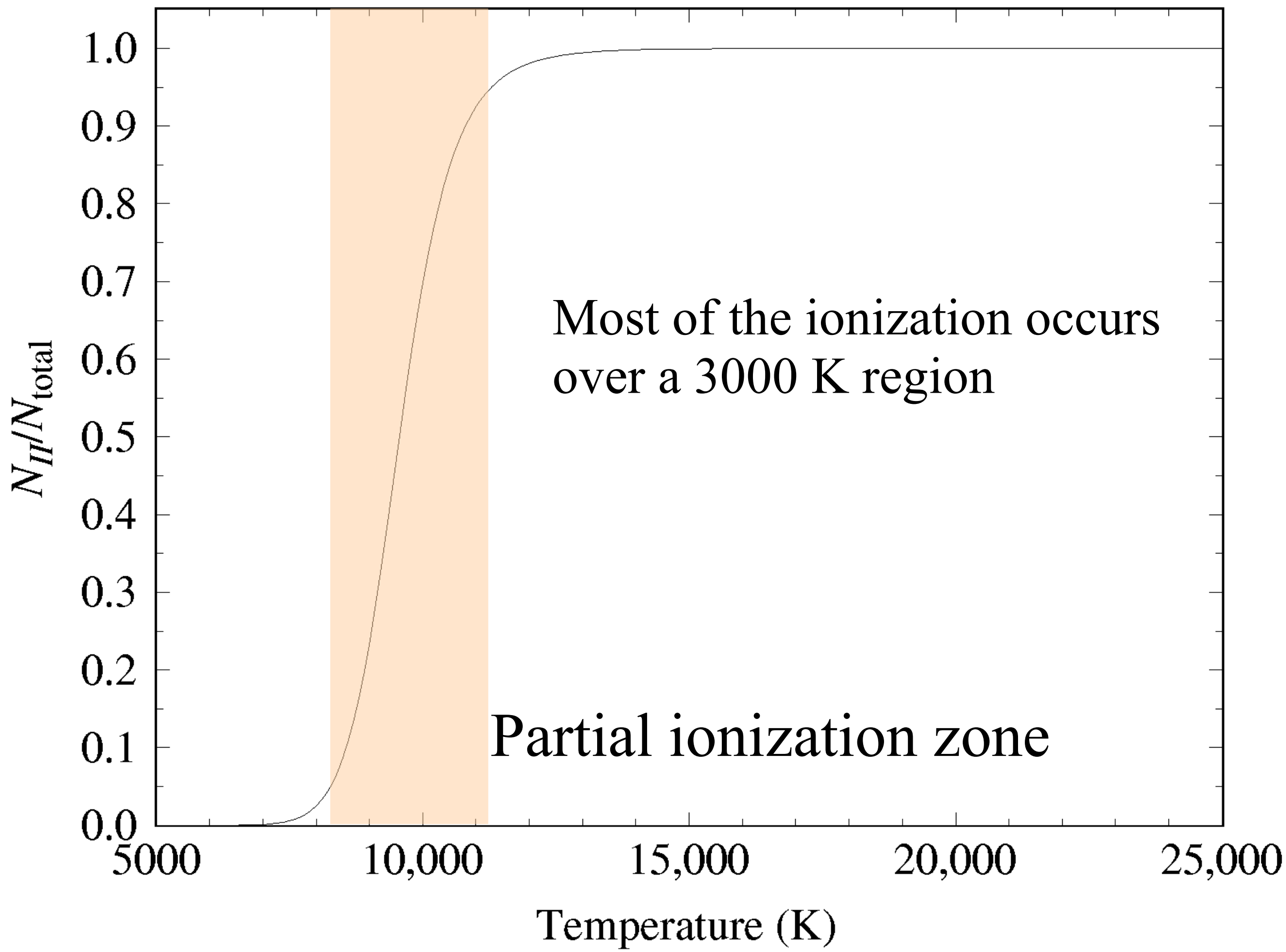
$k \cdot T = 2.15\text{ eV}$

Example 8.3

- Degree of Ionization

$$\frac{N_{II}}{N_I} = \frac{2kT(1)}{P_e(2)}\left(\frac{2\pi\, m_e kT}{h^2}\right)^{\frac{3}{2}} e^{-\chi_i kT}$$

$$\frac{N_{II}}{N_I + N_{II}} = \frac{N_{II}/N_I}{1 + N_{II}/N_I}$$



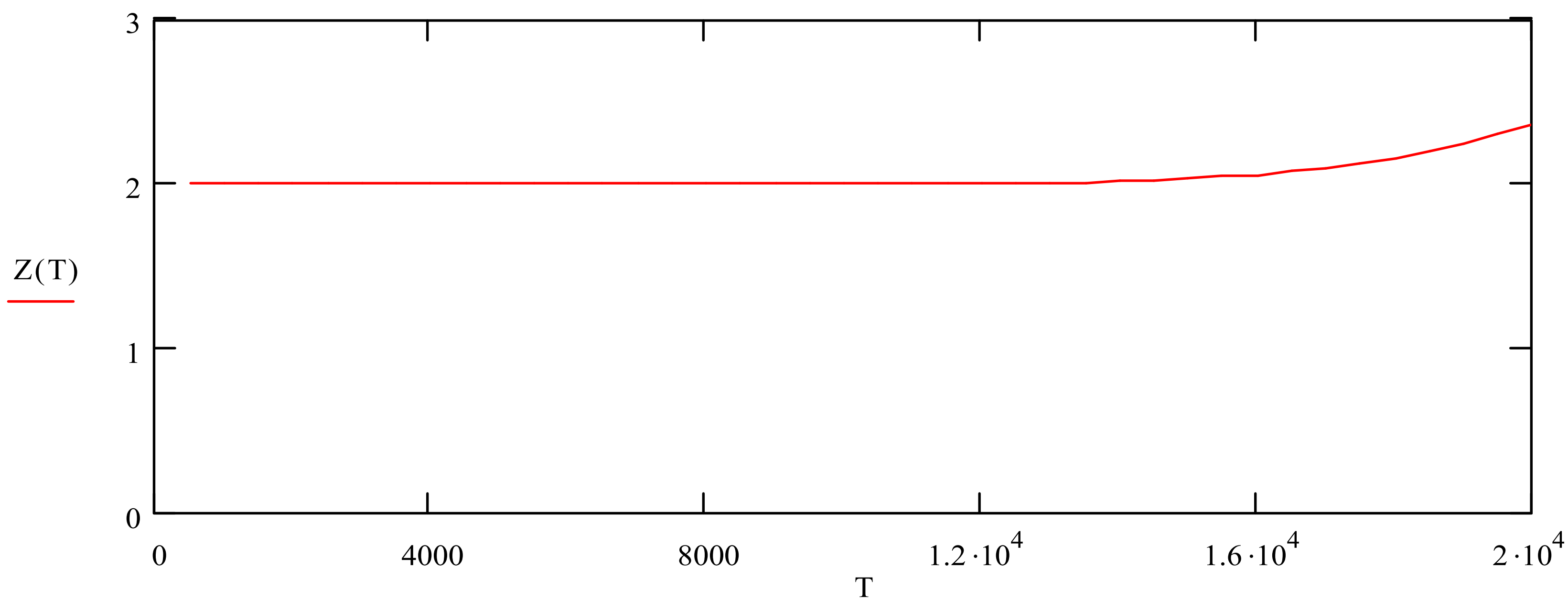
Problem 8.7

- Evaluate the first three terms of the partition function for 10000K

Partition Function: Counting the first ten states... <u>Energy:</u> $E(n) := \frac{-13.6\text{eV}}{n^2}$ <u>Degeneracy:</u> $g(n) := 2 \cdot n^2$

$$f_B(n, T) := \exp\left[\frac{-(E(n) - E(1))}{k \cdot T}\right] \qquad Z(T) := \sum_{n=1}^{10} \left(g(n) \cdot f_B(n, T)\right) \qquad T := 0, 500 .. 20000$$

$Z(6000K) = 2.0000$ $\quad Z(10000K) = 2.0002$ $\quad Z(15000K) = 2.0292$



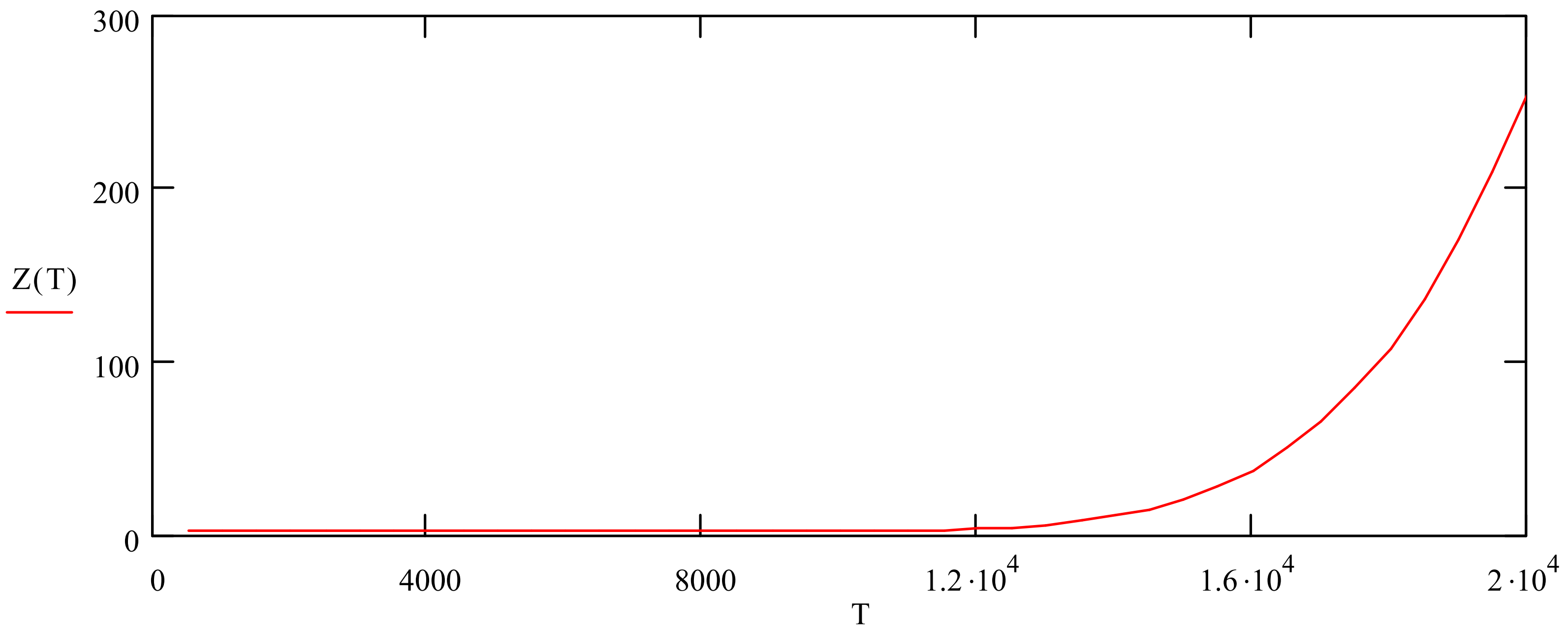
Problem 8.8

- The partition function diverges at $n \rightarrow \infty$
  - Why do we ignore large n?

Partition Function: Counting the first 100 states... Energy: $E(n) := \frac{-13.6\text{eV}}{n^2}$ Degeneracy: $g(n) := 2 \cdot n^2$

$$f_B(n,T) := \exp\left[\frac{-(E(n) - E(1))}{k \cdot T}\right] \qquad Z(T) := \sum_{n=1}^{100} \left(g(n) \cdot f_B(n,T)\right) \qquad T := 0, 500 .. 20000$$

$Z(6000K) = 2.0000$ $Z(10000K) = 2.0952$ $Z(15000K) = 20.2988$

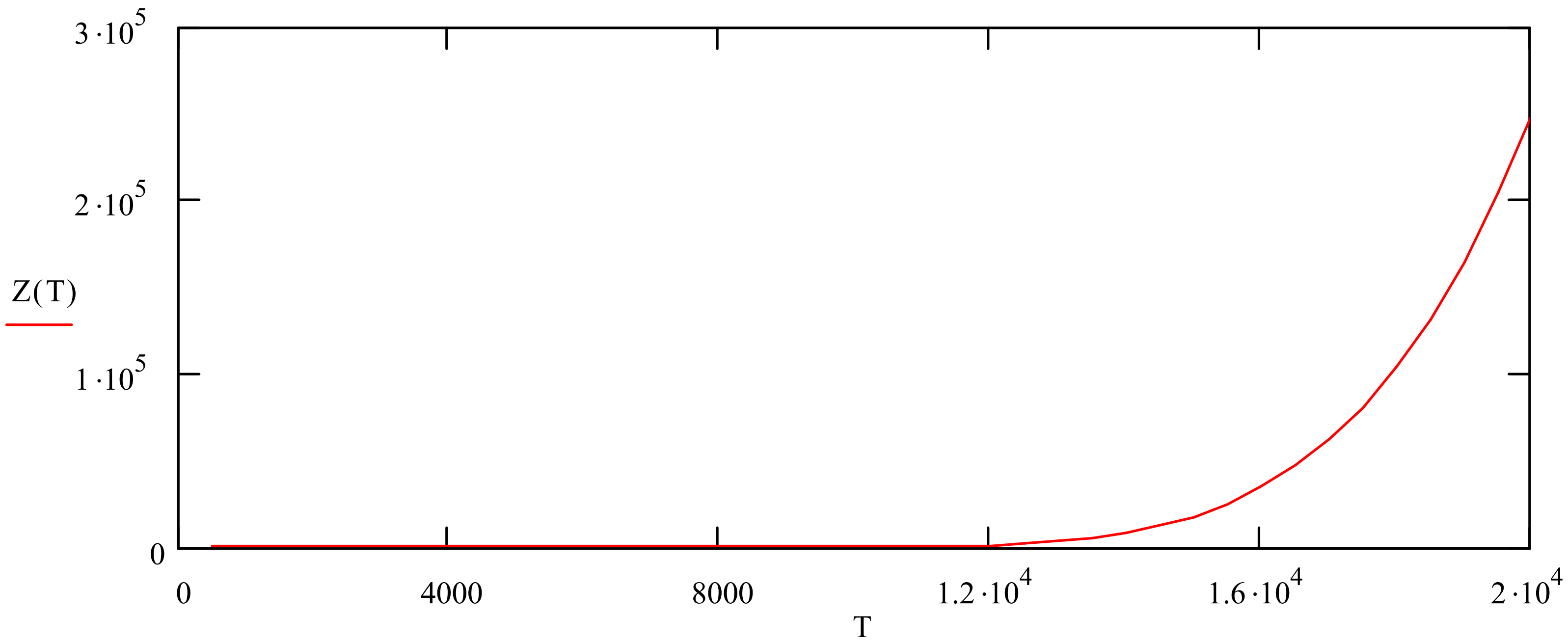


Problem 8.8

Partition Function: Counting the first 1000 states... Energy: $E(n) := \frac{-13.6\text{eV}}{n^2}$ Degeneracy: $g(n) := 2 \cdot n^2$

$$f_B(n,T) := \exp\left[\frac{-(E(n) - E(1))}{k \cdot T}\right] \qquad Z(T) := \sum_{n=1}^{1000} \left(g(n) \cdot f_B(n,T)\right) \qquad T := 0, 500 .. 20000$$

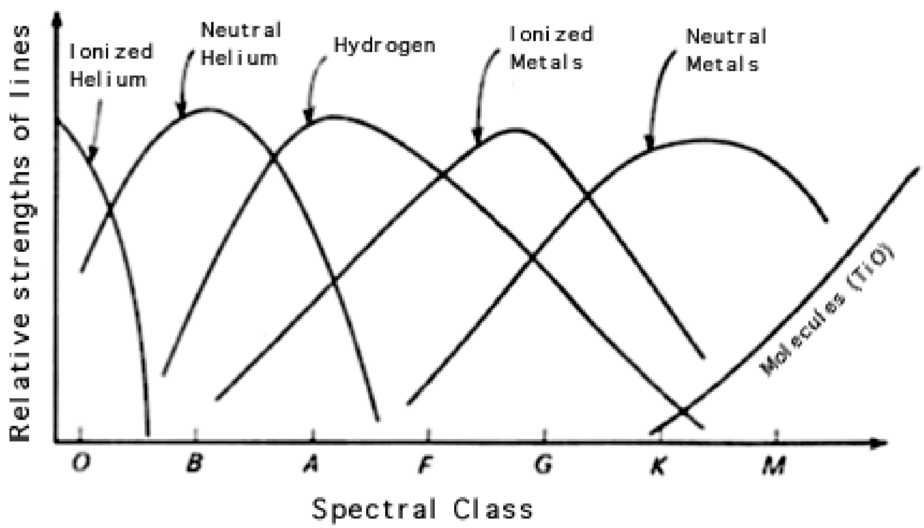
$Z(6000\text{K}) = 2.0025$ $\quad Z(10000\text{K}) = 95.4311$ $\quad Z(15000\text{K}) = 1.7998 \times 10^4$



- Ionization
- Unphysical orbital size $\quad r_n = a_o n^2$

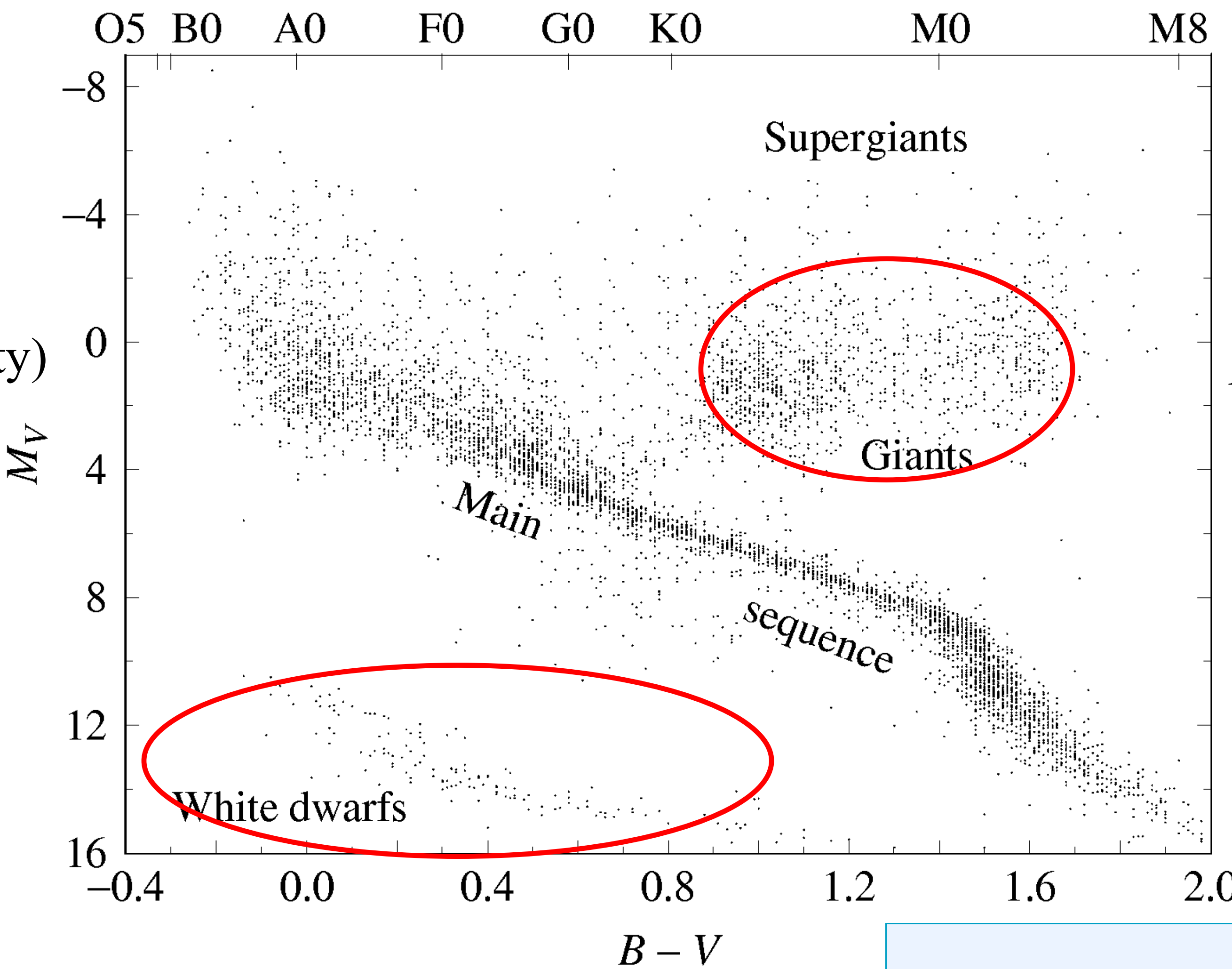
Example 8.4

- Surface of the Sun has 500,000 hydrogen atoms per calcium atom, but calcium absorption lines are much stronger than the Balmer series lines.
- The Boltzmann and Saha equations reveal that there are 400× more Ca atoms in the ground electronic state than in the *n=2* hydrogen state.
- Calcium is not more abundant
- Differences are due to sensitive temperature dependence



Hertzsprung-Russell (H-R) Diagram

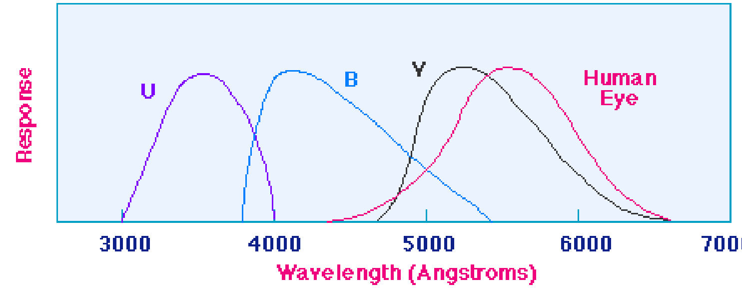
Absolute Magnitude (Luminosity)

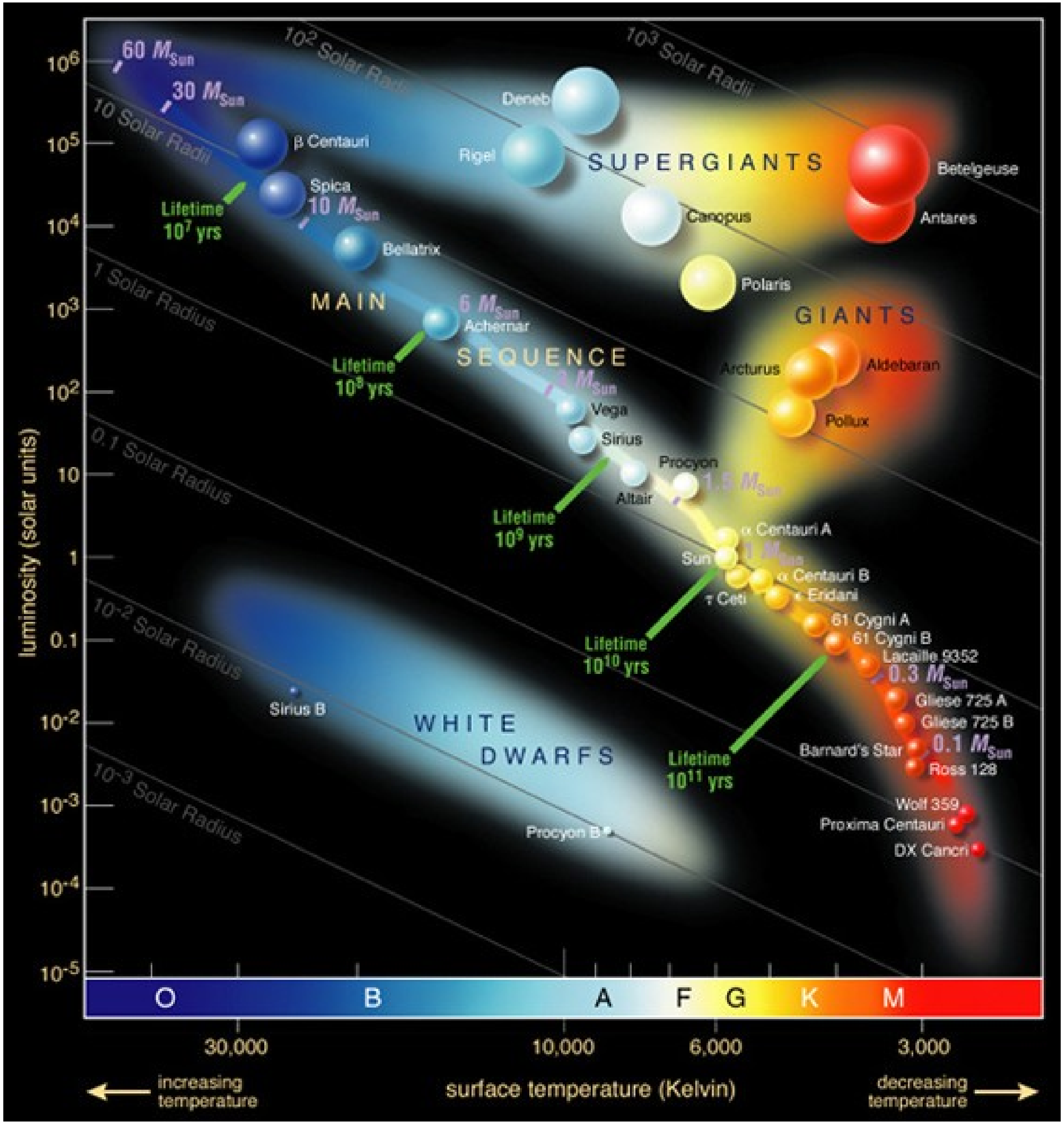


Spectral class

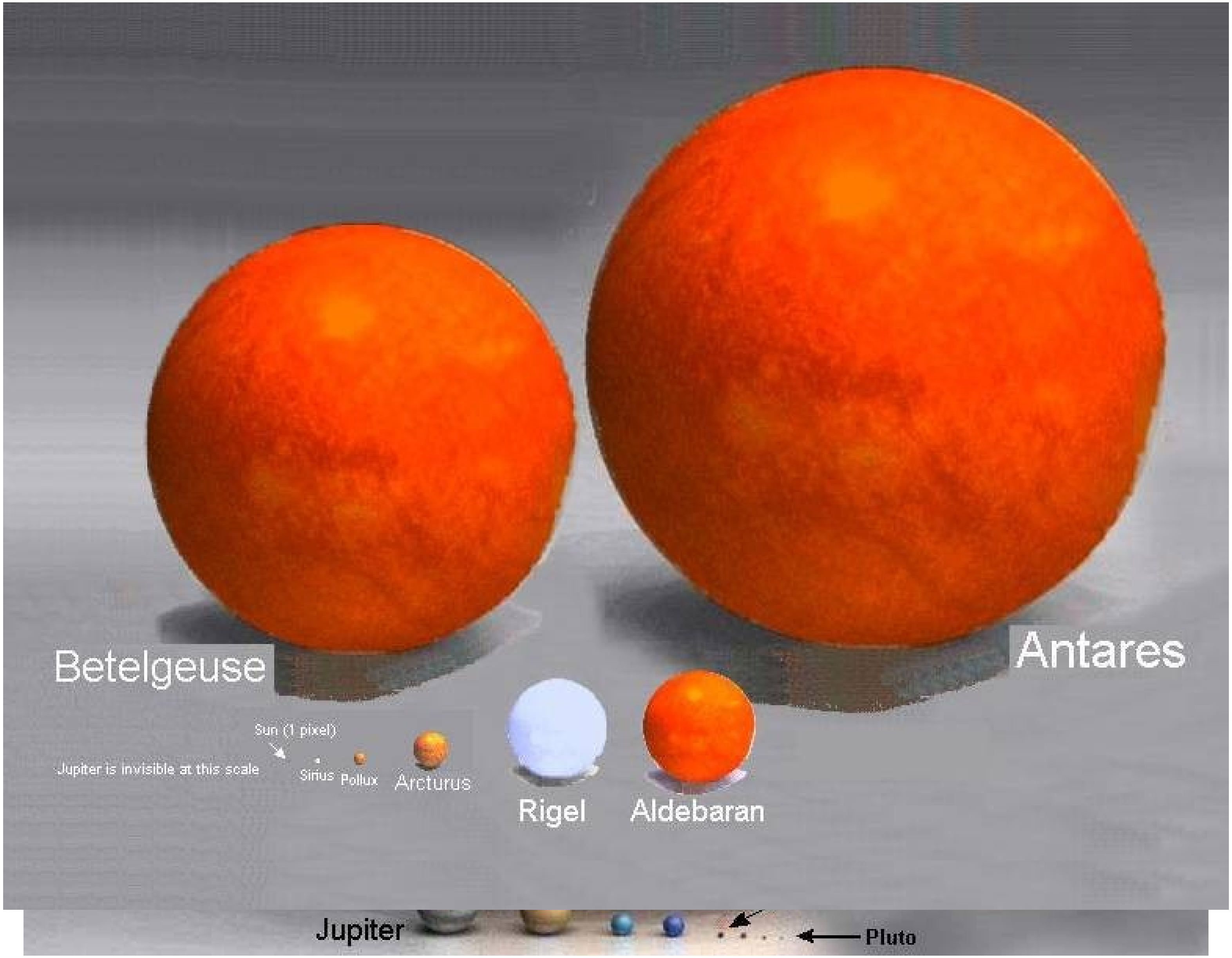
$$R = \frac{1}{T^2}\sqrt{\frac{L}{4\pi\sigma}}$$

Color index



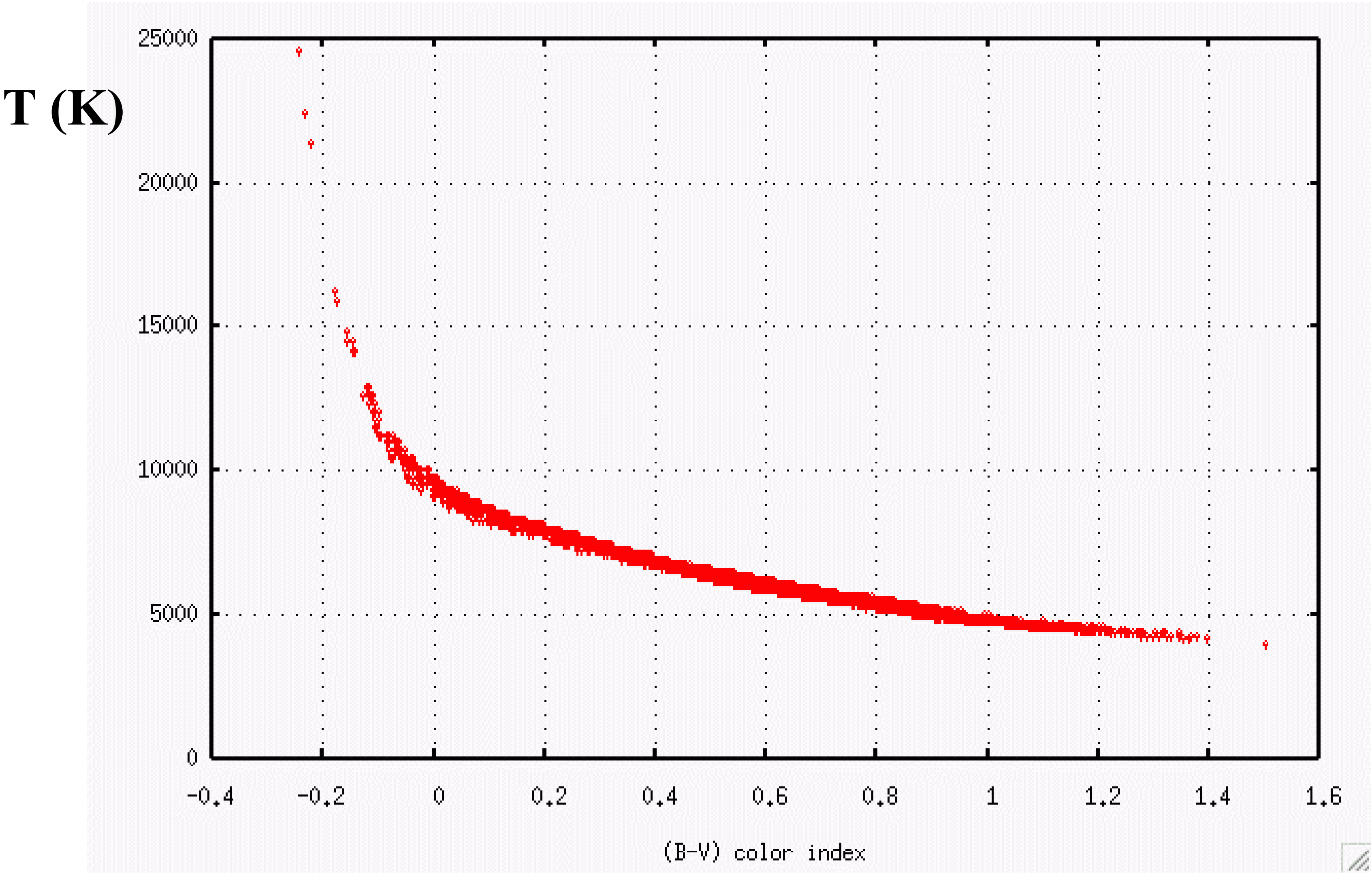


A colorful
H–R Diagram


Betelgeuse
Antares
Sun (1 pixel)
Jupiter is invisible at this scale
Sirius
Pollux
Arcturus
Rigel
Aldebaran
Jupiter
Pluto

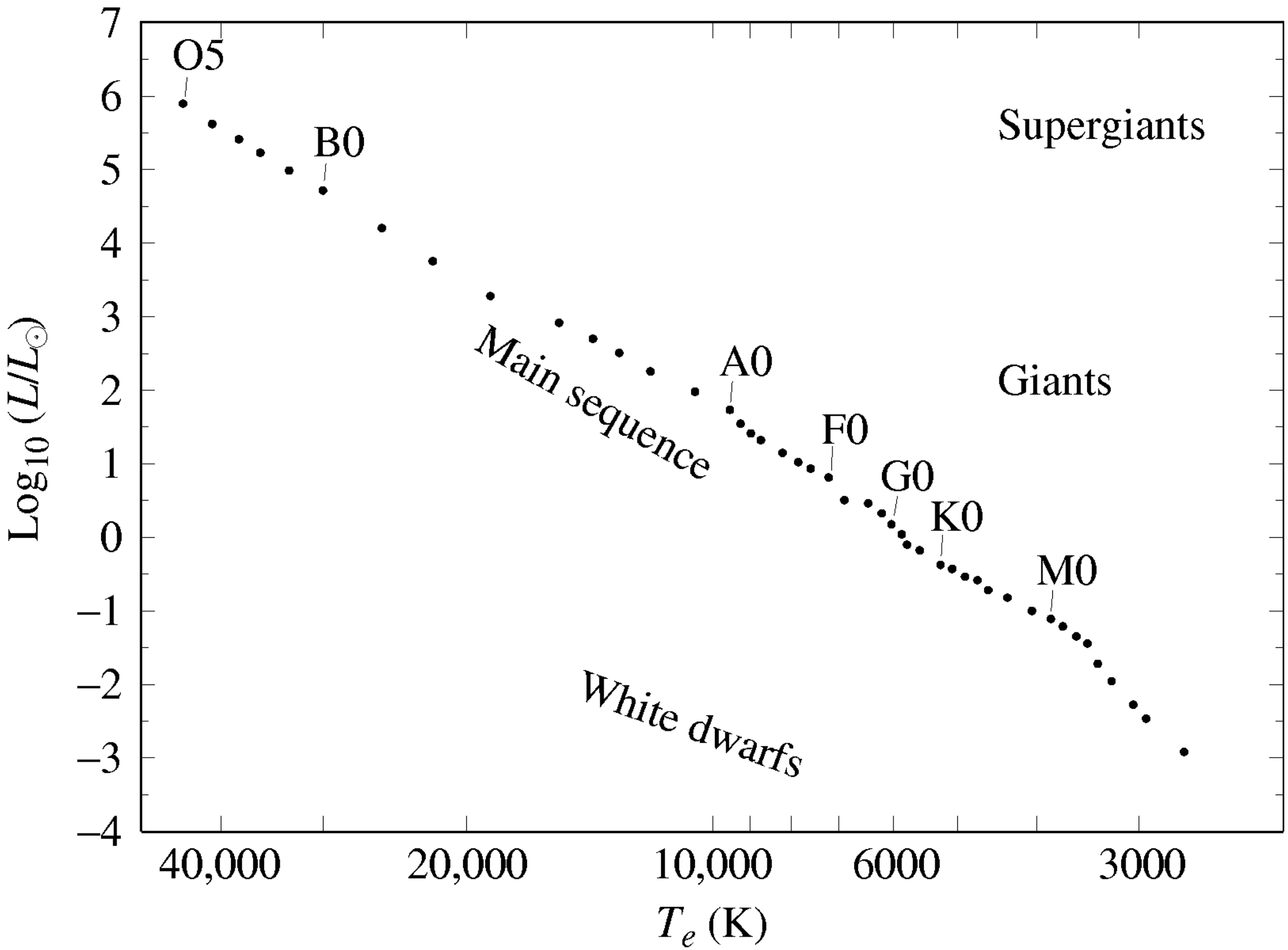
How temperature relates to color index

……………………….



Hertzsprung-Russell (H-R) Diagram

- Luminosity and Temperature rather than Magnitude and Color Index

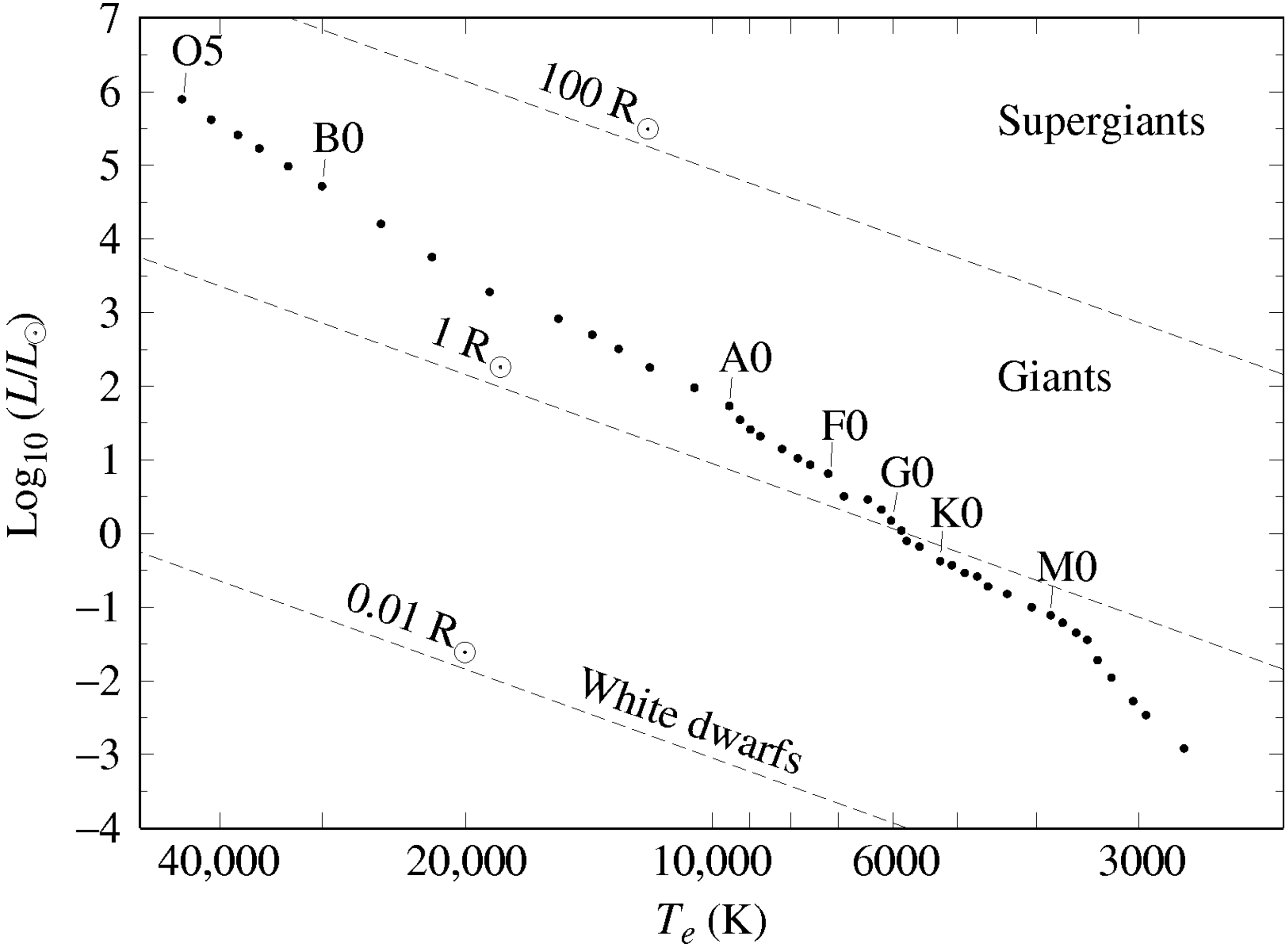


The "theorists H-R Diagram". Nuclear processes vary along MS.

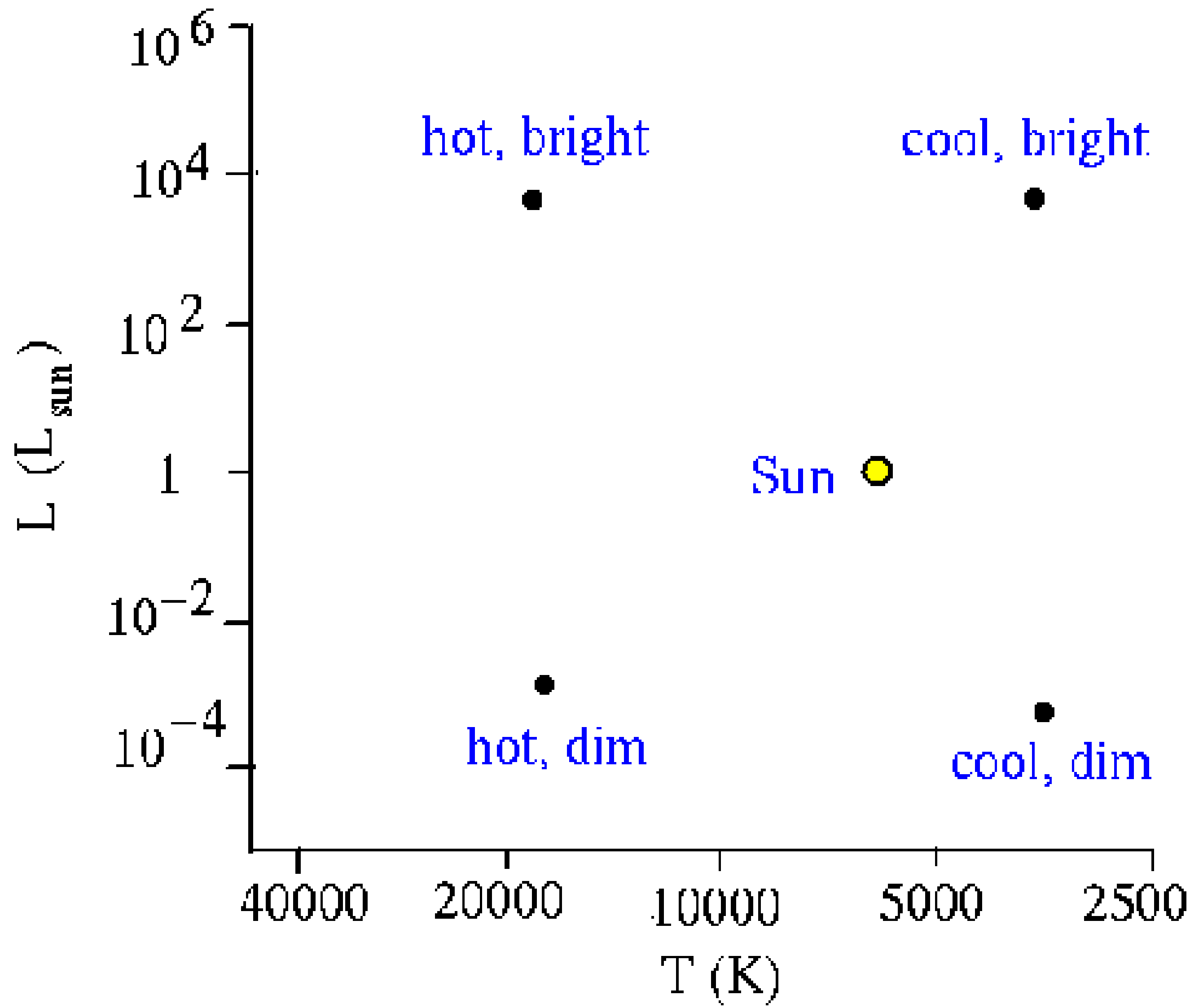
Hertzsprung-Russell (H-R) Diagram

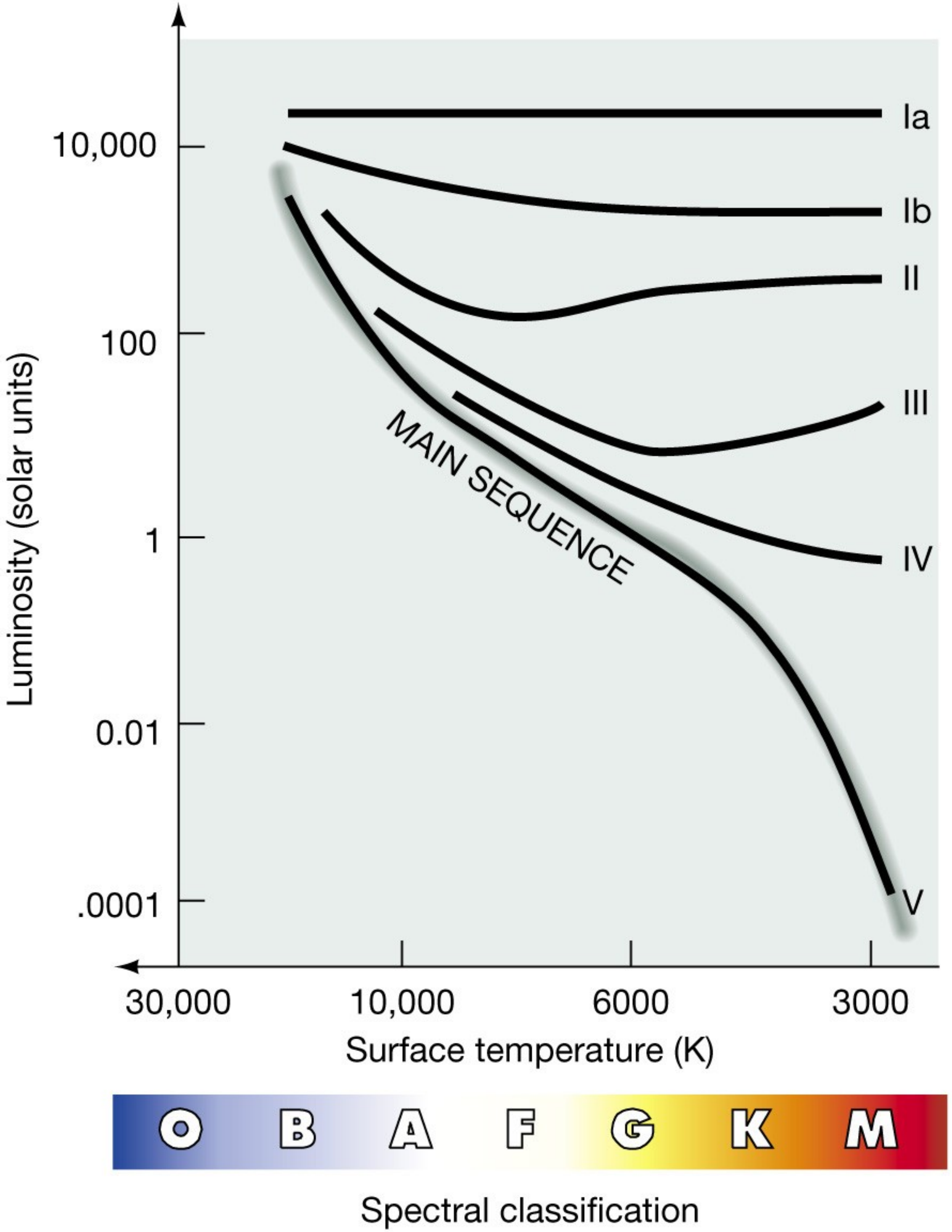
- Star Radius

$$R = \frac{1}{T^2}\sqrt{\frac{L}{4\pi\sigma}}$$



Hertzsprung-Russell (H-R) Diagram





Luminosity Classes

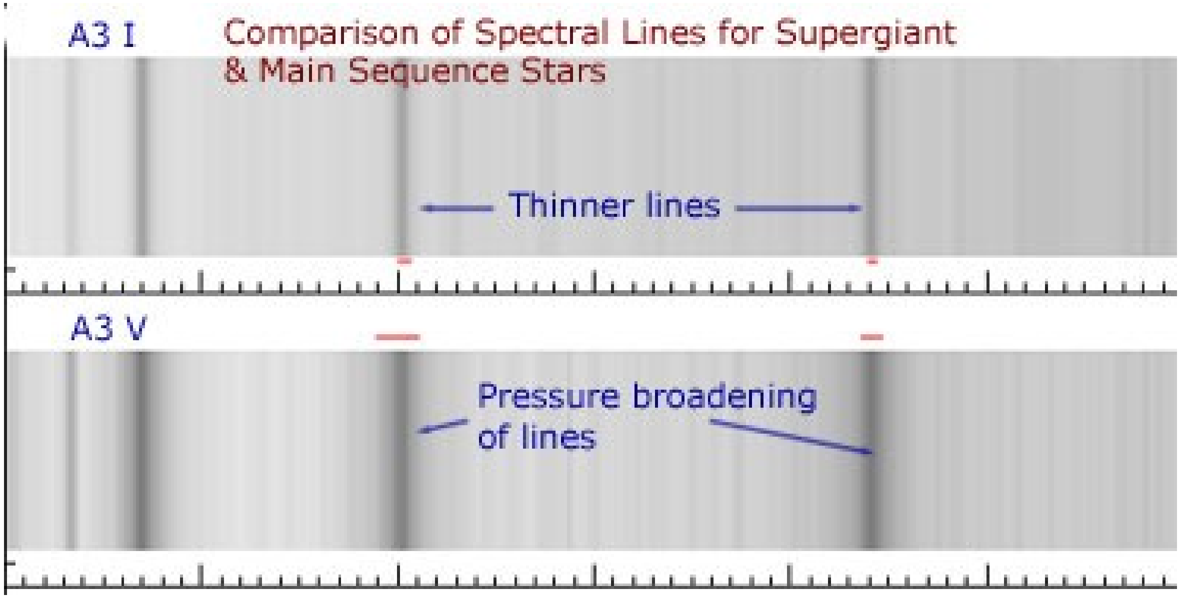
Stellar Luminosity Classes

TABLE 17.3 Stellar Luminosity Classes

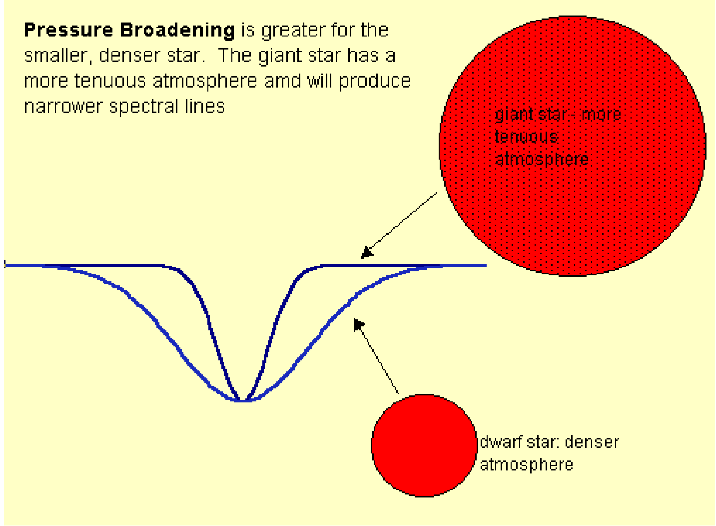
Class	Description
Ia	Bright supergiants
Ib	Supergiants
II	Bright giants
III	Giants
IV	Subgiants
V	Main-sequence stars and dwarfs

Some define VI and wd (or D)

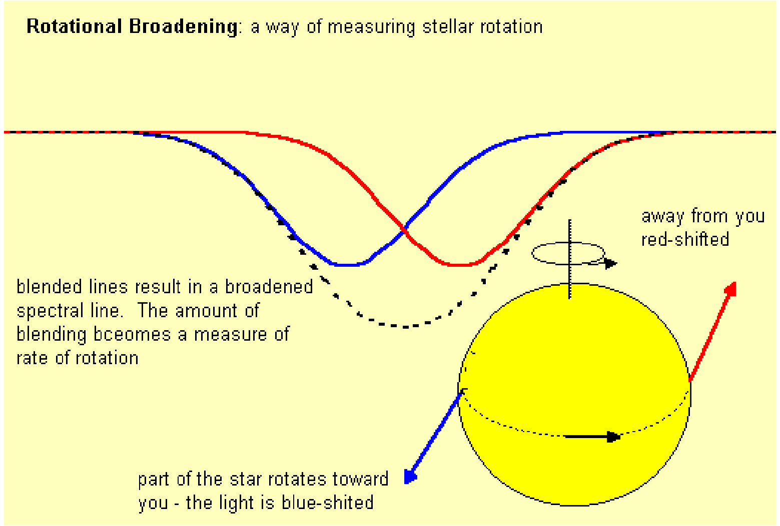
Luminosity classes can be discerned by line widths.



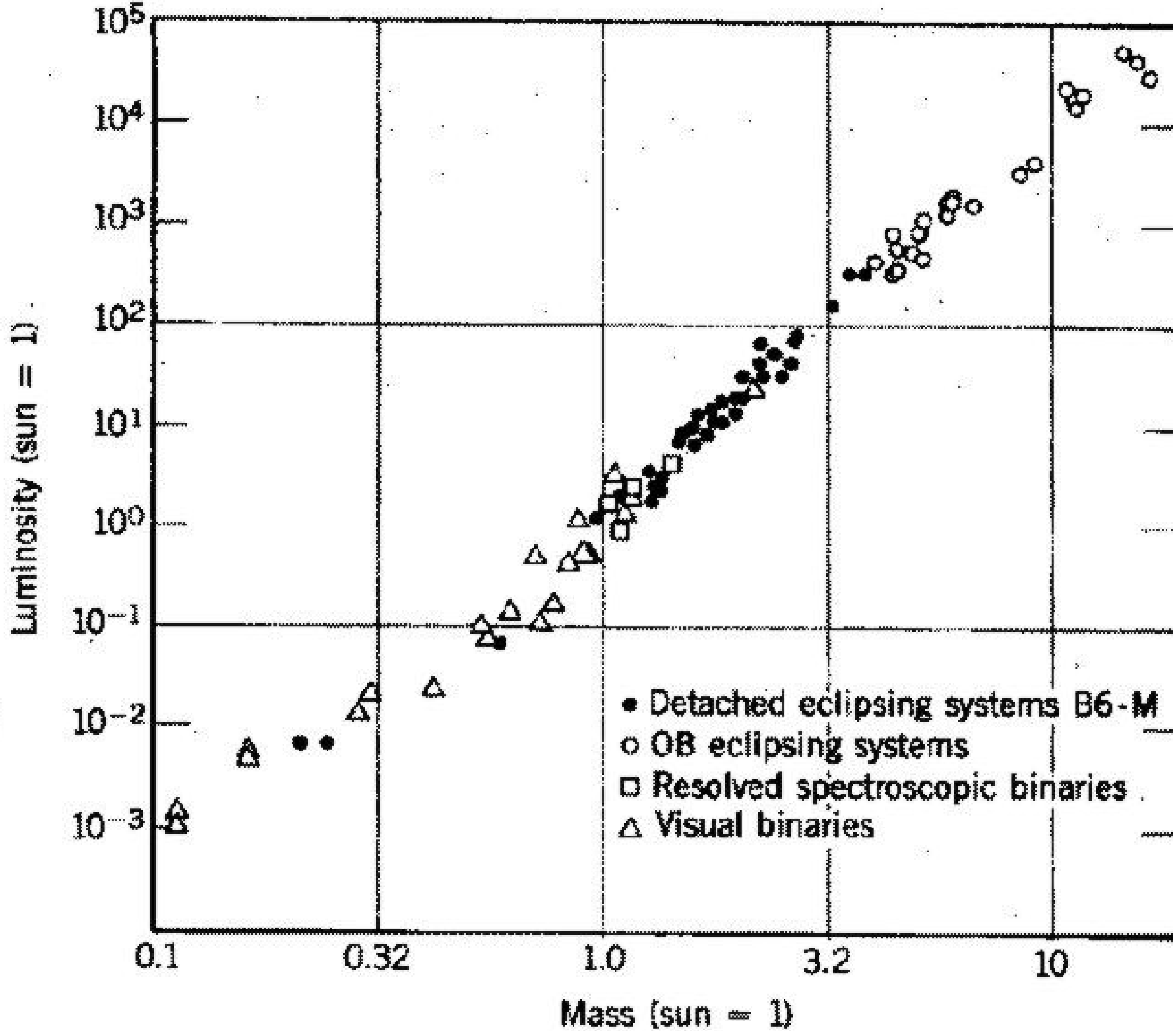
Courtesy ANU.



However,
Other processes
Can
Broaden lines...



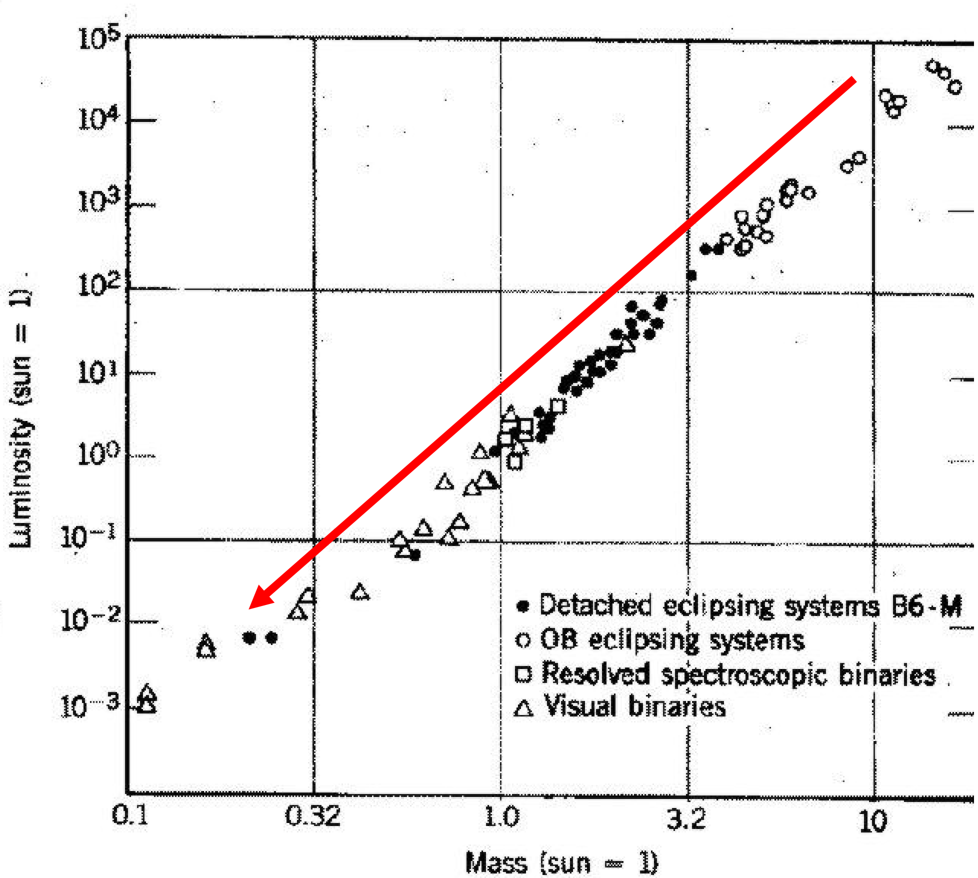
Mass-Luminosity Relation from Binary Systems



The mass – luminosity relation for stars, as determined from binary systems, in which the individual masses can be found.

Mass-Luminosity Relation

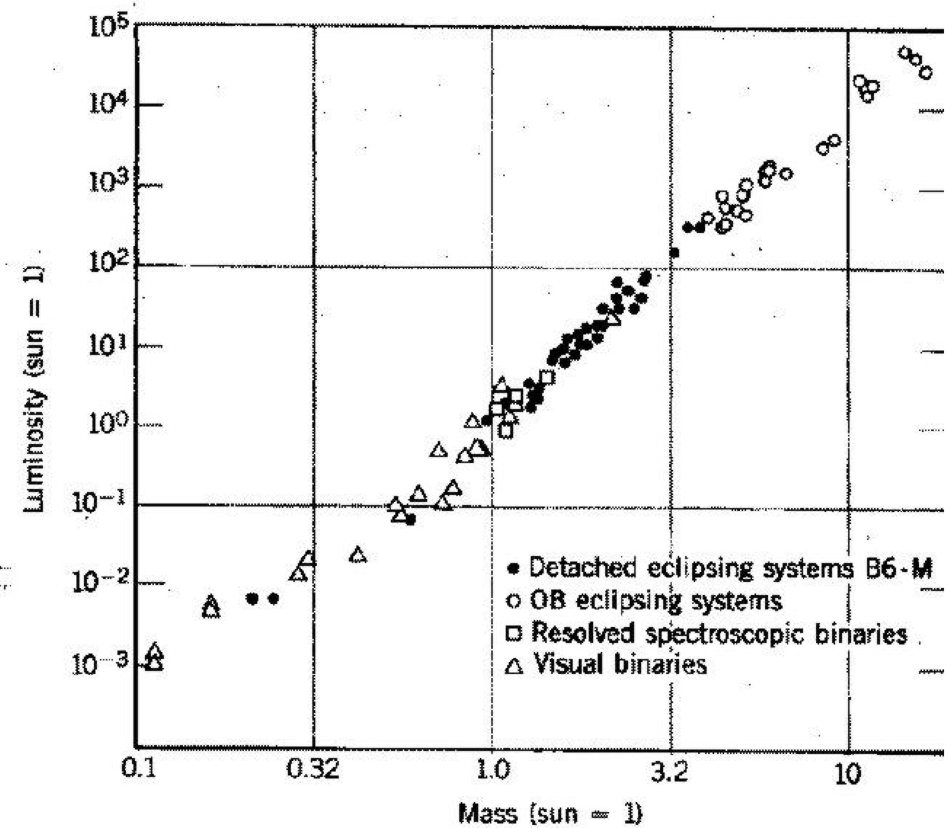
- Early theories had “early” O-type (bright, hot, massive) stars evolving to “old” M-type stars (dim, cool, less massive)



The mass–luminosity relation for stars, as determined from binary systems, in which the individual masses can be found.

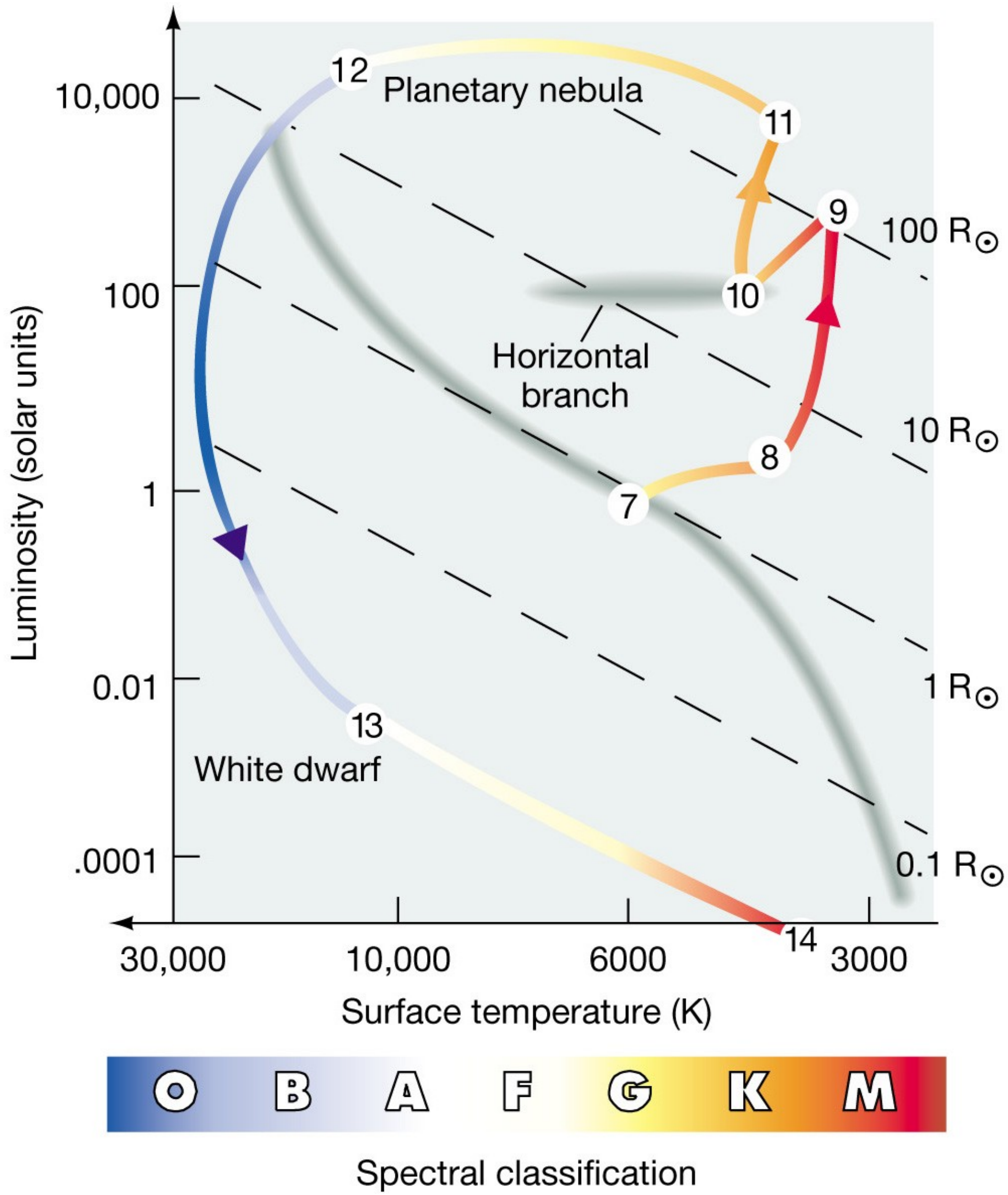
Mass-Luminosity Relation

- Luminosity (power output) comes from nuclear fusion at the core of the stars.
- L increases dramatically with M: $L \sim M^{3.5}$ (from M-L relation)
- From this, we can derive a lifetime for stars on the Main Seq.:
  - Lifetime = Fuel/(Rate of burning fuel)
  - Lifetime = M/L
  - Lifetime = $M/M^{3.5} = M^{-2.5}$
- Actually, $L \sim M^4$ for M>1, so
- Lifetime $\sim M^{-3}$

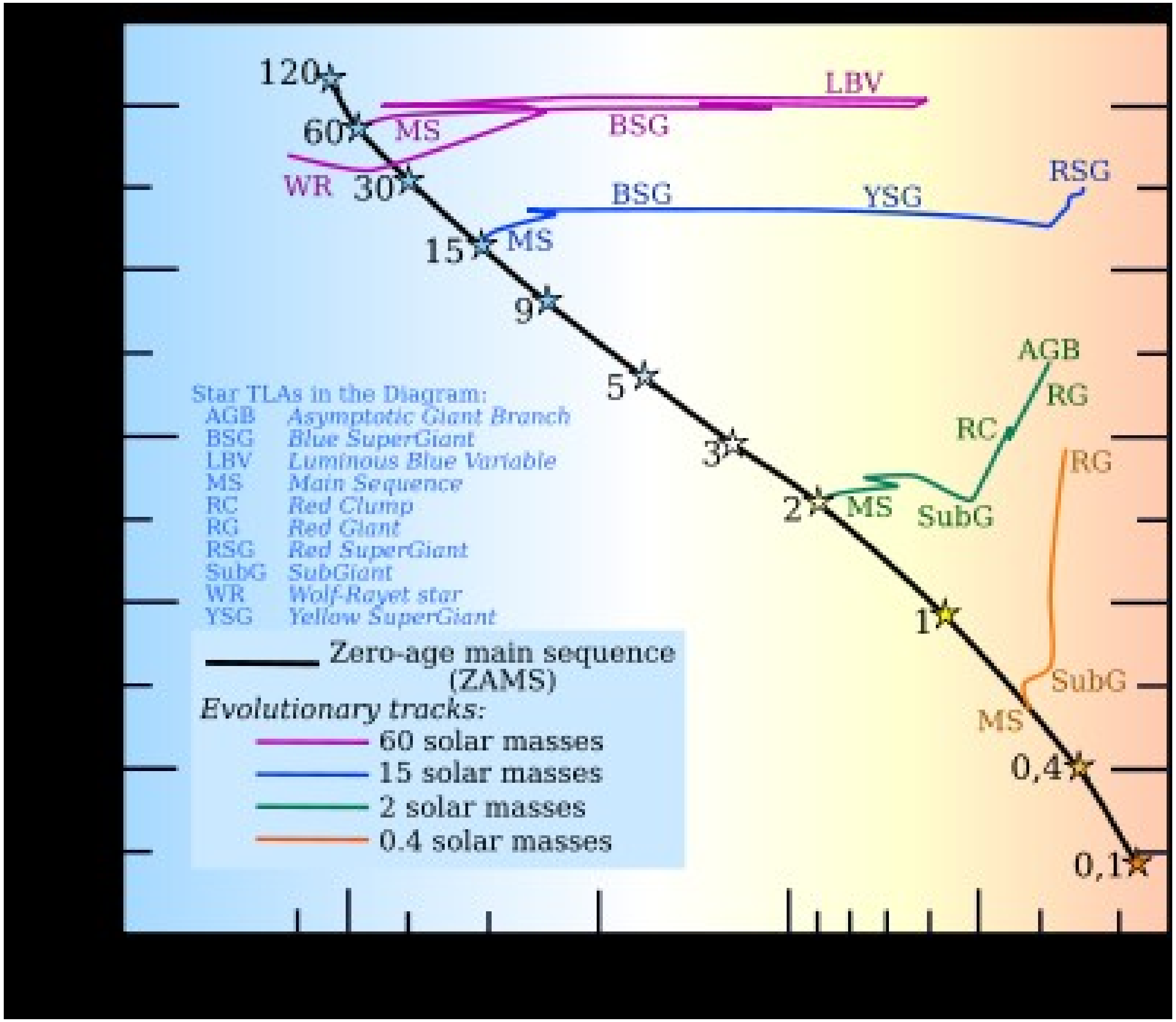


The mass-luminosity relation for stars, as determined from binary systems in which the individual masses can be found.

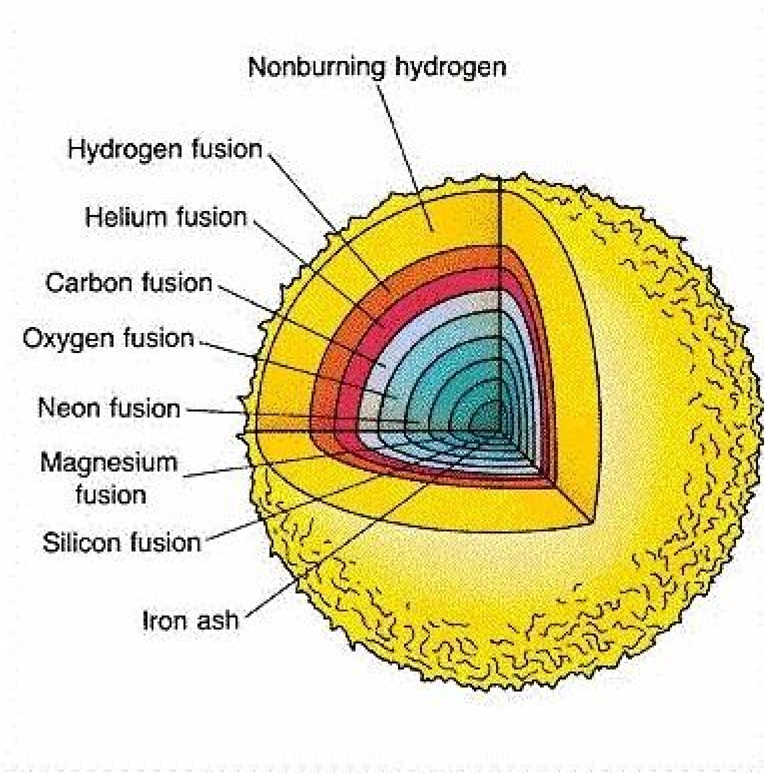
Evolution of 1 $M_\odot$ star.

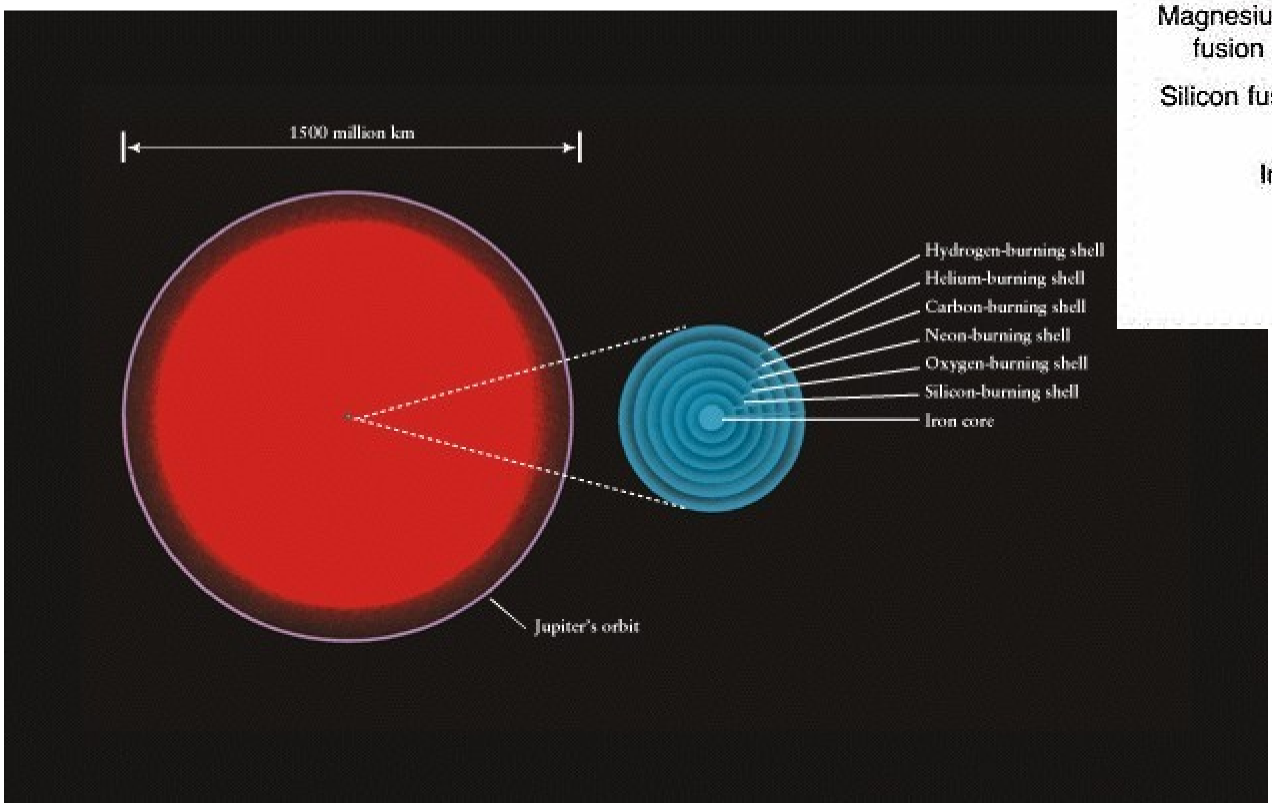


Evolutionary tracks.

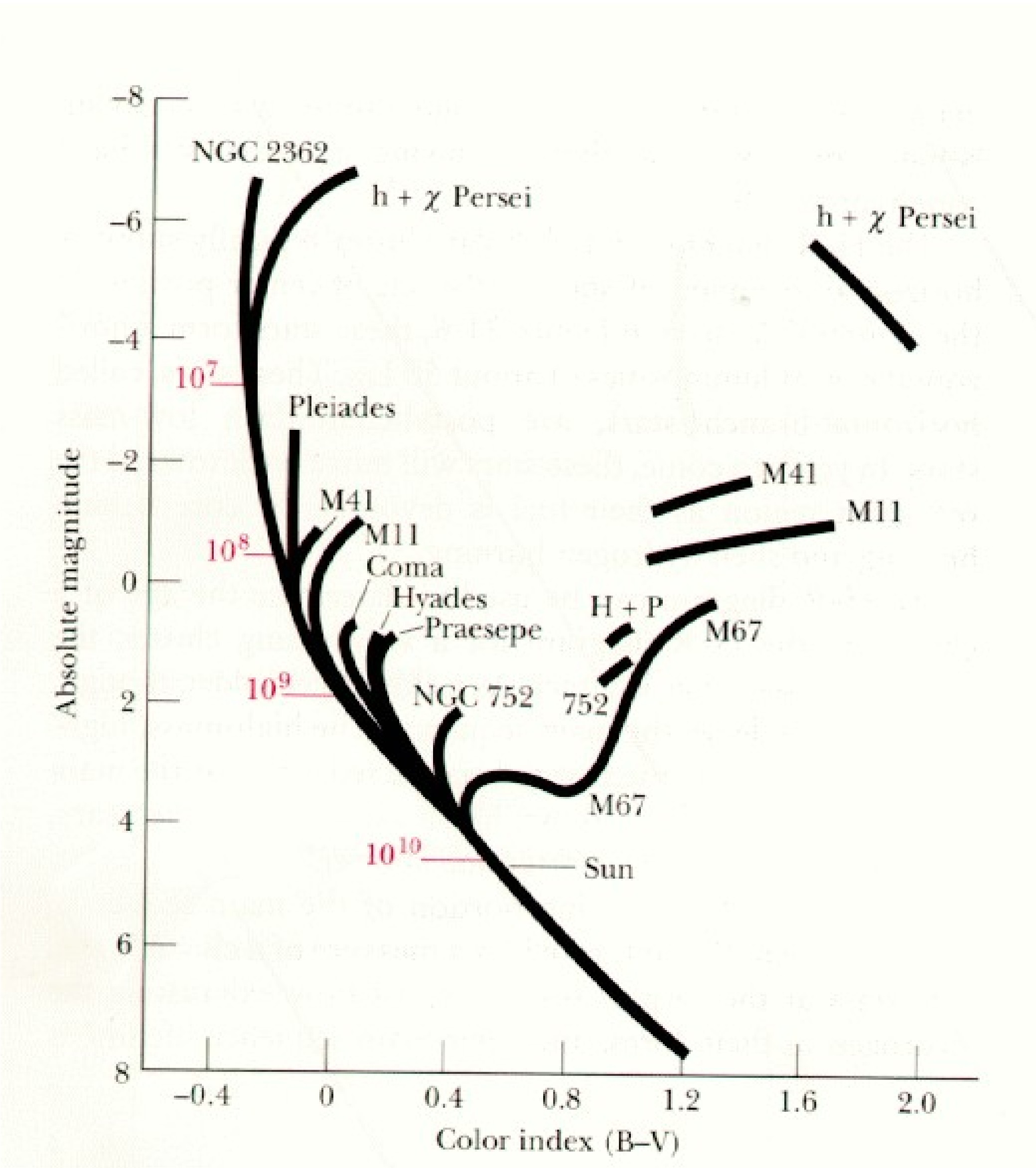


Massive star fusion





HR Diagrams of star clusters.



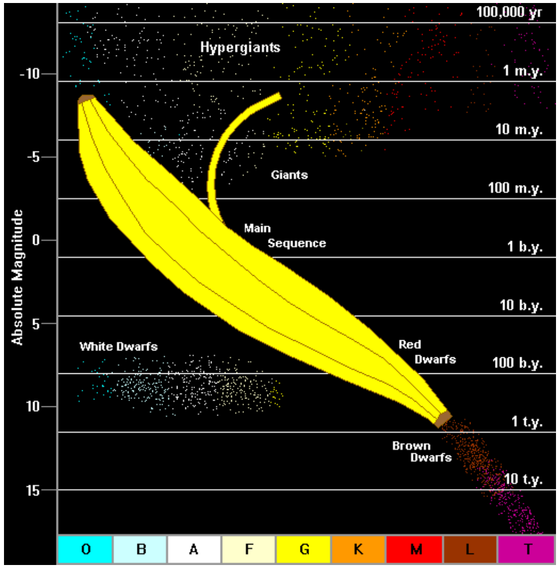
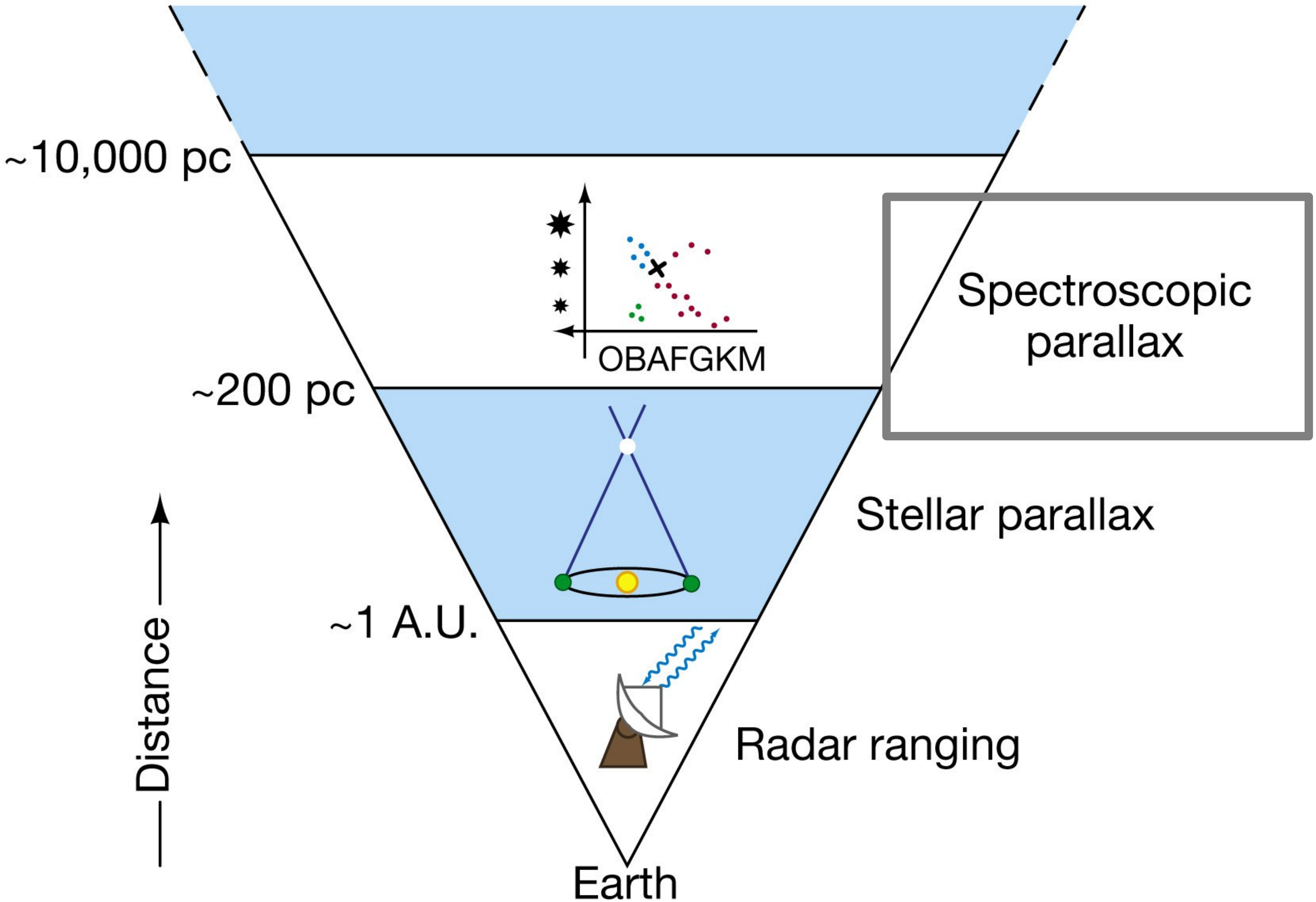


Figure 17-17
Stellar Distances



Spectroscopic "Parallax"

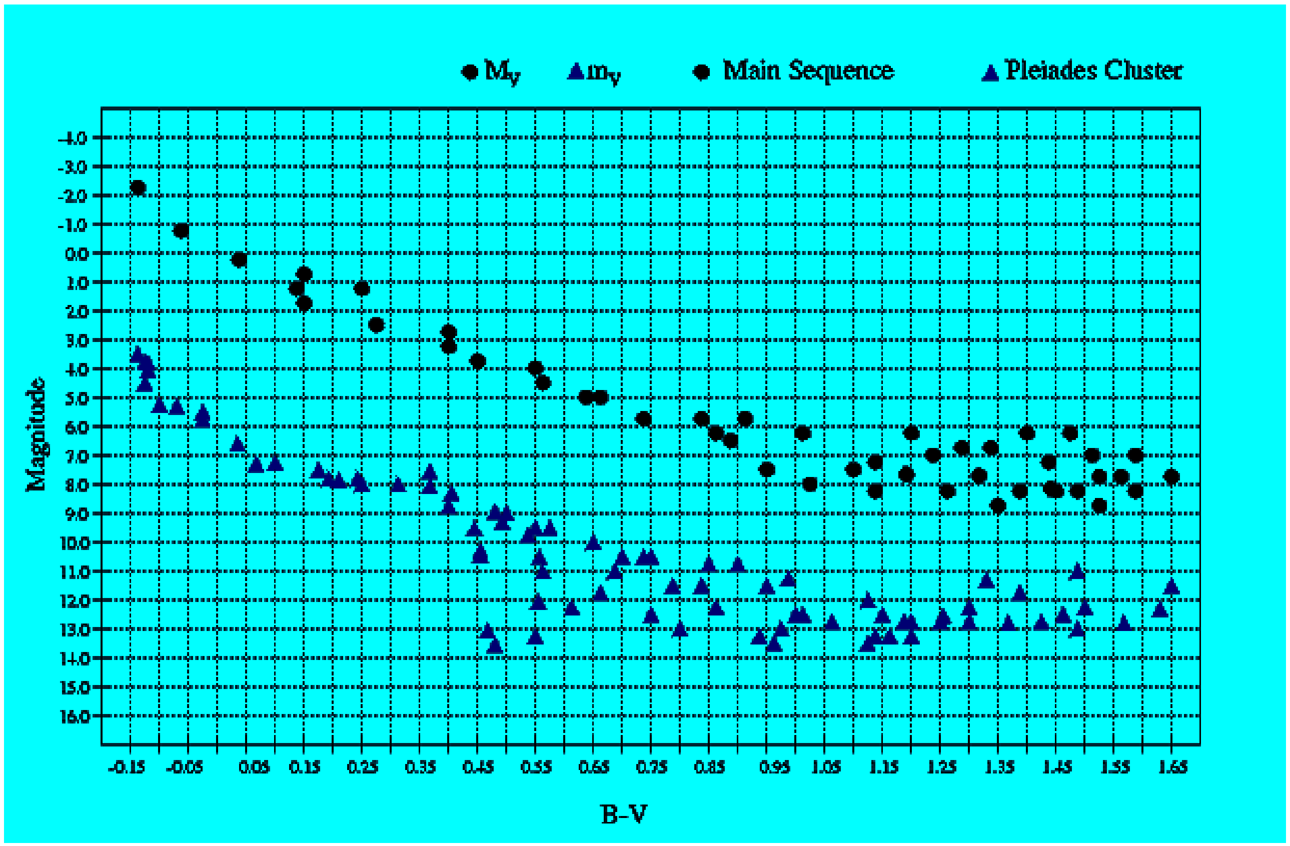
- Method to determine a stars distance
  - Determine the spectral class and luminosity class.
  - Measure apparent magnitude.
    - Correct for crowding
    - Correct for extinction
  - Read the absolute magnitude from the H-R diagram
  - Compare to apparent magnitude to determine distance: $d=10^{(m-M-A+5)/5}$

Stellar and Spectroscopic Parallax

<u>Stellar Parallax</u> works out to 200pc (ground), 1000 pc (Hipparcos)

<u>Spectroscopic Parallax</u> works for stars for which a good spectrum can be observed (about 8 kpc), but ...

- **Not precise for individual stars, especially giants**
- **Entire clusters of stars works better! ("main-sequence fitting")**



m-M=5log(d/10)

Spec Parallax assumes, for example, that all A0V stars have the same M.
That makes A0V stars "standard candles".