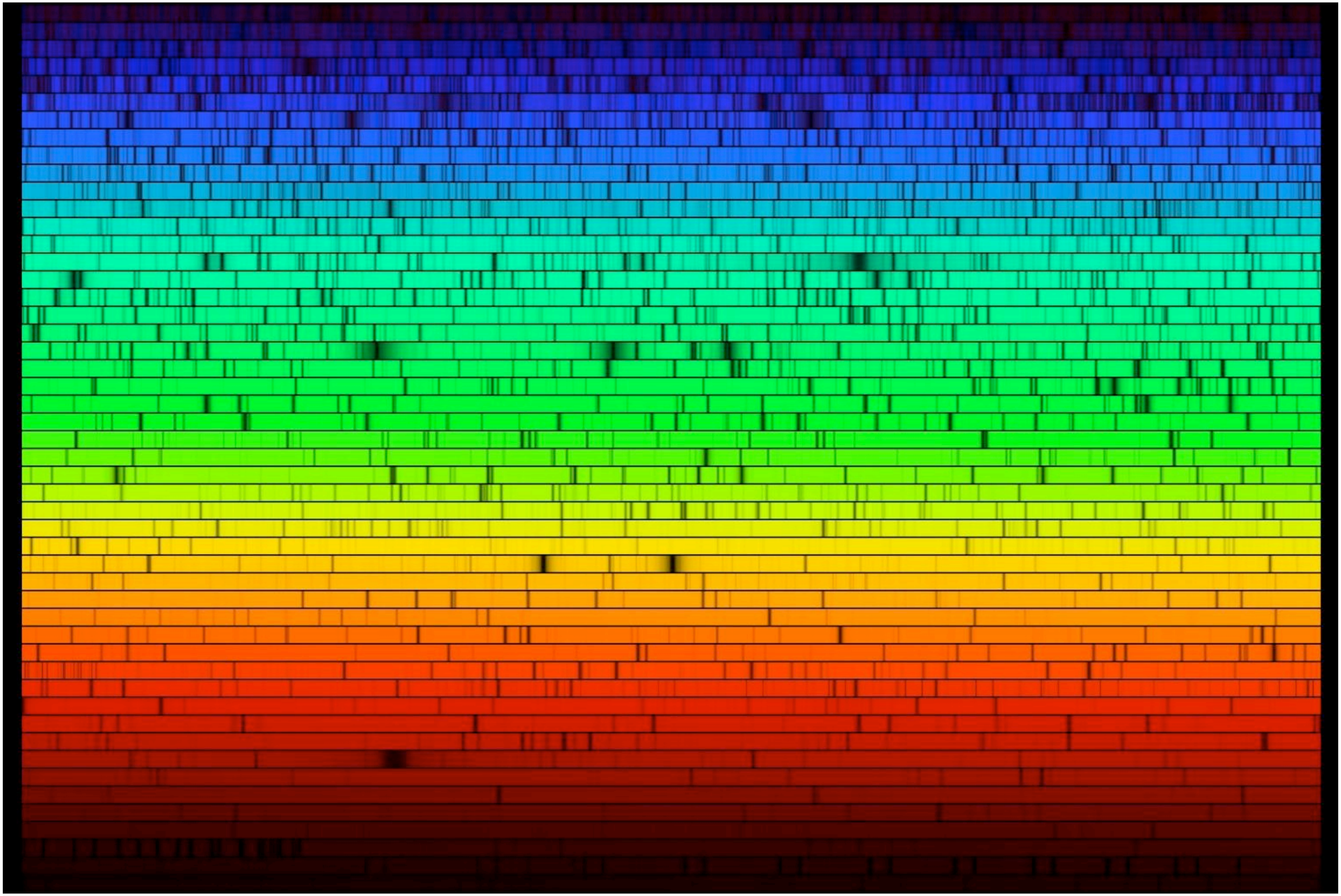
The classification of stellar spectra



Outline

1. What do stellar spectra look like?
2. The classification of stellar spectra
3. Physics of spectral lines: excitation balance (Boltzmann equation) and ionization balance (Saha equation)
4. The Hertzsprung-Russell diagram

Spectral types

- Astronomers classify stars based on the relative strengths of their absorption lines
- Spectral sequence: O B A F G K M L T
  - ➢ type A has the strongest H lines
- Each *spectral type* is further divided into 10 subclasses

  e.g. A0, A1, A2, … , A9, F0, F1, …

Spectral classification of stars

Stars show various patterns of absorption lines:

- some have strong Balmer lines (Hydrogen, the n_{low}=2 series), but some don't (e.g., the Sun)

- some show strong lines of Ca, Fe, Na

- some show lines from molecules such as TiO, MgH

Notation:

- neutral element: H I, He I, Fe I, etc.

- single-ionized element: H II, O II, etc.

- double-ionized element: O III, etc.

Some history…

at this time, the energy-level structure of atoms was not known.

Balmer

"Henry Draper Catalogue", published by astronomers at the Harvard College Observatory. It listed 225,300 stars.

The classification sequence included 7 categories named with letters: O,B,A,F,G,K,M. The sequence is solely based on the progression of line patterns in the spectra (A. Maury). Many of the original classes from A through O were dropped, and the order was changed! See later why…

A.J. Cannon refined the sequence into subclasses (e.g., from G0 to G9).

How to remember the Spectral Type sequence?

Sun: G2

Early-type — Late-type

O … B … A … F … G … K … M

Subclasses: e.g. A0, A1, A2….A9

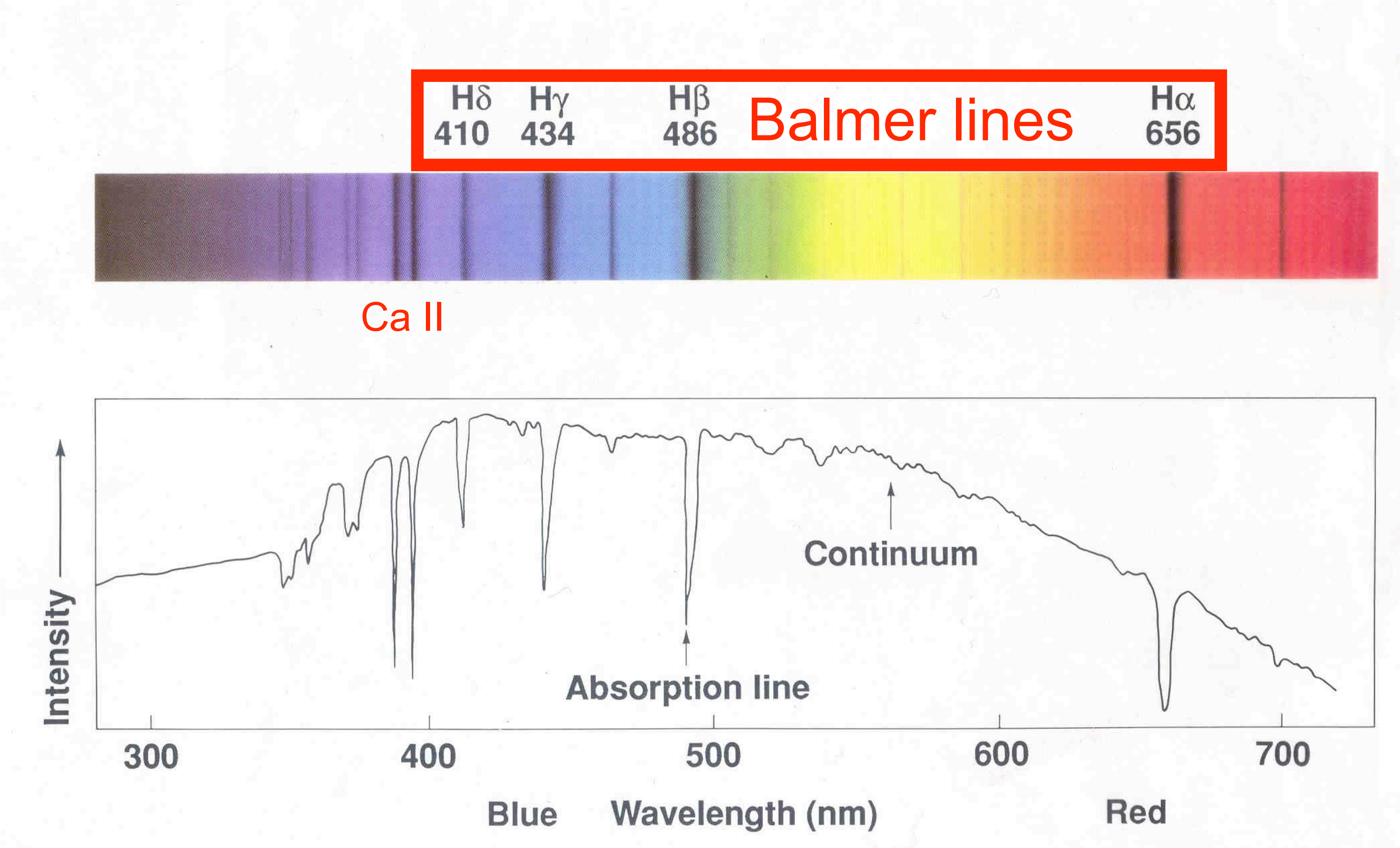
{**Oh…Be…A…Fine…Girl…Kiss…Me**}

{**Oh…Be…A…Fine…Guy…Kiss…Me**}

{**Oh… Boy… An … F …Grade … Kills … Me!**}

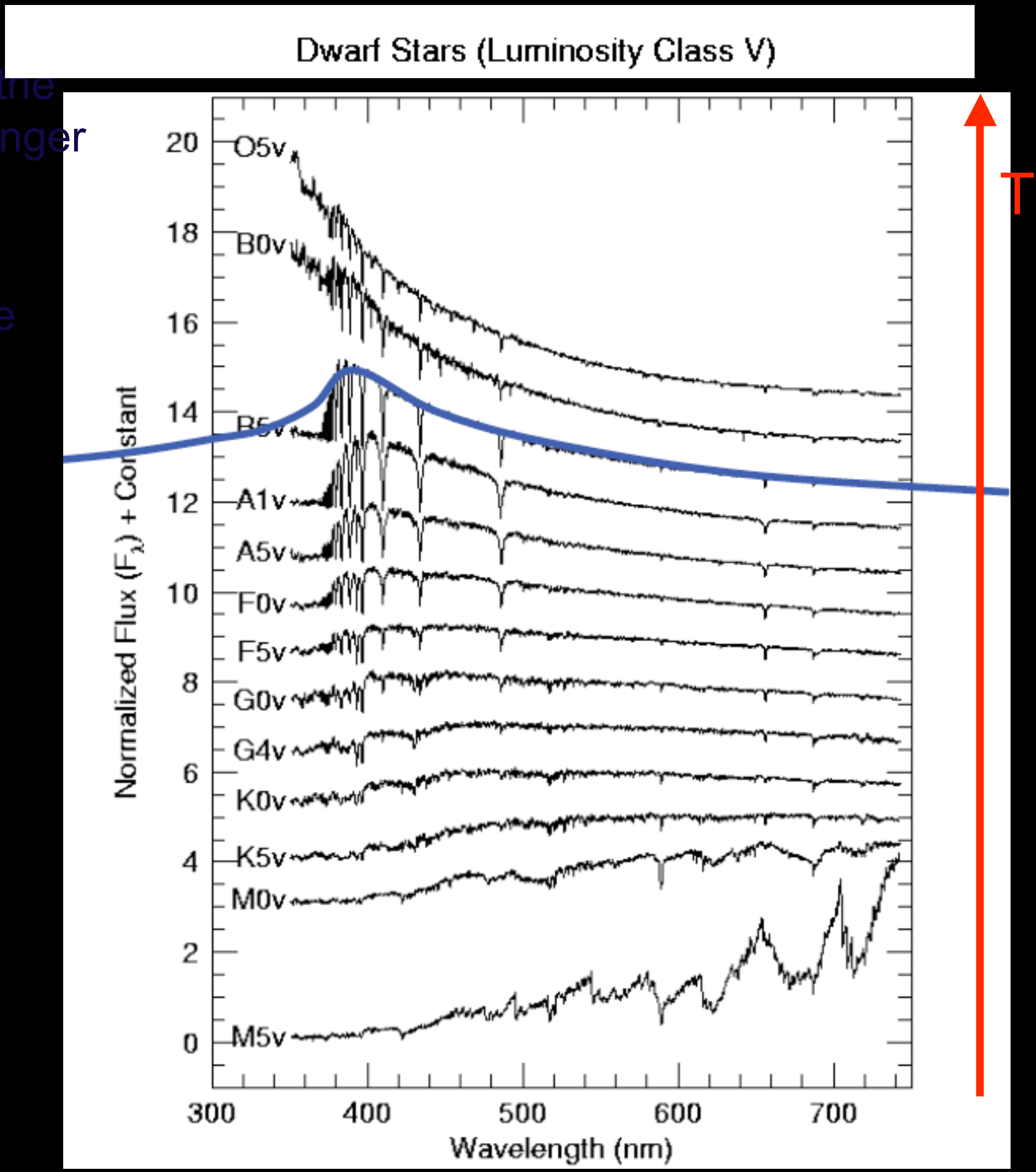
Stellar spectra

Blackbody continuum spectrum by the star's interior (hot dense gas) + a set of absorption lines given by the stellar atmosphere (cooler, low density gas).



• With decreasing temperature, the continuum (BB) peak shifts to longer wavelengths (Wien's law)

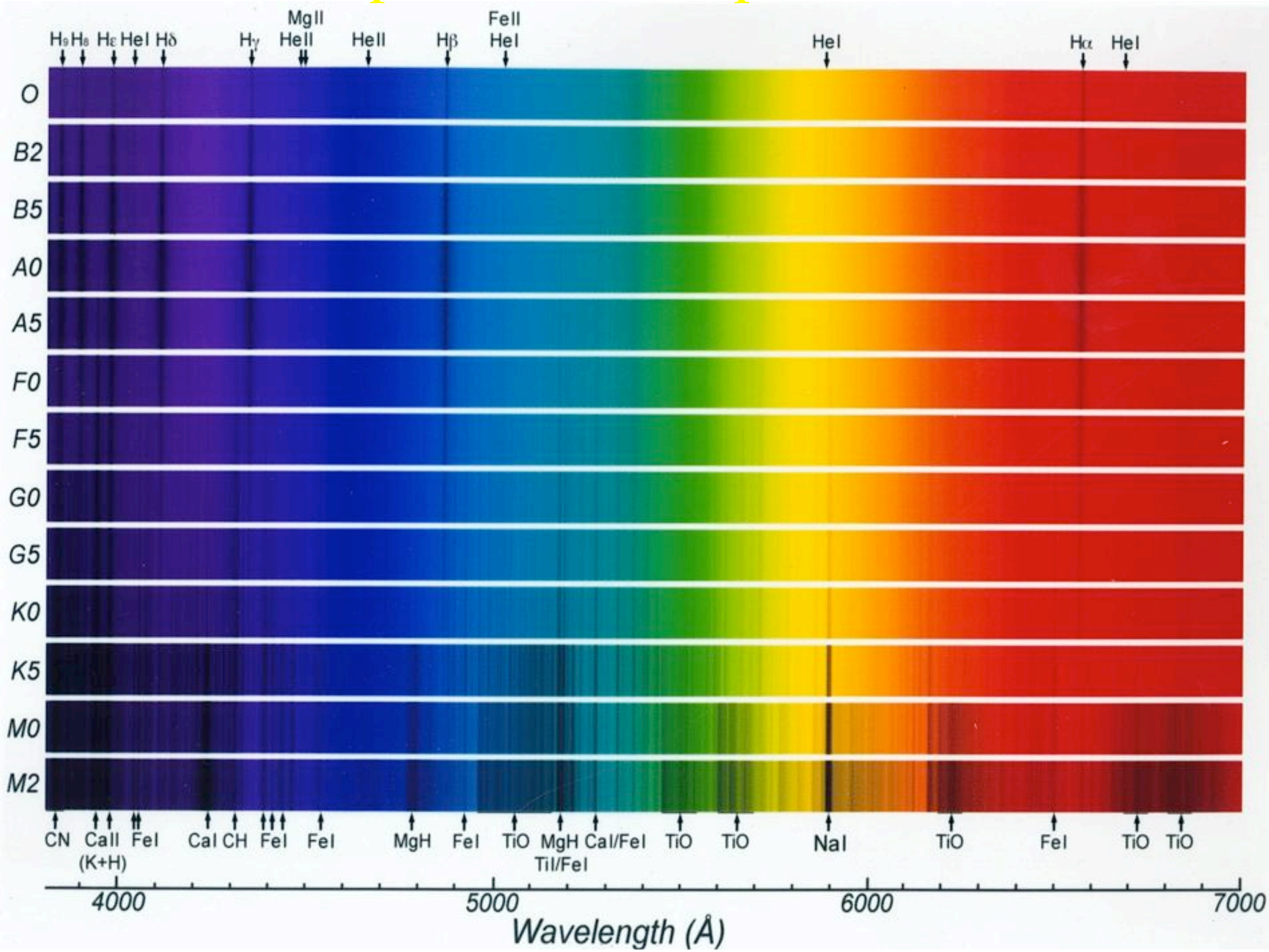
• Since all stars have roughly the same composition, line strength traces mostly the photospheric temperature



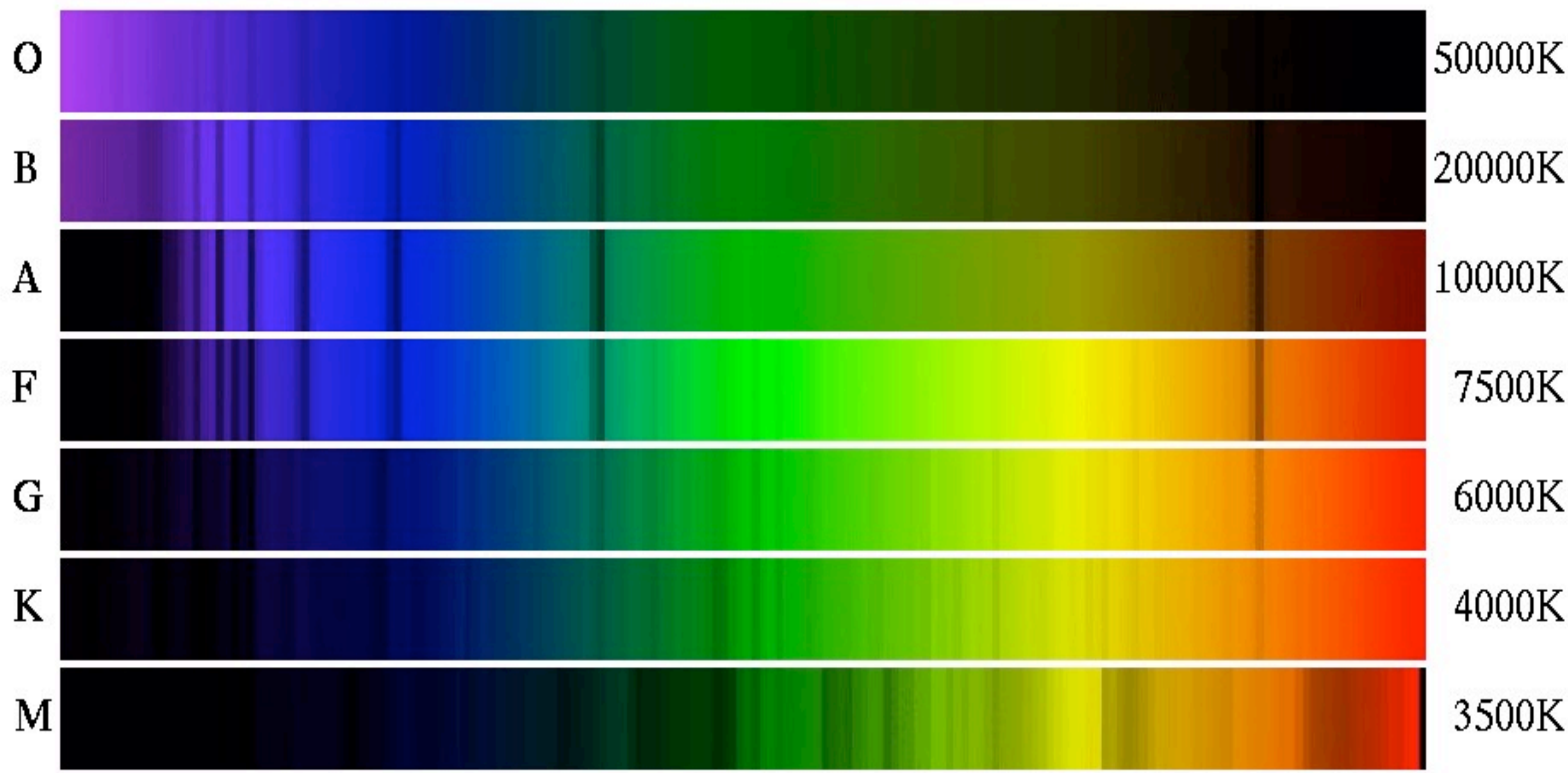
…or, two ways to probe the stellar surface T…

BUT, WHICH ARE THE PHYSICAL PRINCIPLES?

Examples of stellar spectra



Spectral Type or *Color* Indicates *Temperature*



Spectral classification of stars

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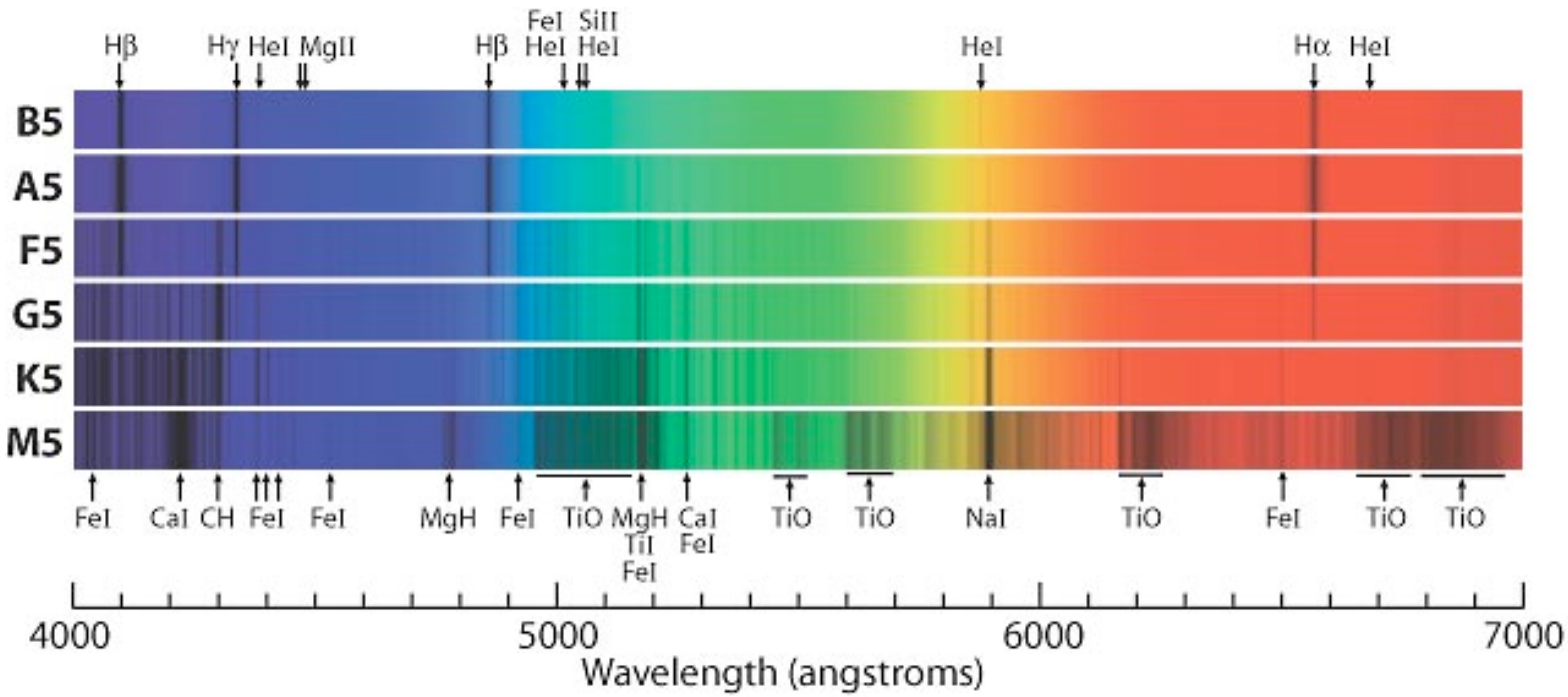
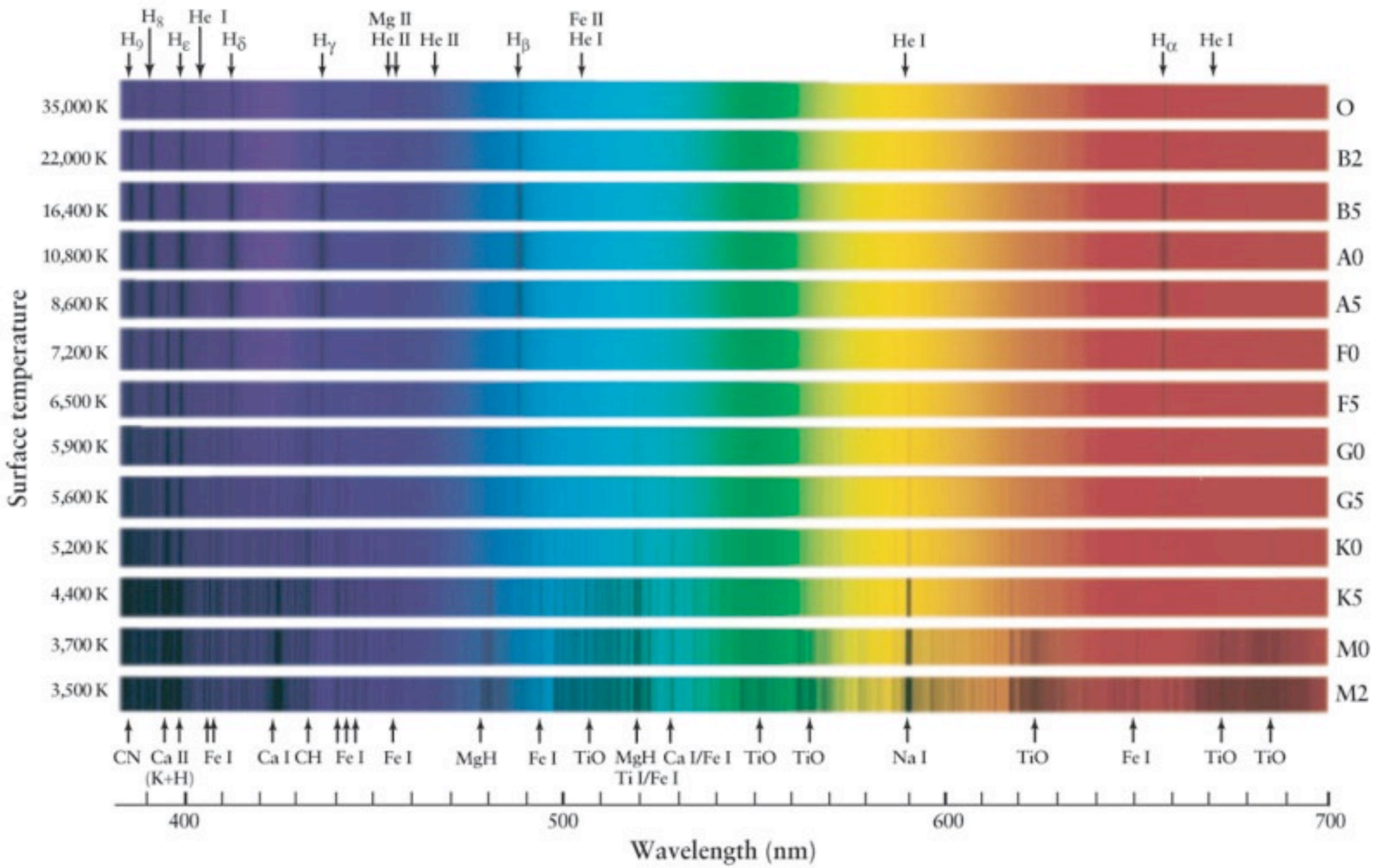


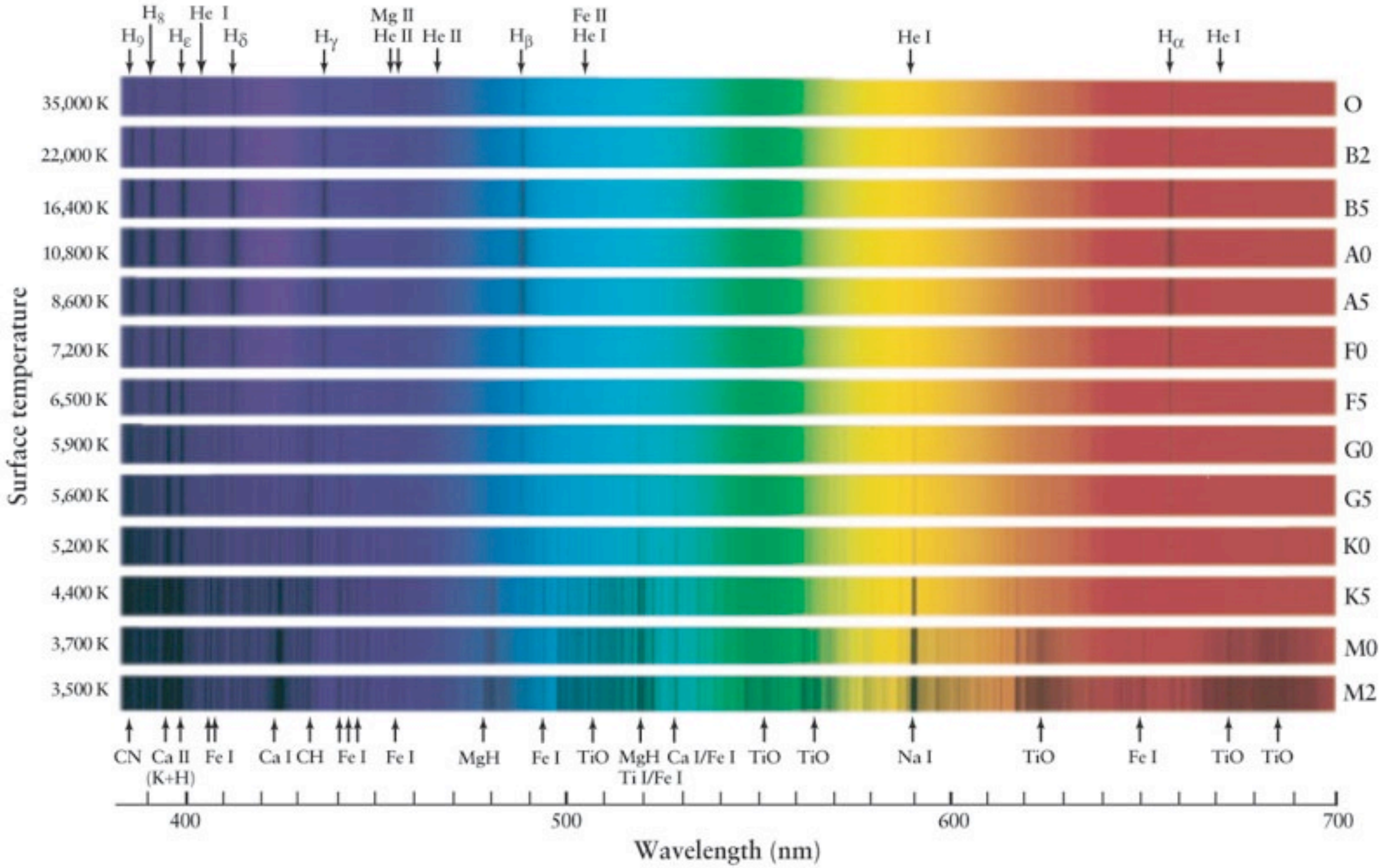
Line strength vs spectral type

He I lines: strongest in B2 stars



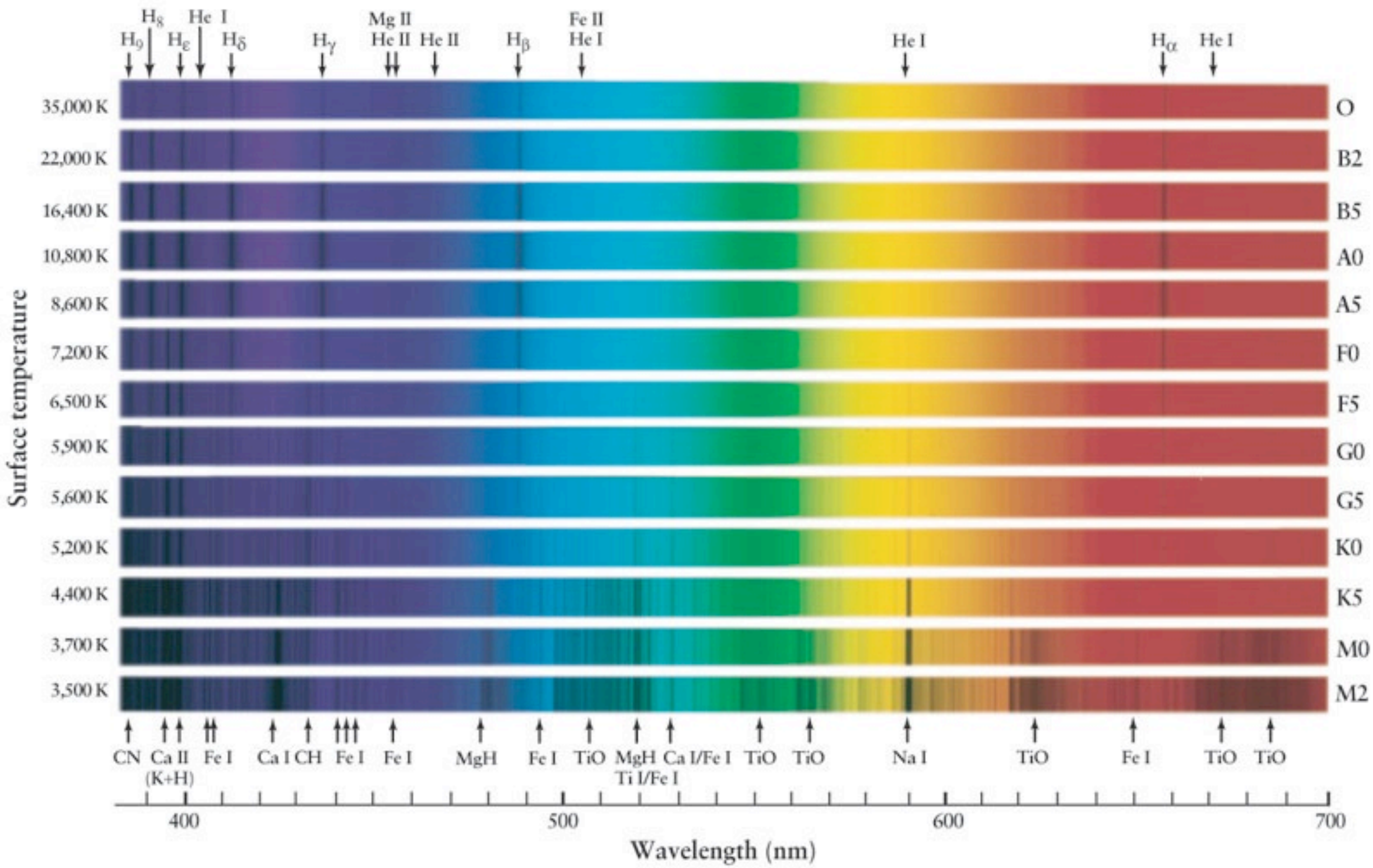
Line strength vs spectral type

H I Balmer lines: strongest in A0 stars



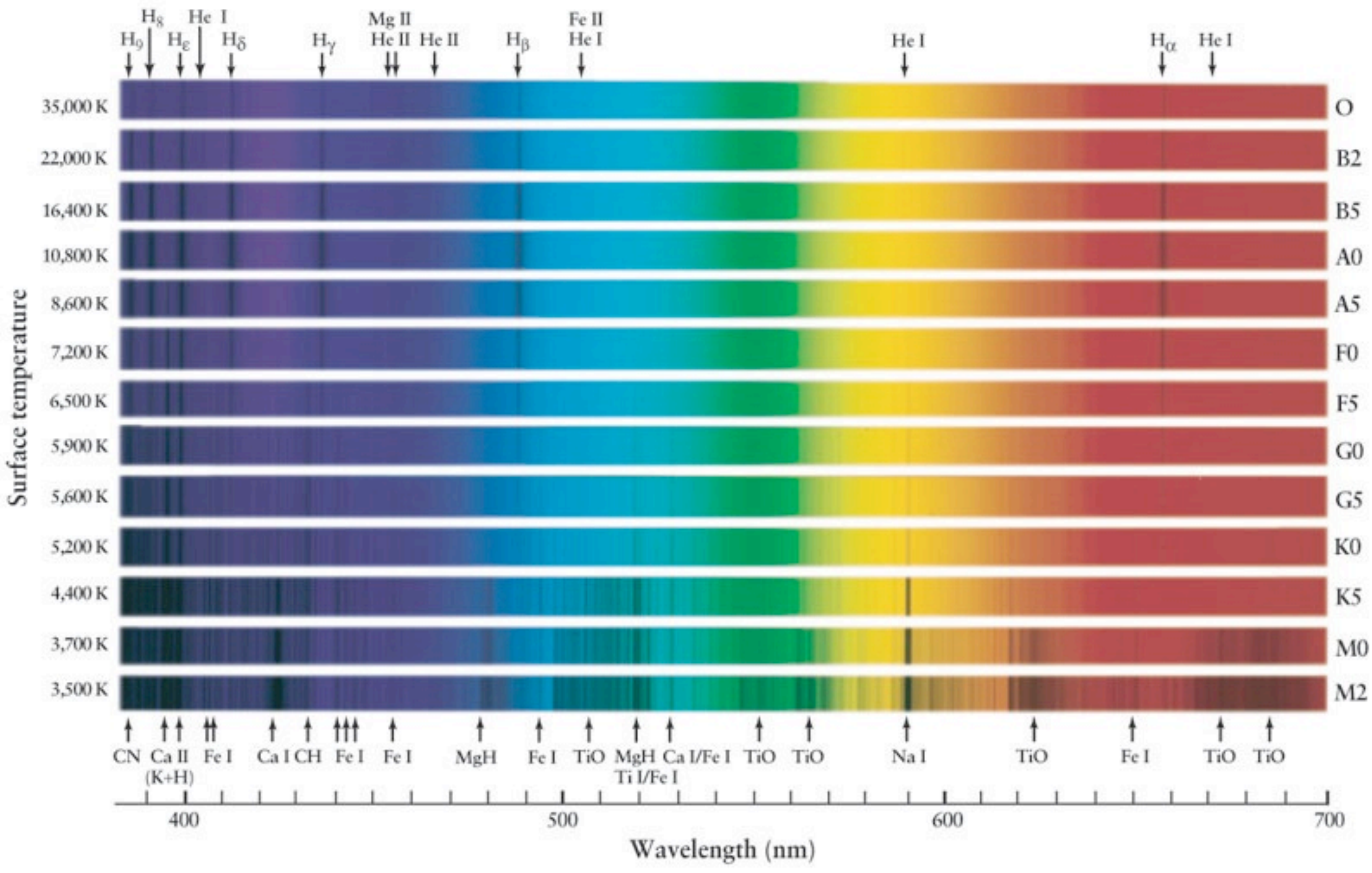
Line strength vs spectral type

Ca II H and K lines: strongest in K0 stars



Line strength vs spectral type

Molecular absorption bands (TiO, VO): strongest in M stars



The physics of spectral lines

Boltzmann equation predicts the number $N_{a,b}$ of atoms in a given excitation state with energy $E_{a,b}$ and degeneracy $g_{a,b}$:

$$\frac{N_b}{N_a} = \frac{g_b\, e^{-E_b/kT}}{g_a\, e^{-E_a/kT}} = \frac{g_b}{g_a}\, e^{-(E_b-E_a)/kT}.$$

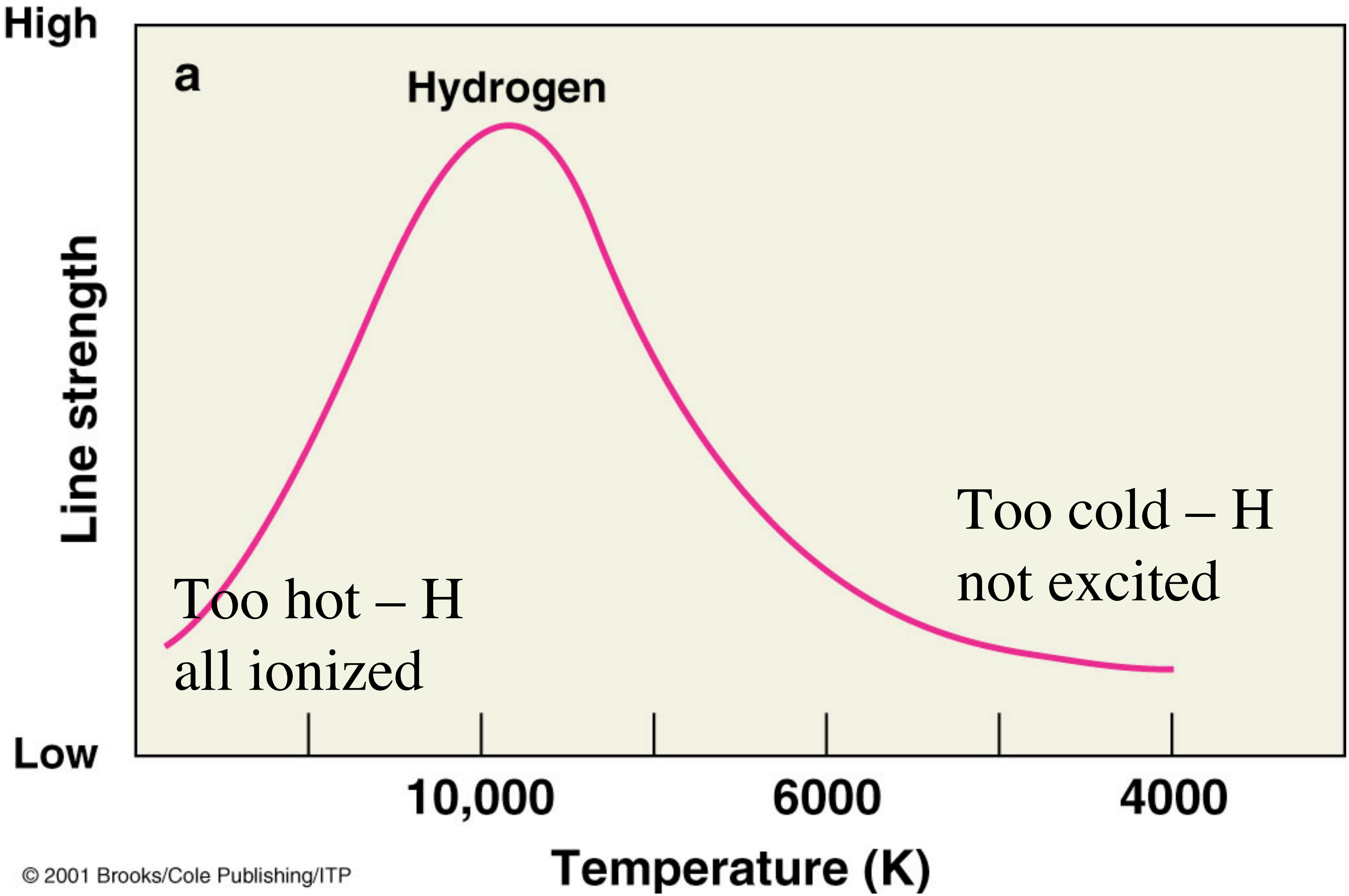
Saha equation predicts the number $N_{i,i+1}$ of atoms in a given ionization state with ionization energy χ_i:

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

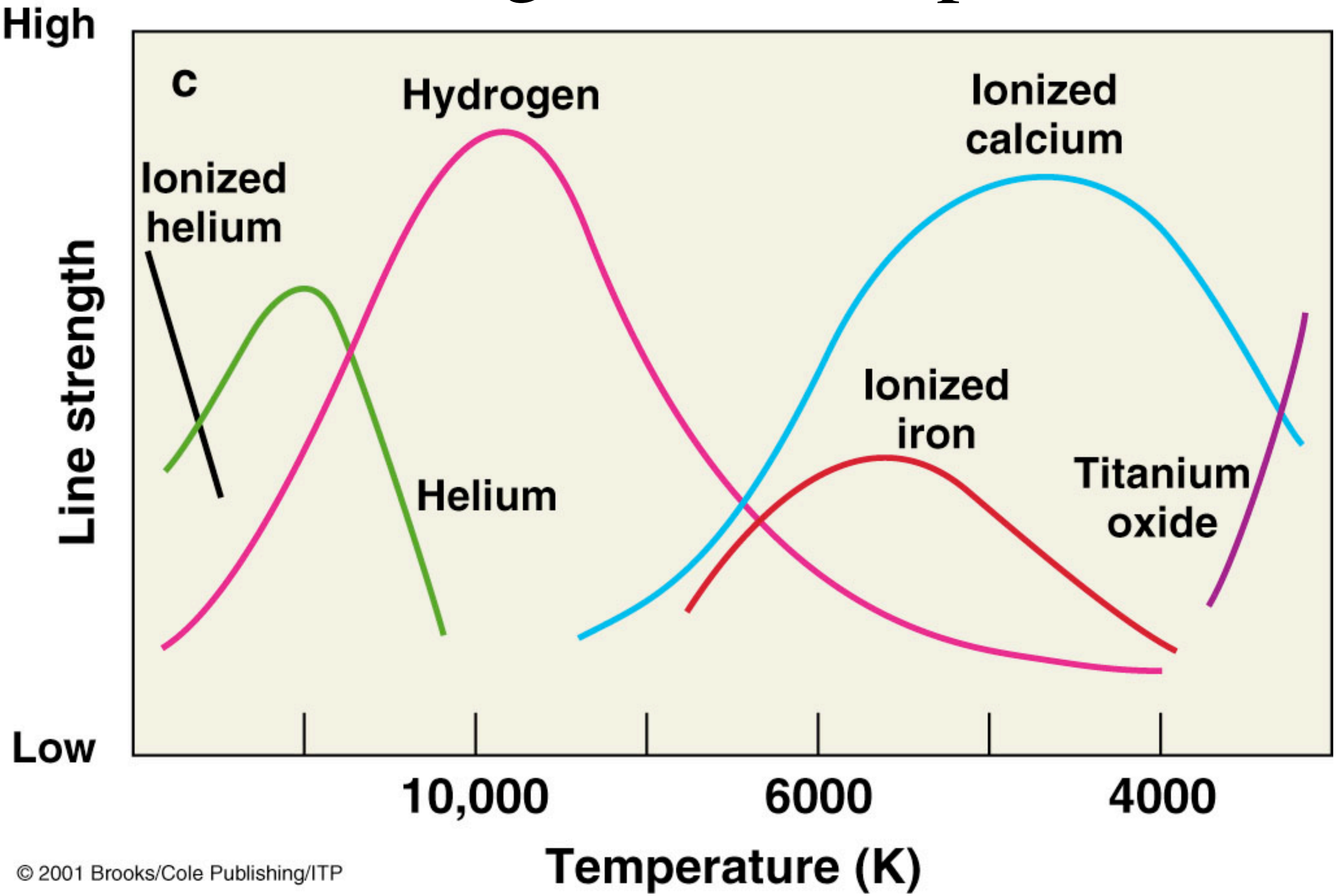
$$Z = \sum_{j=1}^{\infty} g_j\, e^{-(E_j-E_1)/kT}.$$

Partition function: sum of the number of ways to arrange the atomic electrons, weighted by the Boltzmann factor

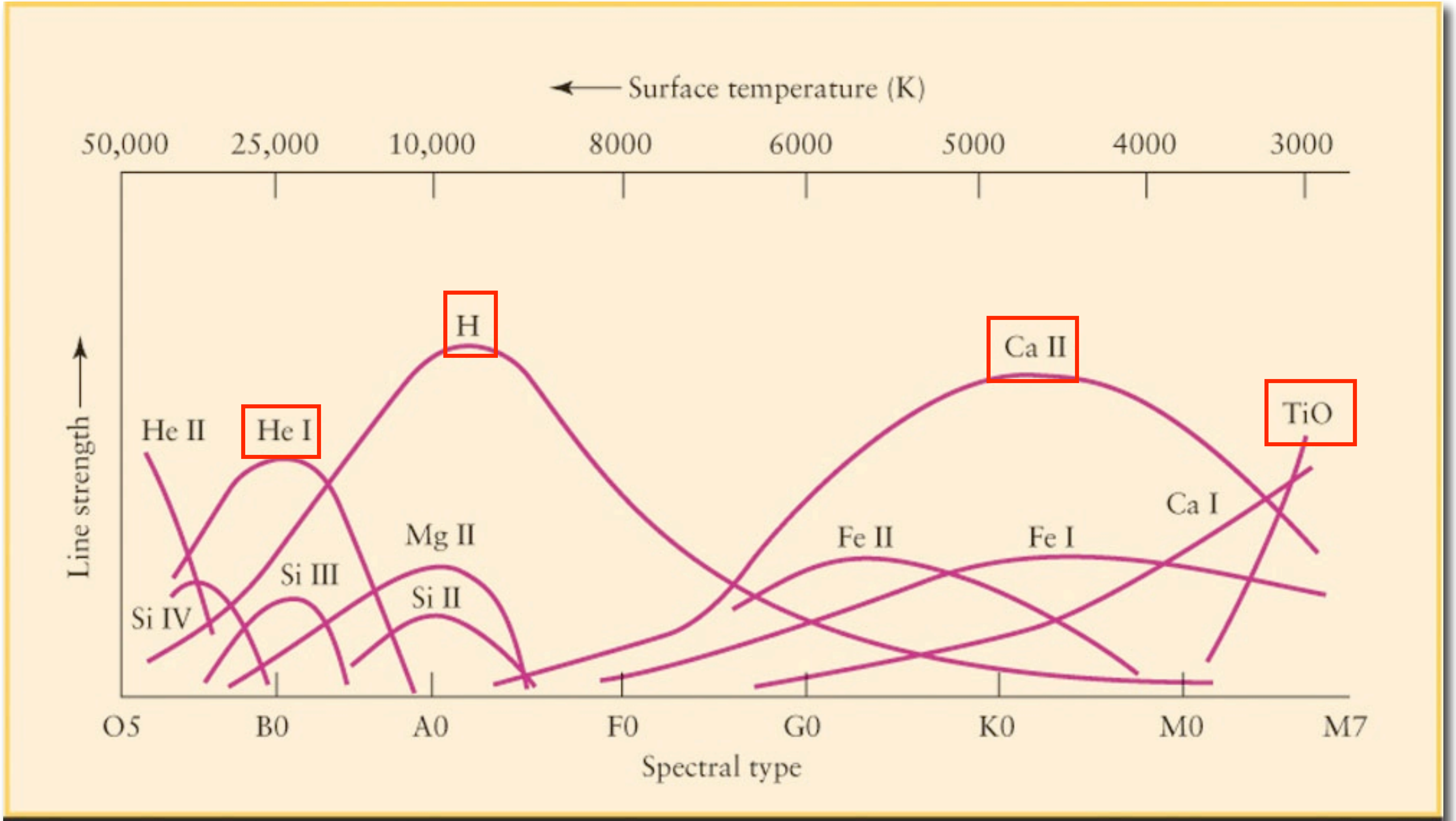
Line Strengths vs Temperature

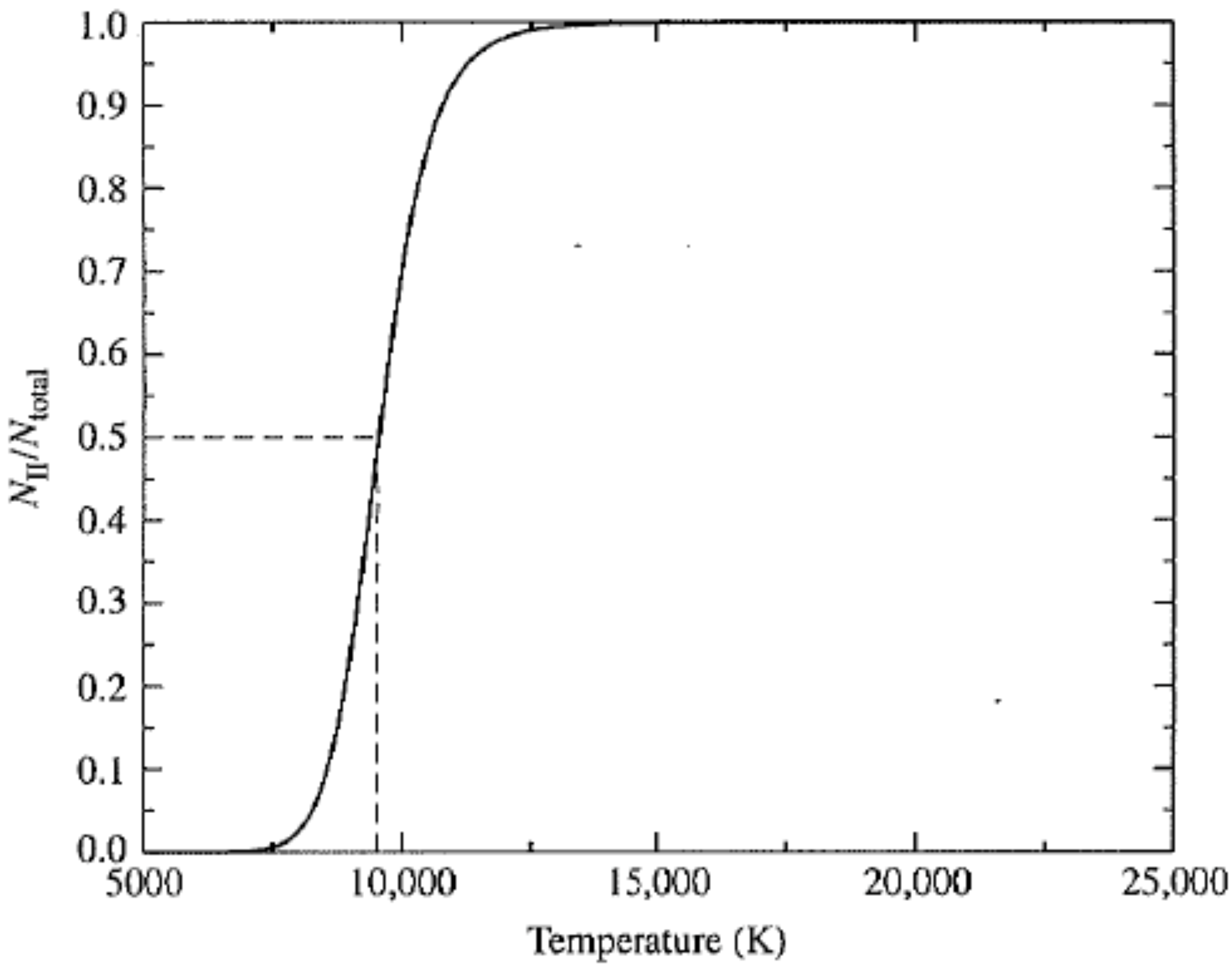


Line Strengths vs Temperature

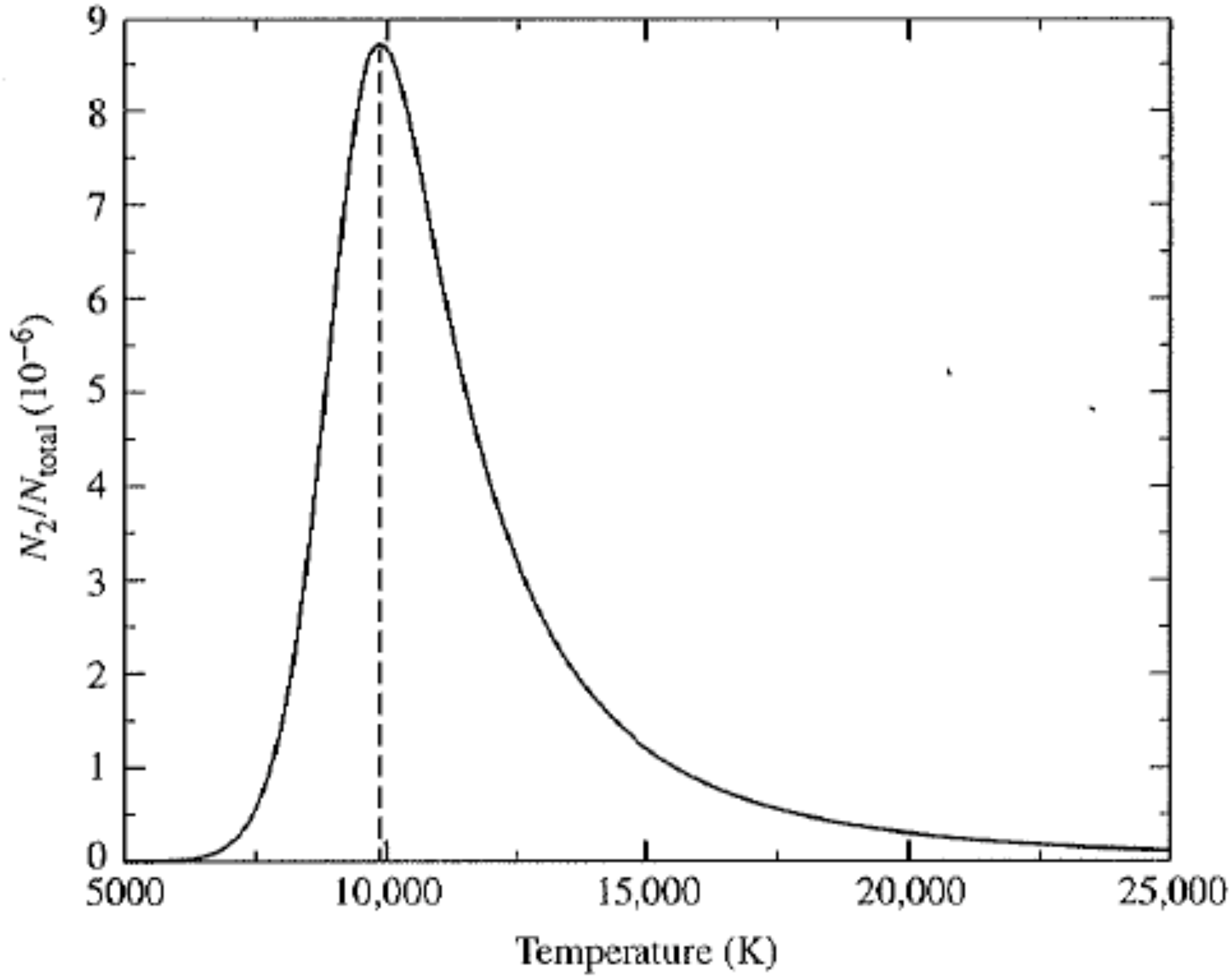


In other words: what determines the temperature range in which a given atom produces prominent absorption lines in the visible part of the spectrum?



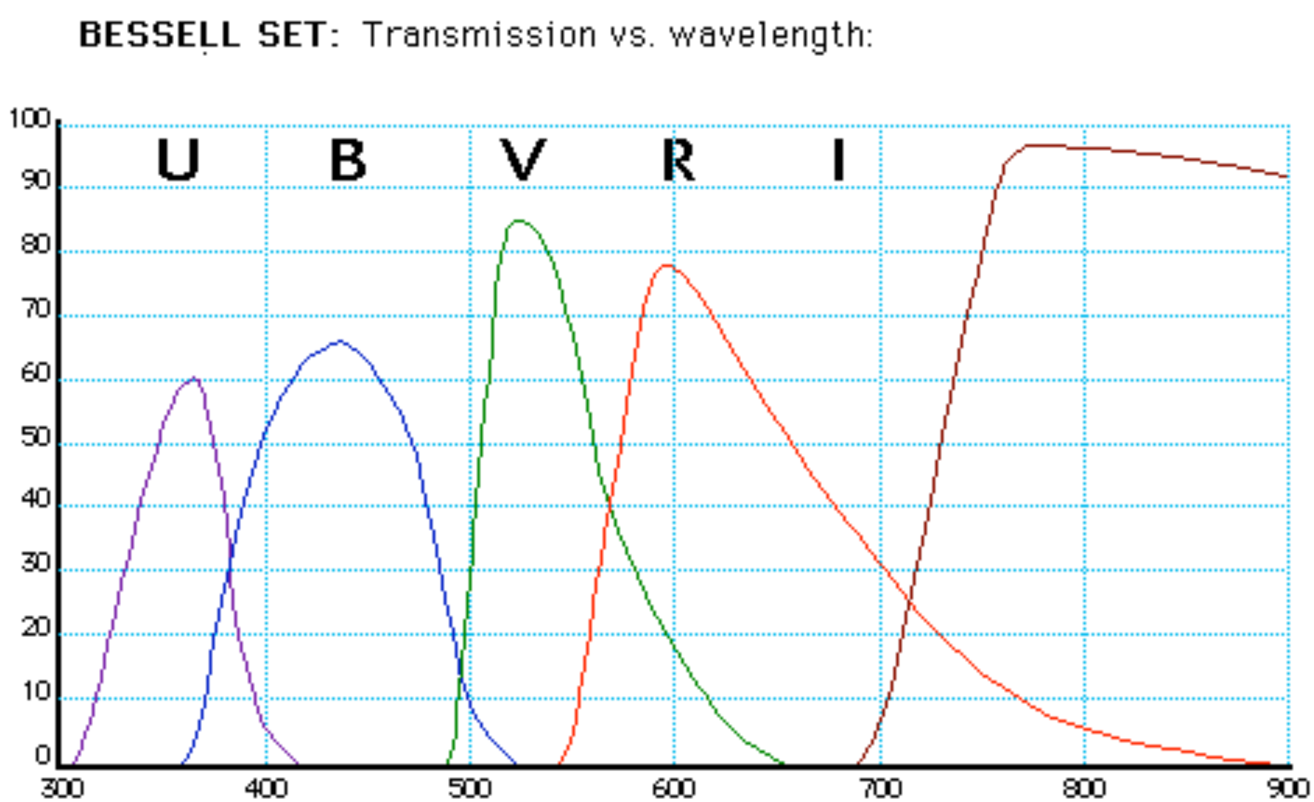


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
N_{II}/N_{total}
5000
10,000
15,000
20,000
25,000
Temperature (K)



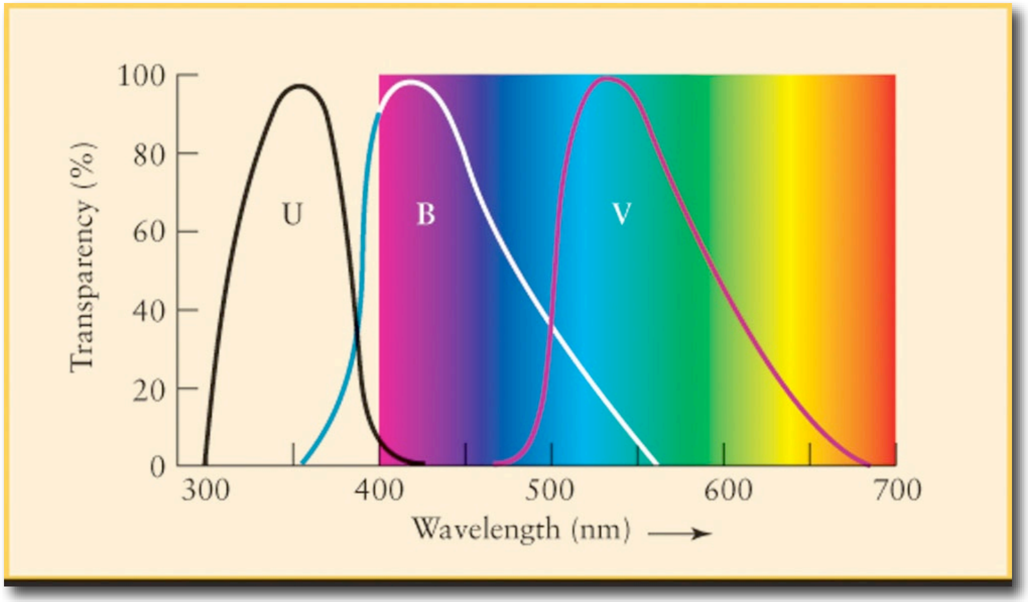
0
1
2
3
4
5
6
7
8
9
N_2/N_{total} (10^{-6})
5000
10,000
15,000
20,000
25,000
Temperature (K)

Broad band filters used to measure brightness of objects at various wavelengths: Photometry



Color index vs temperature

The use of filters to measure the apparent magnitudes (brightness) of stars in U (364 nm - ultraviolet), B (442 nm - blue) and V (540 nm - yellow-green) is called UBV photometry.



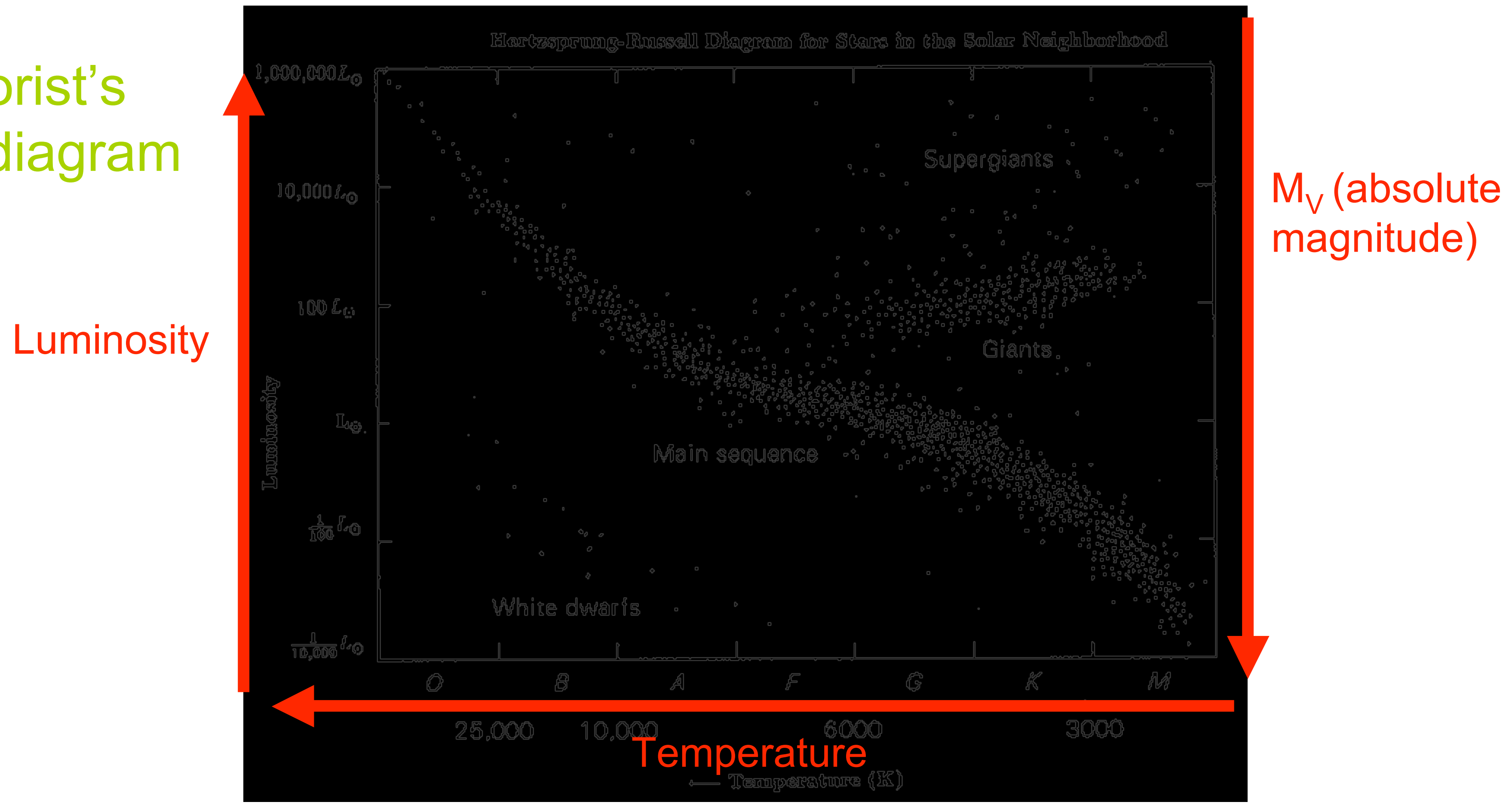
$B-V = m_B - m_V$ measures the relative flux in the B and V bands, so it is a proxy for the temperature (remember Wien's law!):

- $B-V>0$: cool stars; $B-V<0$: hot stars
- B-V does NOT depend on the distance!!!

Hertzsprung-Russell Diagram

The most important stellar quantities are the luminosity and the surface temperature. The H-R diagram is a plot of stellar luminosities (absolute magnitudes) versus surface temperatures (spectral type).

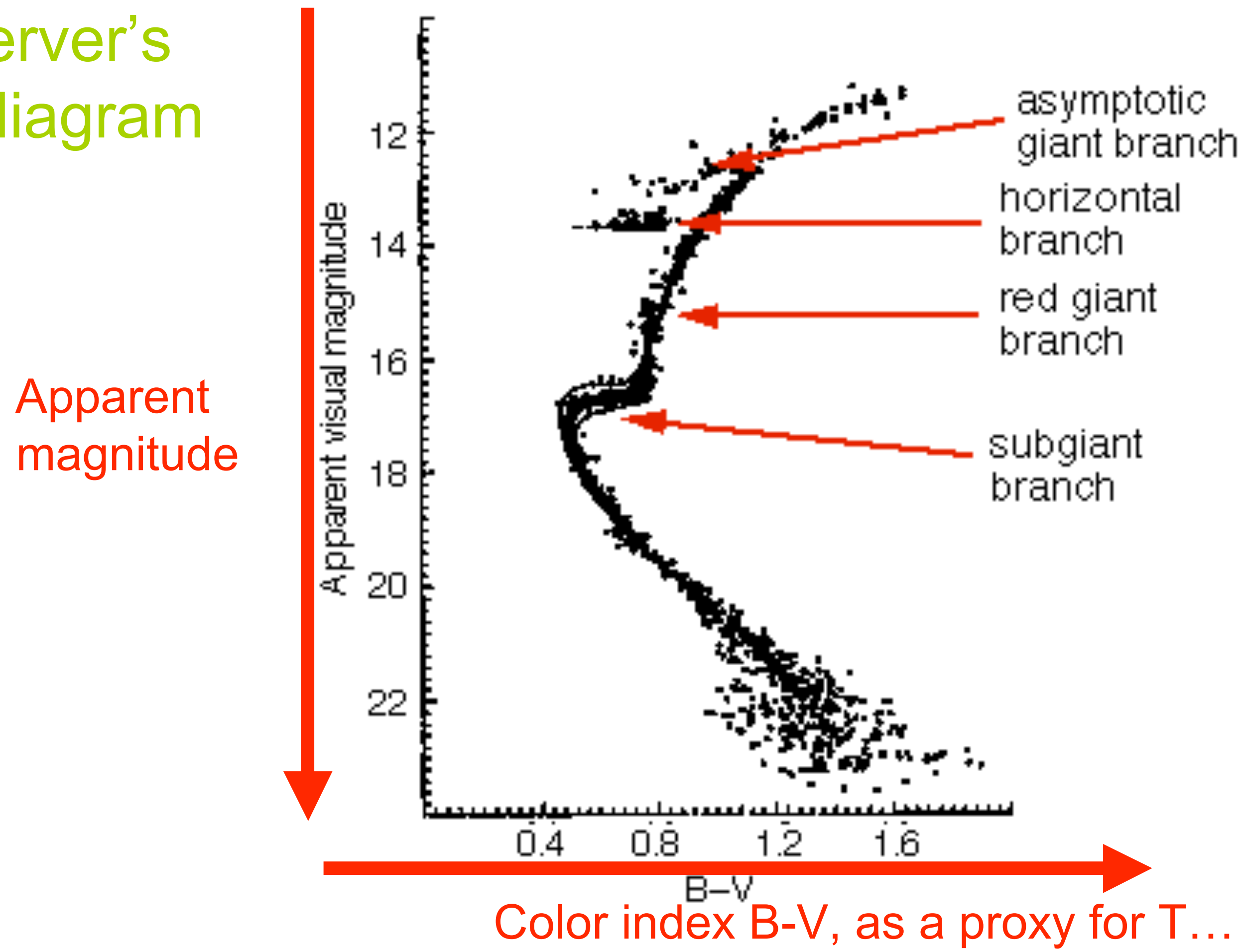
Theorist's HR diagram



Maybe an artifact of distance measurements? NO, the same trend is observed in Globular Clusters! (i.e., for stars at the same distance)

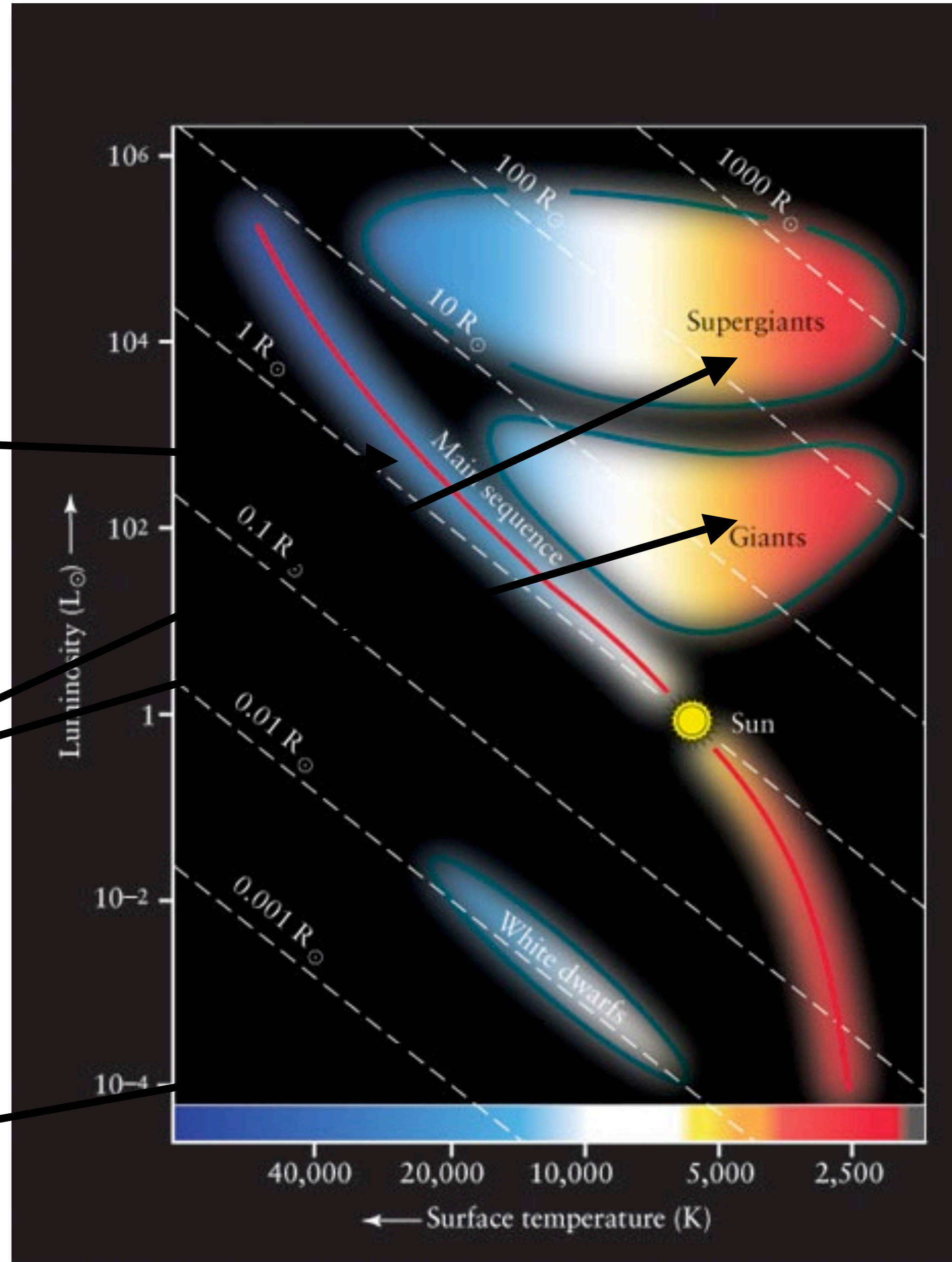
47 Tucanae

Observer's HR diagram



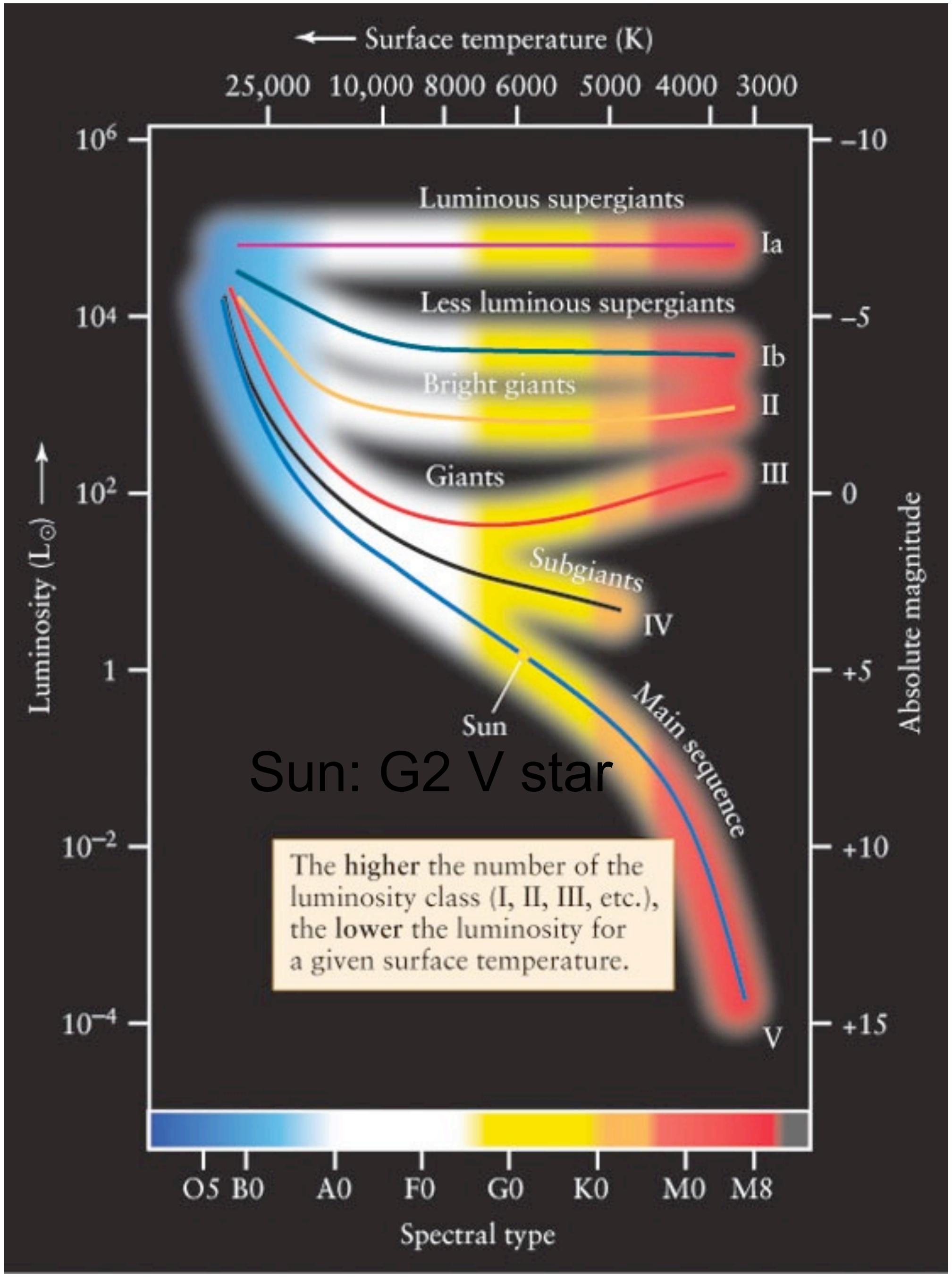
$L=4\pi R^2 \sigma T^4$ for a BB:

- most of the stars lie on the MAIN SEQUENCE, with increasing L as T increases
- a relatively cool star can be quite luminous if it has a large enough radius (10-100 $R_\odot$): RED GIANTS and SUPERGIANTS
- a relatively hot star can have very low luminosity, if its radius is very small (0.01 $R_\odot$): WHITE DWARFS



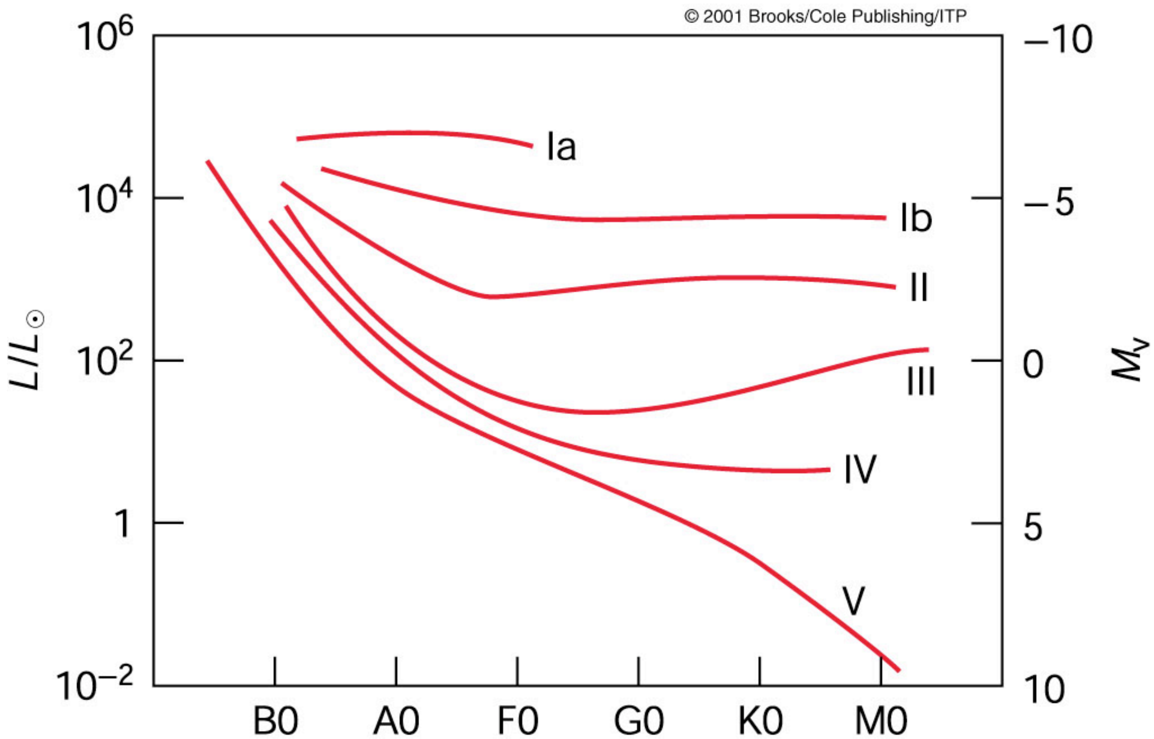
The Morgan-Keenan Luminosity Class

L. Class	Star
Ia	Luminous supergiant
Ib	supergiant
II	bright giant
III	giant
IV	subgiant
V	main sequence



Sun: G2 V star

Luminosity classes



- I: supergiants
- II: bright giants
- III: giants
- IV: subgiants
- V: main sequence

- For stars of given temperature, brighter luminosity classes ("giants") have narrower lines; spectral type and luminosity class locates star in H-R diagram

Summary

The stellar absorption line spectrum gives the following information for a star:

- surface temperature from the strengths of specific spectral lines

- luminosity class (via the radius) from the broadening of spectral lines

- chemical composition from the presence and quantitative analysis of spectral lines

-radial velocity, from Doppler shifts in spectral lines

- distanc with spectroscopic parallax $d=10^{(m-M+5)/5}$

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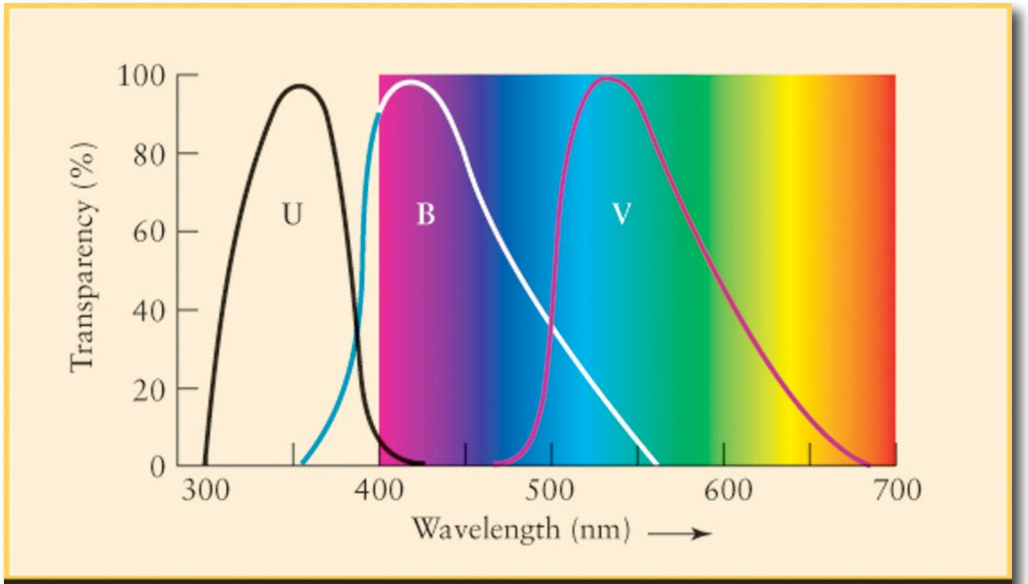

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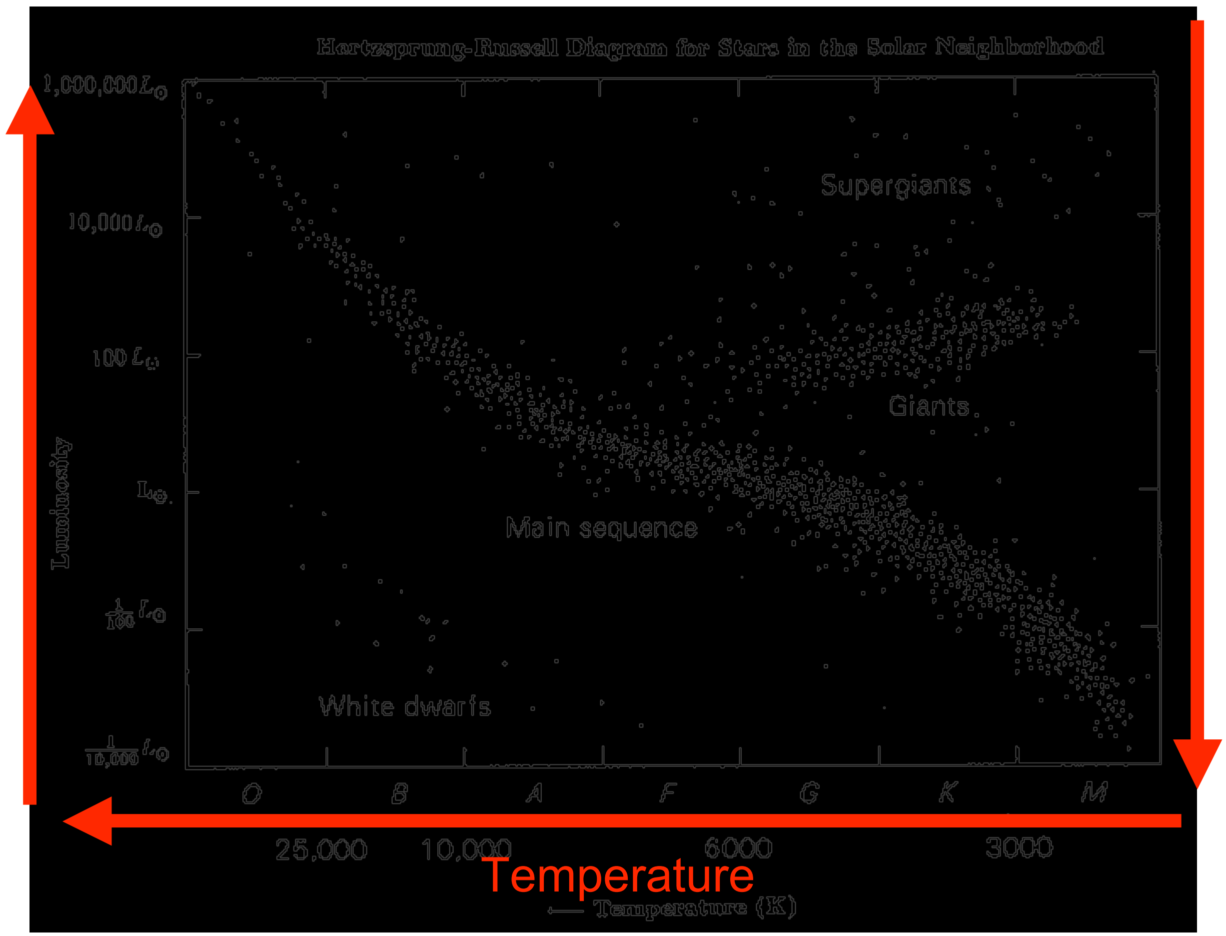
Luminosity



M_V (absolute magnitude)

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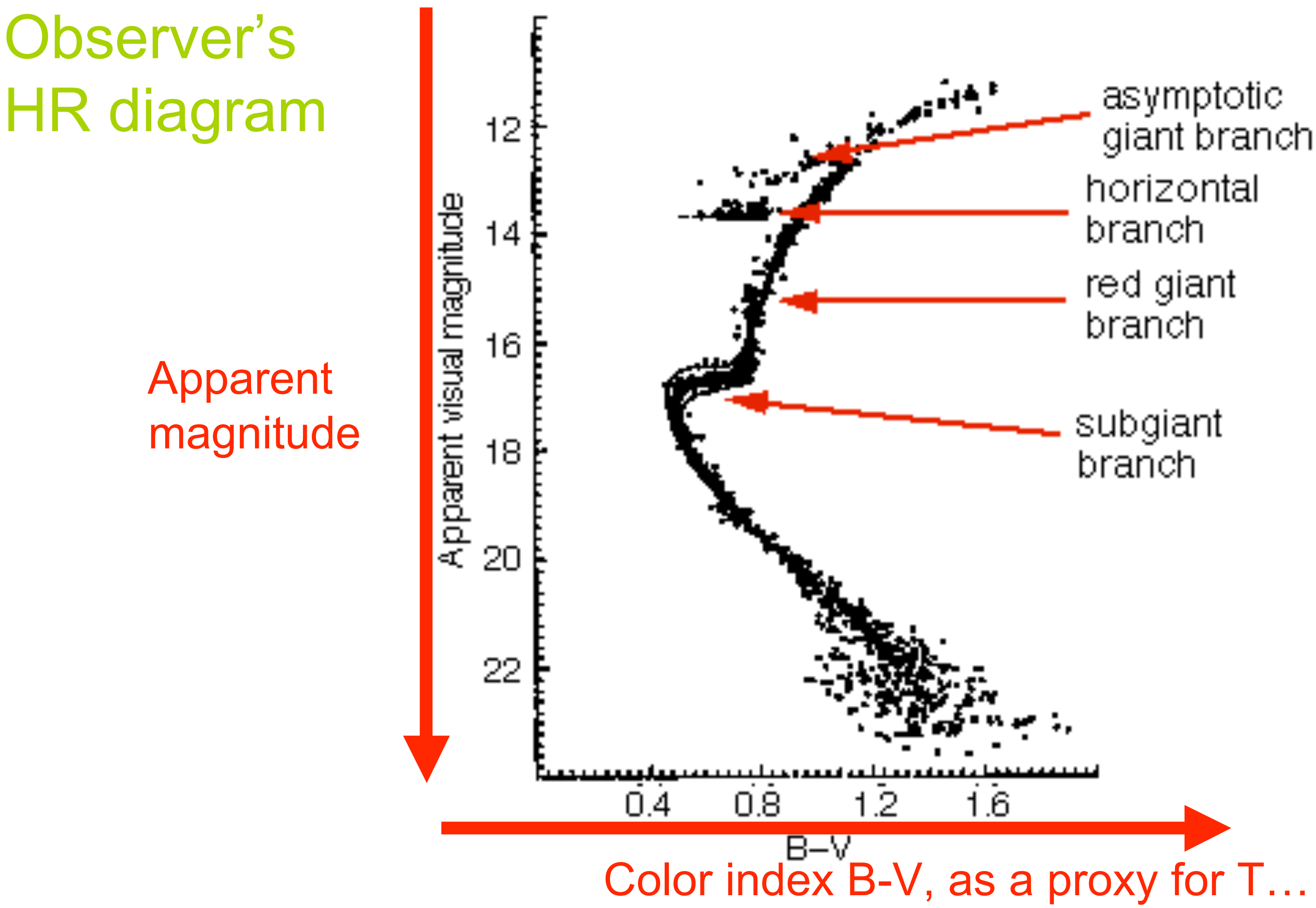
47 Tucanae



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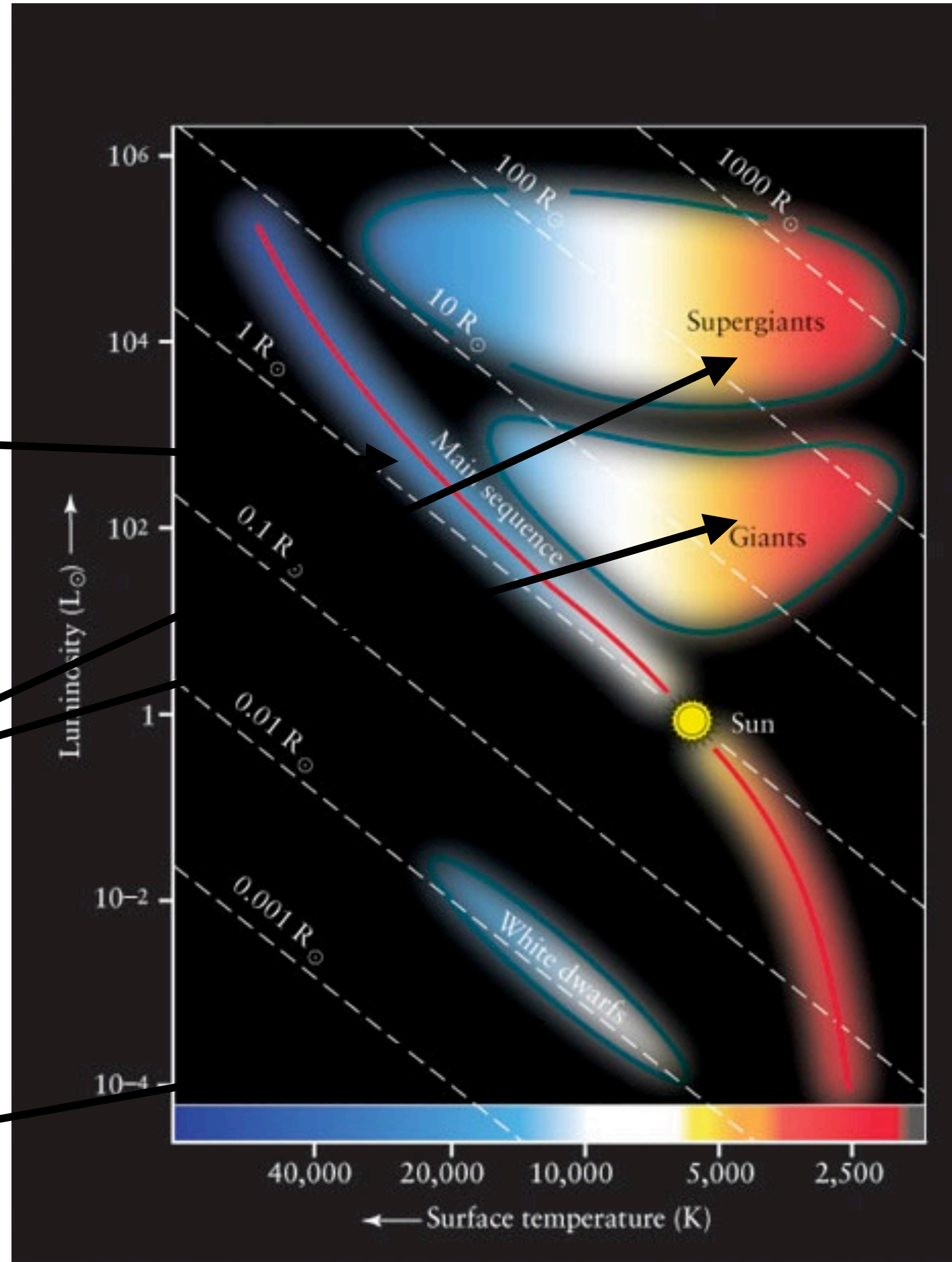

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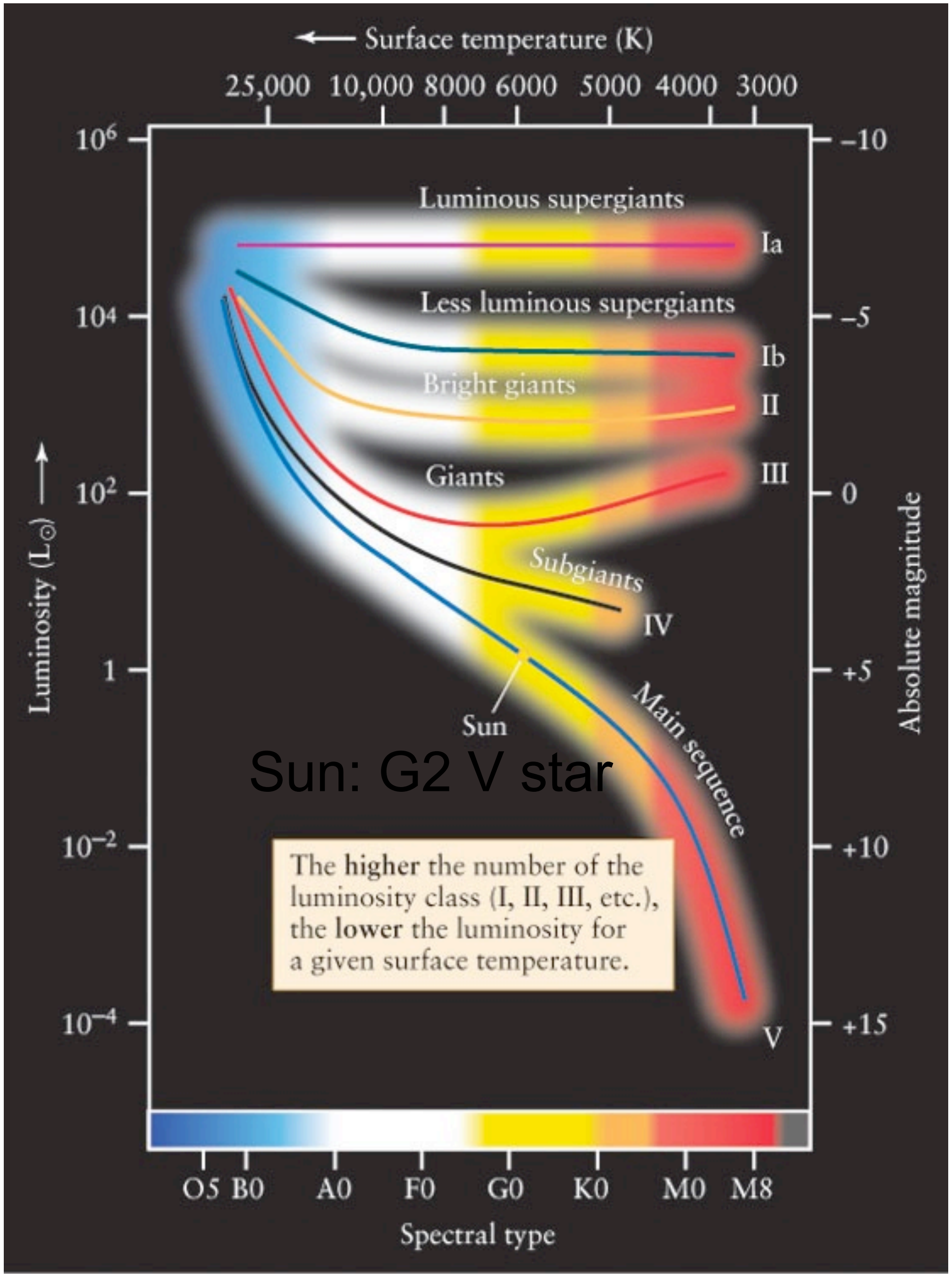
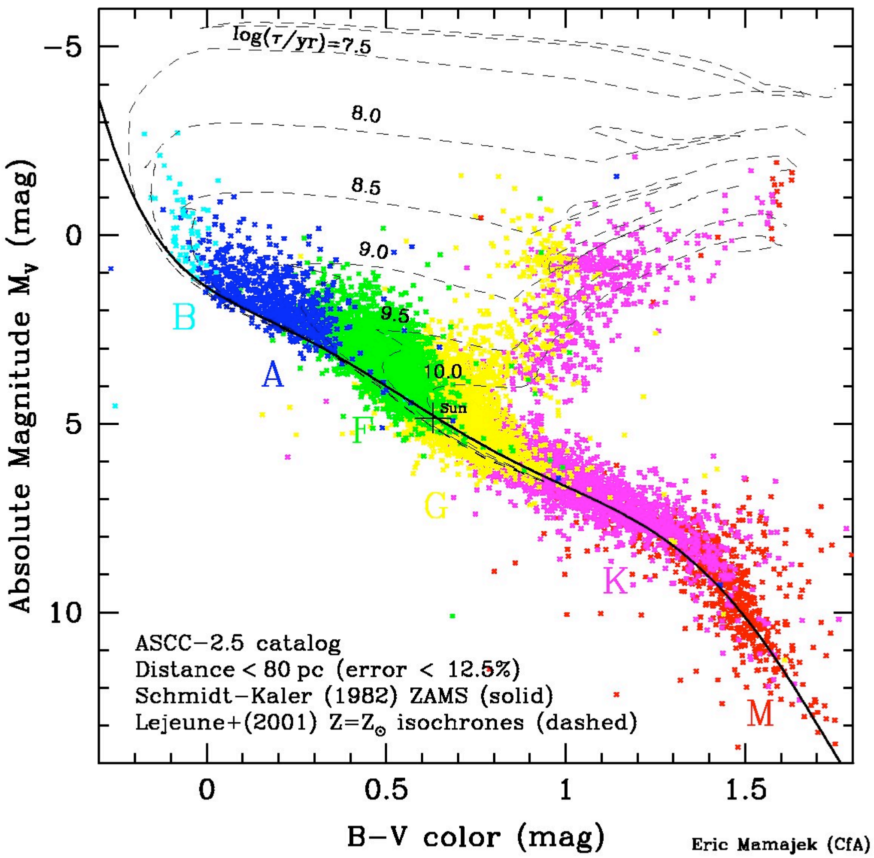


Hertzsprung-Russell (HR) diagram

- Also, plot of absolute magnitude vs. color
- Most stars lie along a line (*Main Sequence)*



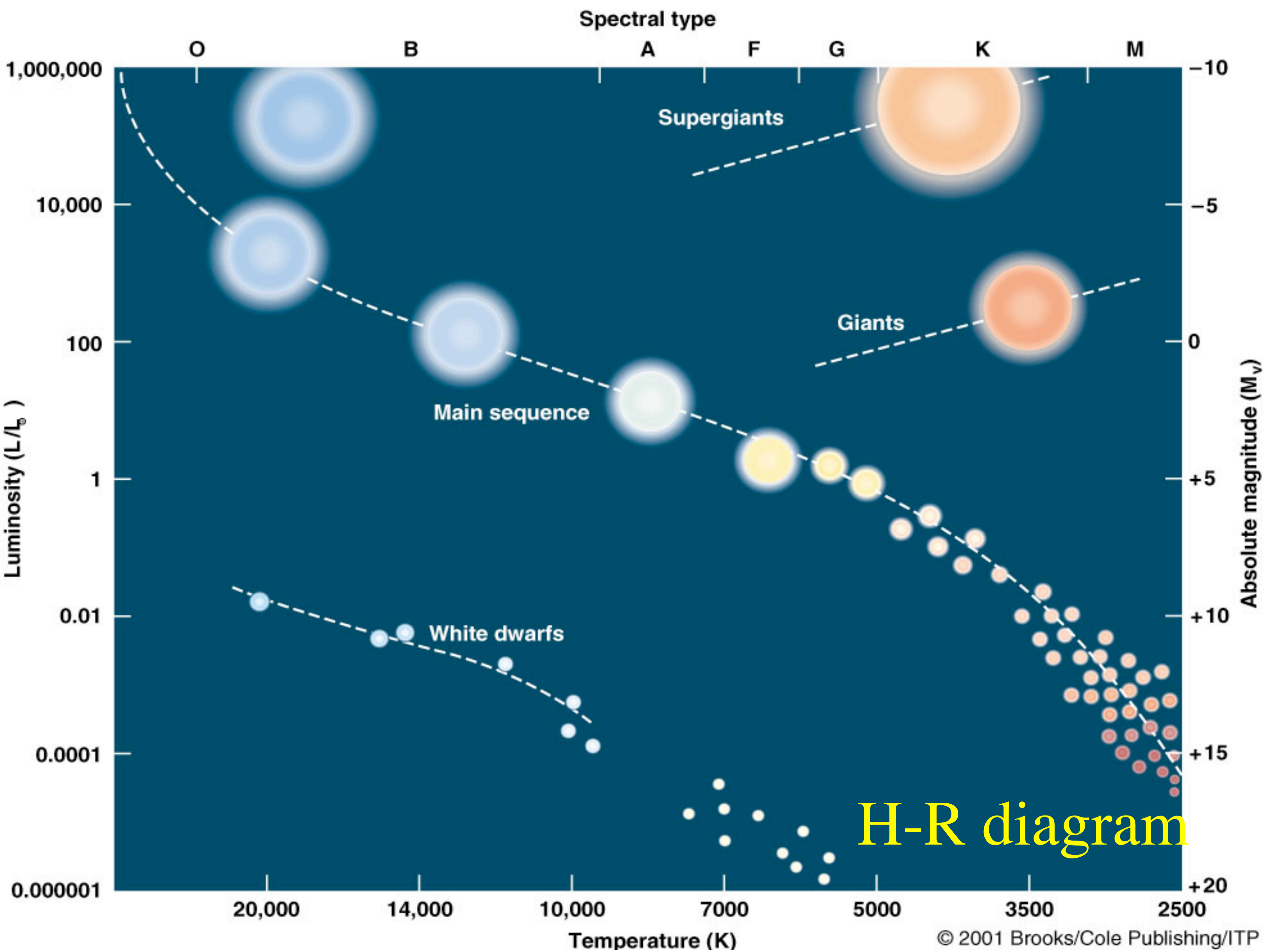
Main sequence stars burn hydrogen to helium in their cores

Hertzsprung-Russell (HR) diagram

- Plot of luminosity versus temperature
- Most stars lie along a line (*Main Sequence)*
- Stars off the main sequence must have different sizes

$$\frac{L}{L_{sun}} = \left(\frac{R}{R_{sun}}\right)^2 \left(\frac{T}{T_{sun}}\right)^4$$

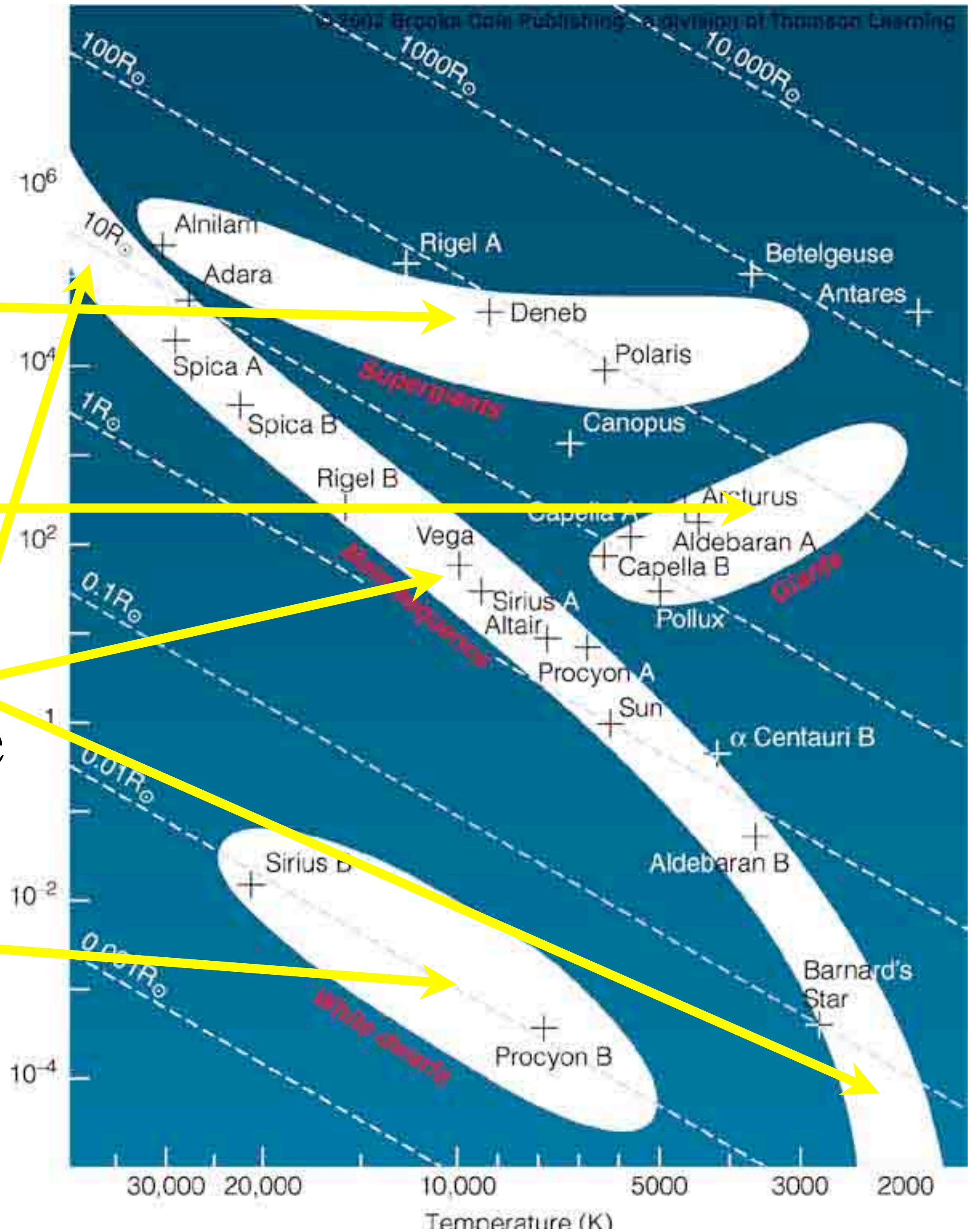
$$R \propto (L/T^4)^{1/2}$$


Spectral type
O
B
A
F
G
K
M
1,000,000
10,000
100
1
0.01
0.0001
0.000001
Luminosity (L/L⊙)
−10
−5
0
+5
+10
+15
+20
Absolute magnitude (Mv)
Supergiants
Giants
Main sequence
White dwarfs
20,000
14,000
10,000
7000
5000
3500
2500
Temperature (K)

H-R diagram

HR diagram

- Supergiants
- Giants
- Main Sequence
- White Dwarfs



HR Diagram: Stellar Radii

- 1000 R_{sun}
- 1 R_{sun} = radius of Sun
- 0.001 R_{sun}