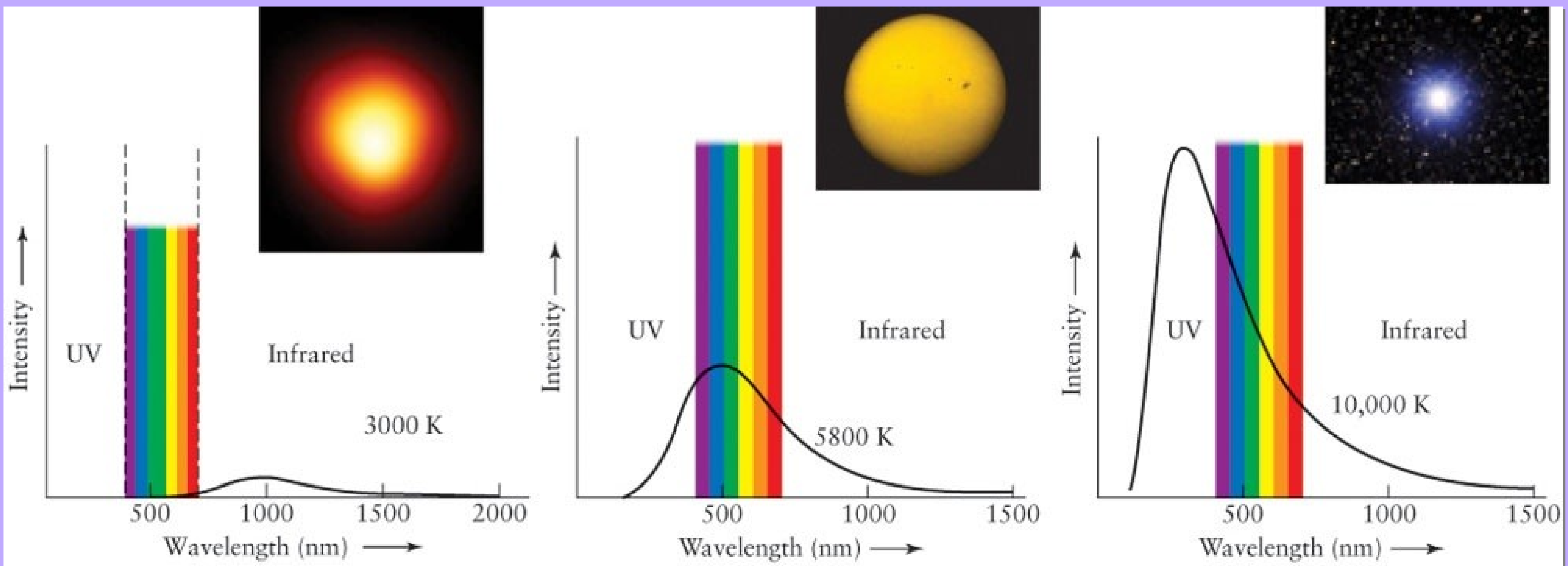
Colors and Temperatures. UBV Photometry

Wien's law implies that hot stars are blue, cool stars are red.

Wavelength_max = b/T



(a) A **cool star** with surface temperature 3000 K emits much more red light than blue light, and so appears red.

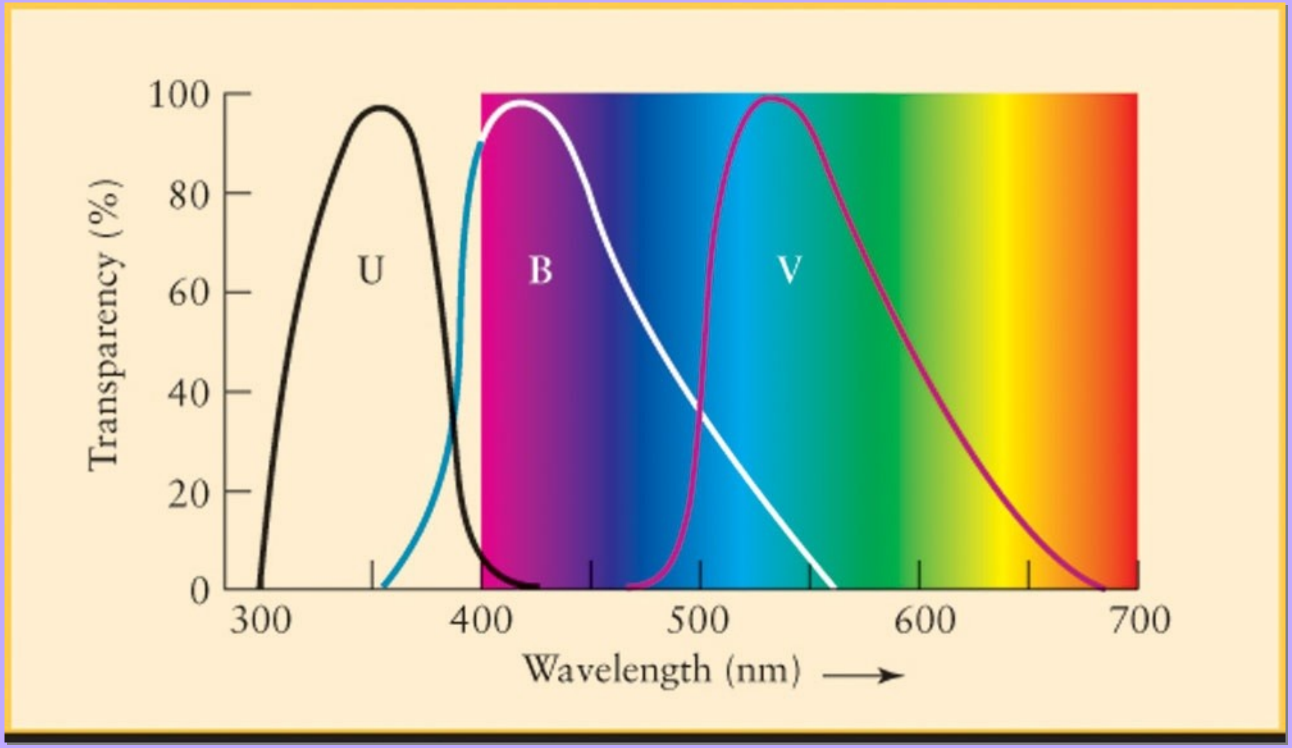
(b) A **warmer star** with surface temperature 5800 K (like the Sun) emits roughly equal amounts of all visible wavelengths, and so appears yellow-white.

(c) A **hot star** with surface temperature 10,000 K emits much more blue light than red light, and so appears blue.

Temperature = surface temperature (that of a blackbody)

Colors and Temperatures. UBV Photometry

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.



Colors and Temperatures. UBV Photometry

m_B (B) - apparent magnitude in the B filter

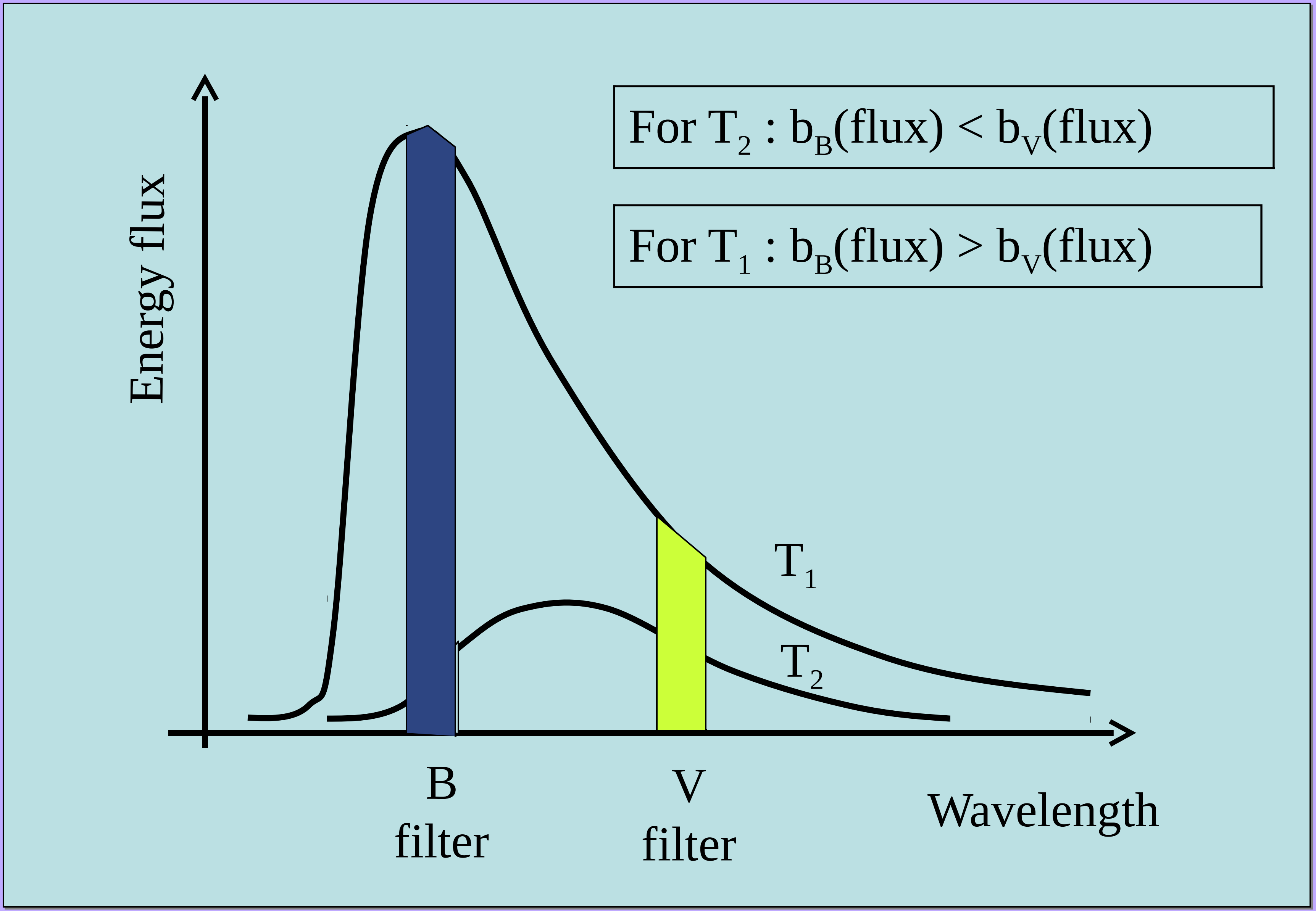
m_V (V) - apparent magnitude in the V filter

The difference in magnitudes in two different filters is called color index or simply color. It corresponds to the ratio of apparent brightness (flux) in the respective filters:

$$m_B - m_V = -2.5 \log (b_B/b_V) \quad \text{or,}$$

$$B\text{-}V = -2.5 \log (b_B/b_V)$$

Filters and the blackbody curve: schematic view

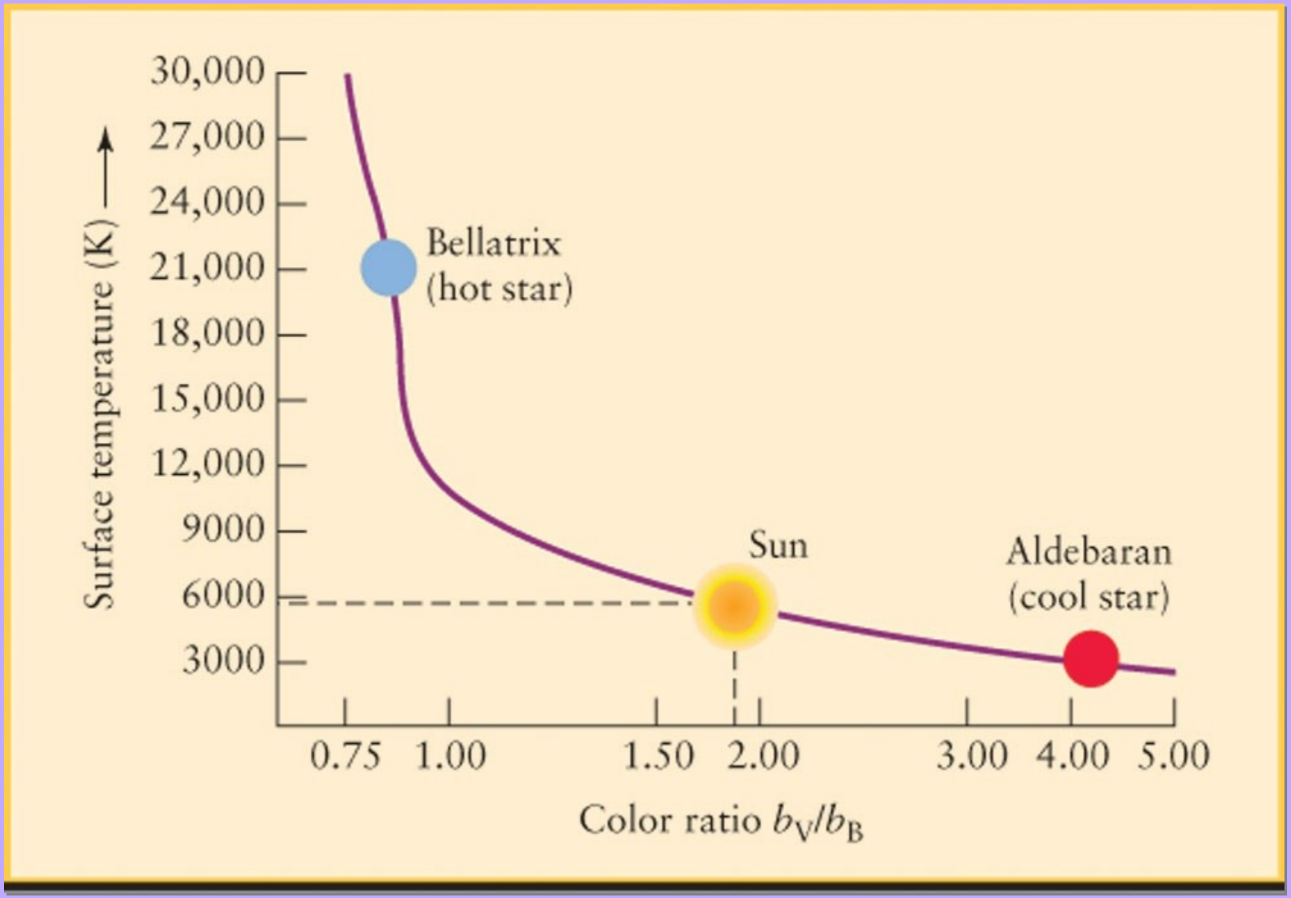


Colors and Temperatures. UBV Photometry

By determining color indices, we can infer the surface temperature of the star, or the blackbody temperature of the star. This is because by sampling different parts of the blackbody cure, we can roughly infer its shape.

Colors and Temperatures. UBV Photometry

Relationship between temperature and B-V color



$$B\text{-}V = -2.5 \log (b_B/b_V)$$

Spectra and Spectral Classification of Stars

Each atom (ion) has its own pattern of spectral lines.

Stars show absorption line spectra: we see the blackbody continuous spectrum given by the star's interior (hot dense gas), and a set of absorption lines given by the stellar atmosphere (cooler, low density gas).

Spectra and Spectral Classification of Stars

Stars show various patterns of lines:

- some have strong Balmer lines (H I, the n=2 series)
- some show He I lines
- some show lines from molecules such as TiO, MgH
- Other elements of the periodic table? Resonance lines?

Notation:

- neutral elements: H I, He I, Fe I, etc.
- single ionized: H II, O II, etc.
- double ionized: O III, etc.

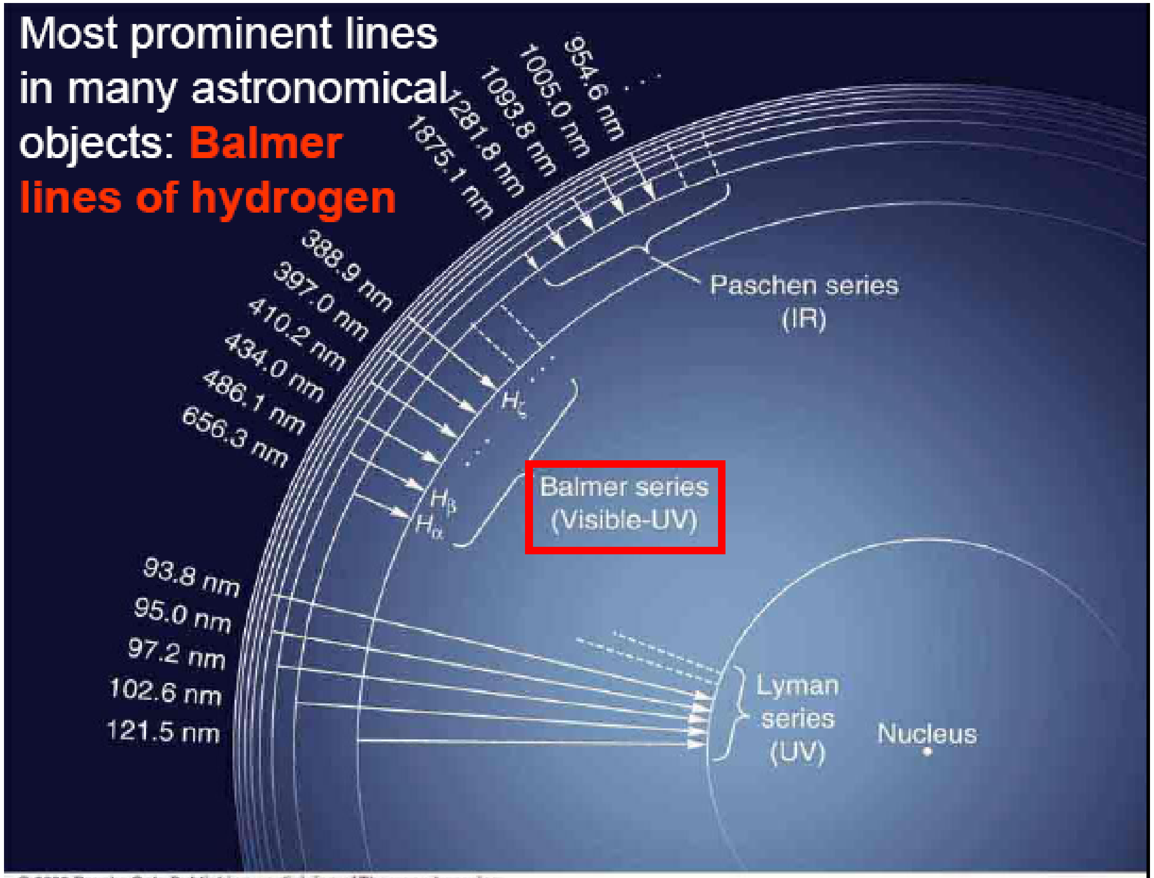
Spectra and Spectral Classification of Stars

Initially (1890s) stars were classified according to the strength of the Balmer lines. At this time, the energy-level structure of atoms was not known.

The first person known to attempt to classify spectra was Father Angelo Secchi S.J., around 1860. He was appointed director of the Vatican Observatory in 1849. The spectra were hand drawn at that time!

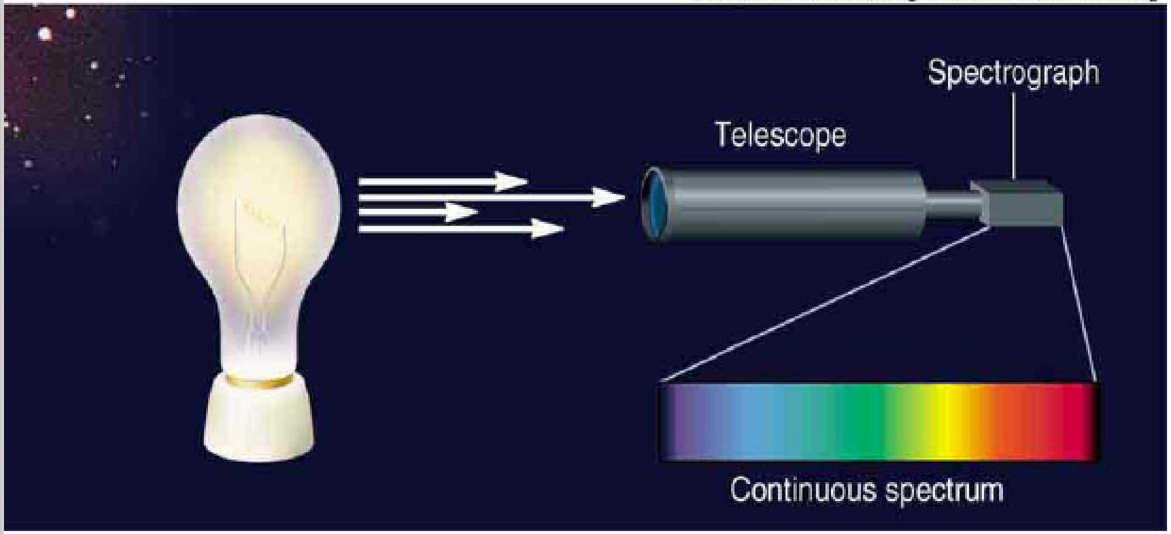
In the late 1890s, the emerging scheme was based on the strength of hydrogen Balmer lines with classes that were assigned a letter from A to O.

Lines of Hydrogen



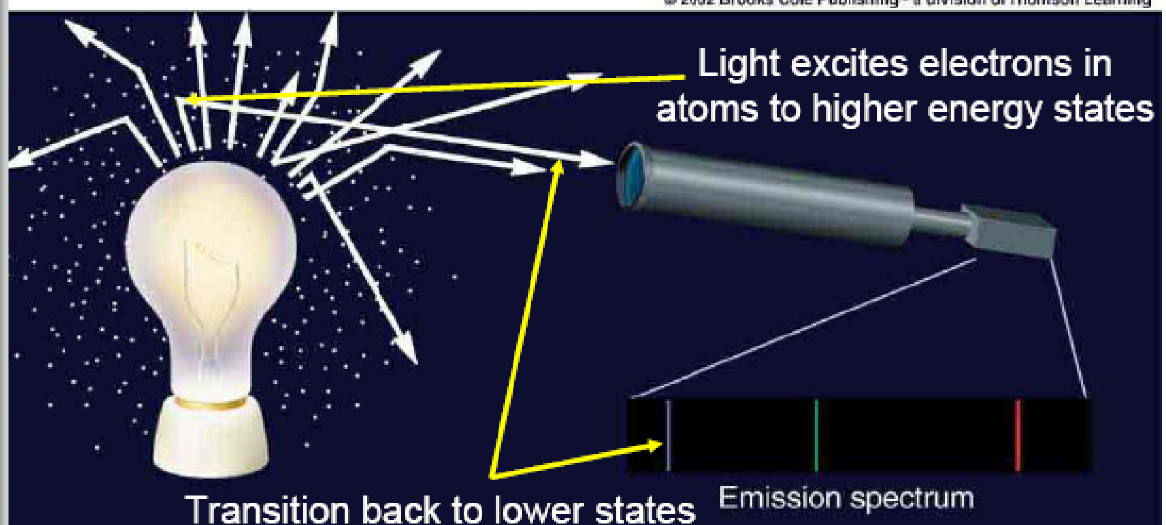
Kirchhoff's Laws of Radiation (1)

1. A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a **continuous spectrum.**

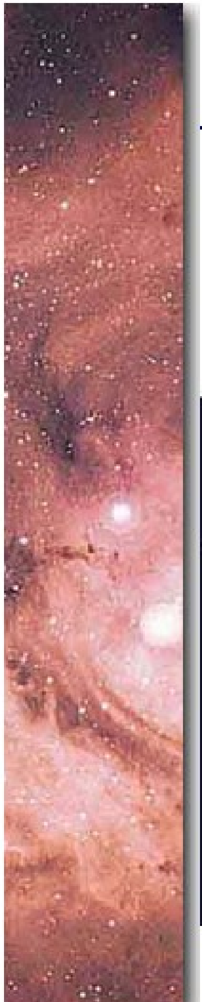


Kirchhoff's Laws of Radiation (2)

2. A low-density gas excited to emit light will do so at specific wavelengths and thus produce an **emission spectrum.**

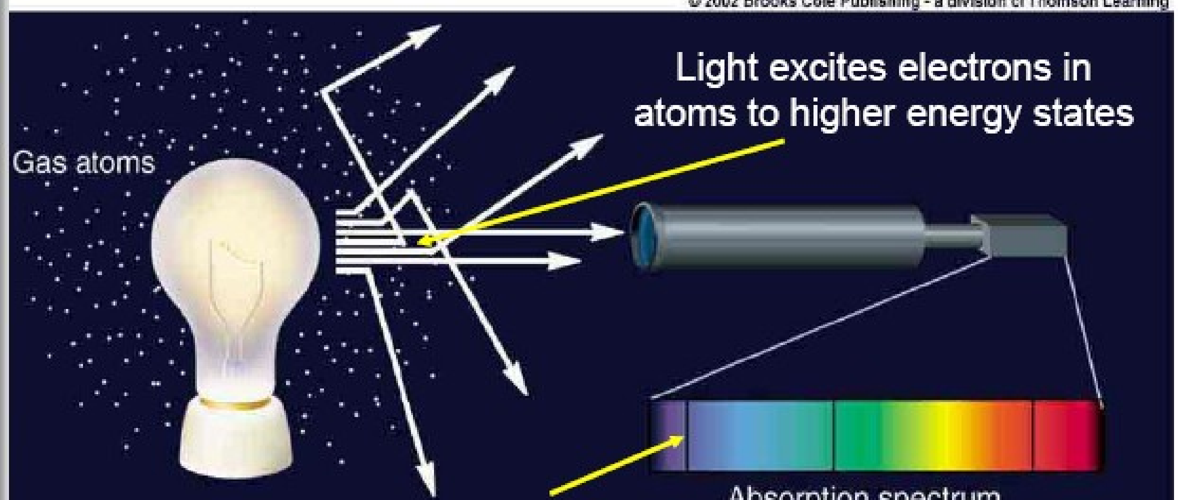


emits light at specific frequencies

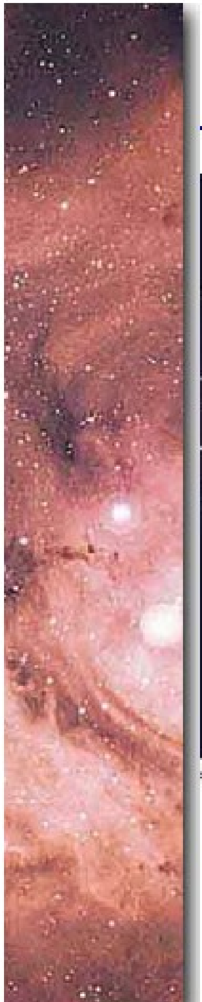


Kirchhoff's Laws of Radiation (3)

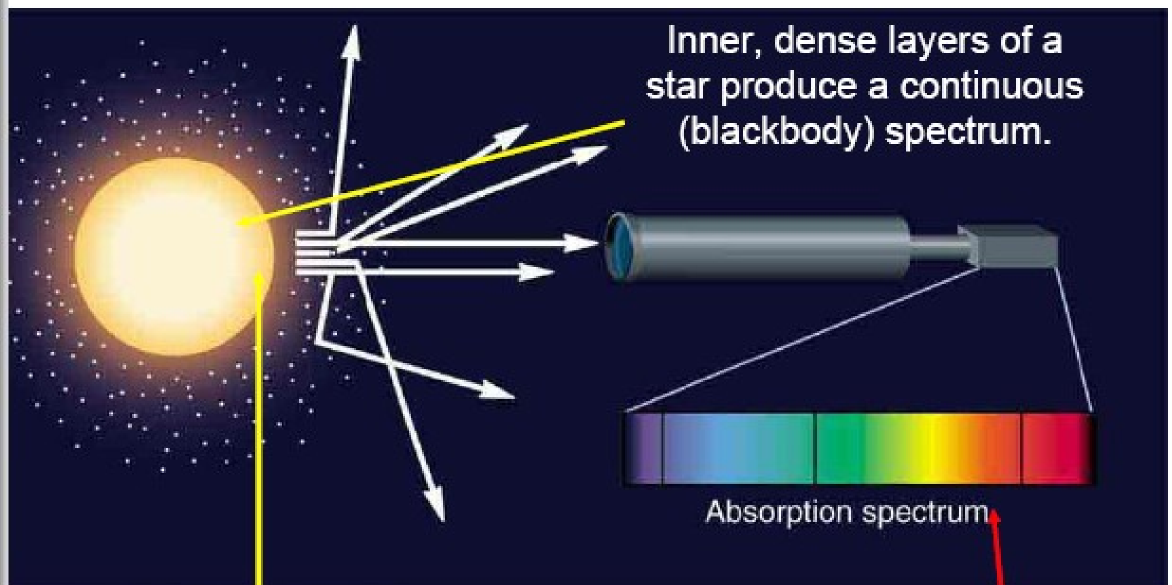
3. If light comprising a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum.



Frequencies corresponding to the transition energies are absorbed from the continuous spectrum.



The Spectra of Stars



Cooler surface layers absorb light at specific frequencies.

=> Spectra of stars are absorption spectra.

1900s :

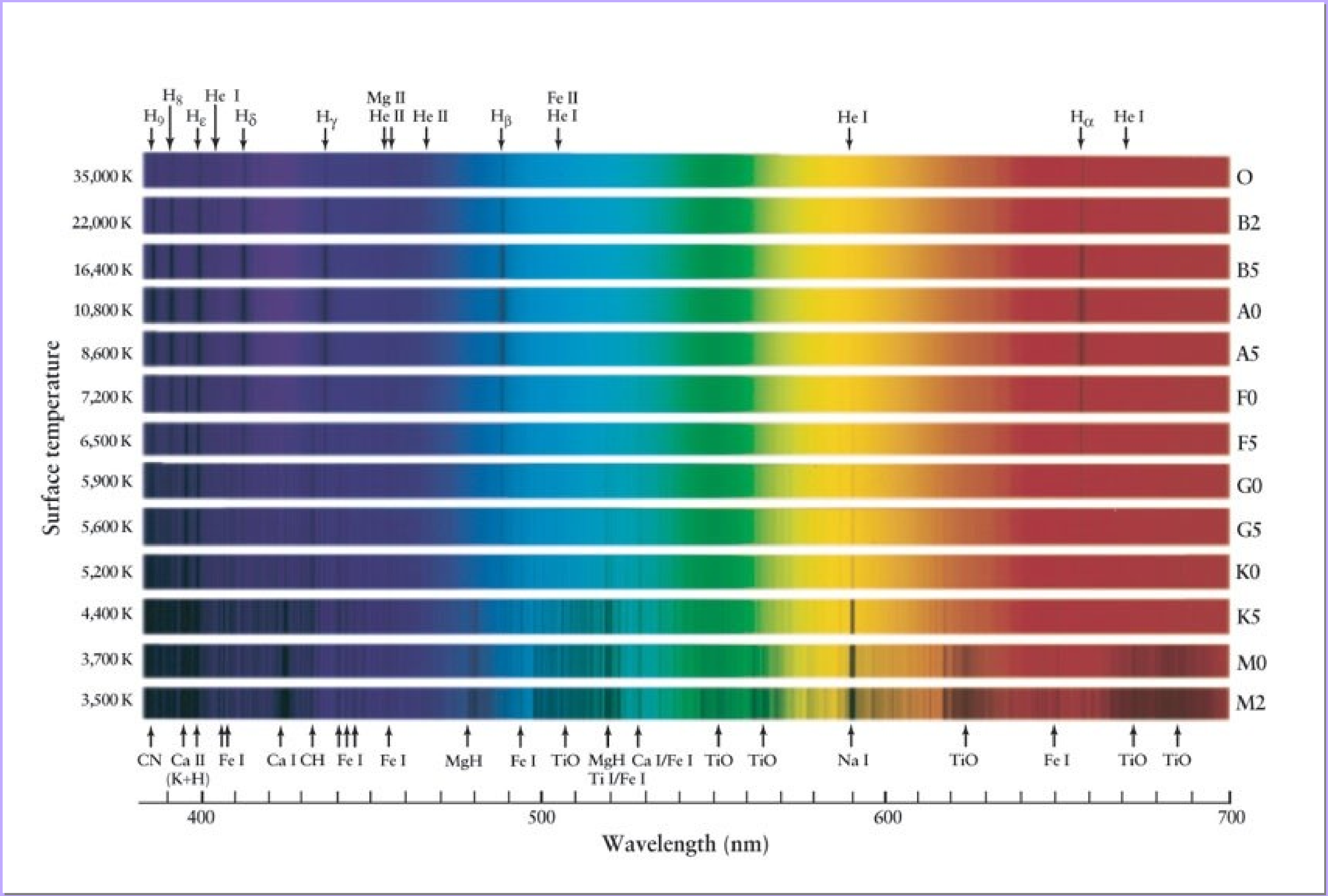
A team of astronomers at Harvard College Observatory started a monumental project to examine stellar spectra and develop a system of spectral classification in which all spectral features (all lines and their strengths) are considered. They have used photographs of spectra.

The Harvard team

The Harvard project:

- financed by Henry Draper, a wealthy physician and amateur astronomer; in 1872 he was the first person to photograph stellar absorption spectra.
- researchers: Edward C. Pickering, Williamina Fleming, Antonia Maury and Annie Jump Cannon.
- the outcome is the "Henry Draper Catalogue", published between 1918 and 1924. It listed 225,300 stars.
- the classification sequence included first 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.
- A.J. Cannon refined the sequence into smaller steps called spectral types. For example, class G includes 10 subclasses, from G0 to G9.

Spectra and Spectral Classification of Stars



Spectra and Spectral Classification of Stars

- In 1920 Harvard astronomer Cecilia Payne-Gaposhkin and the Indian physicist Meghnad Saha demonstrated that the OBAFGKM is a sequence in temperature with O stars being the hottest and M stars the coolest.

Why is it so ?

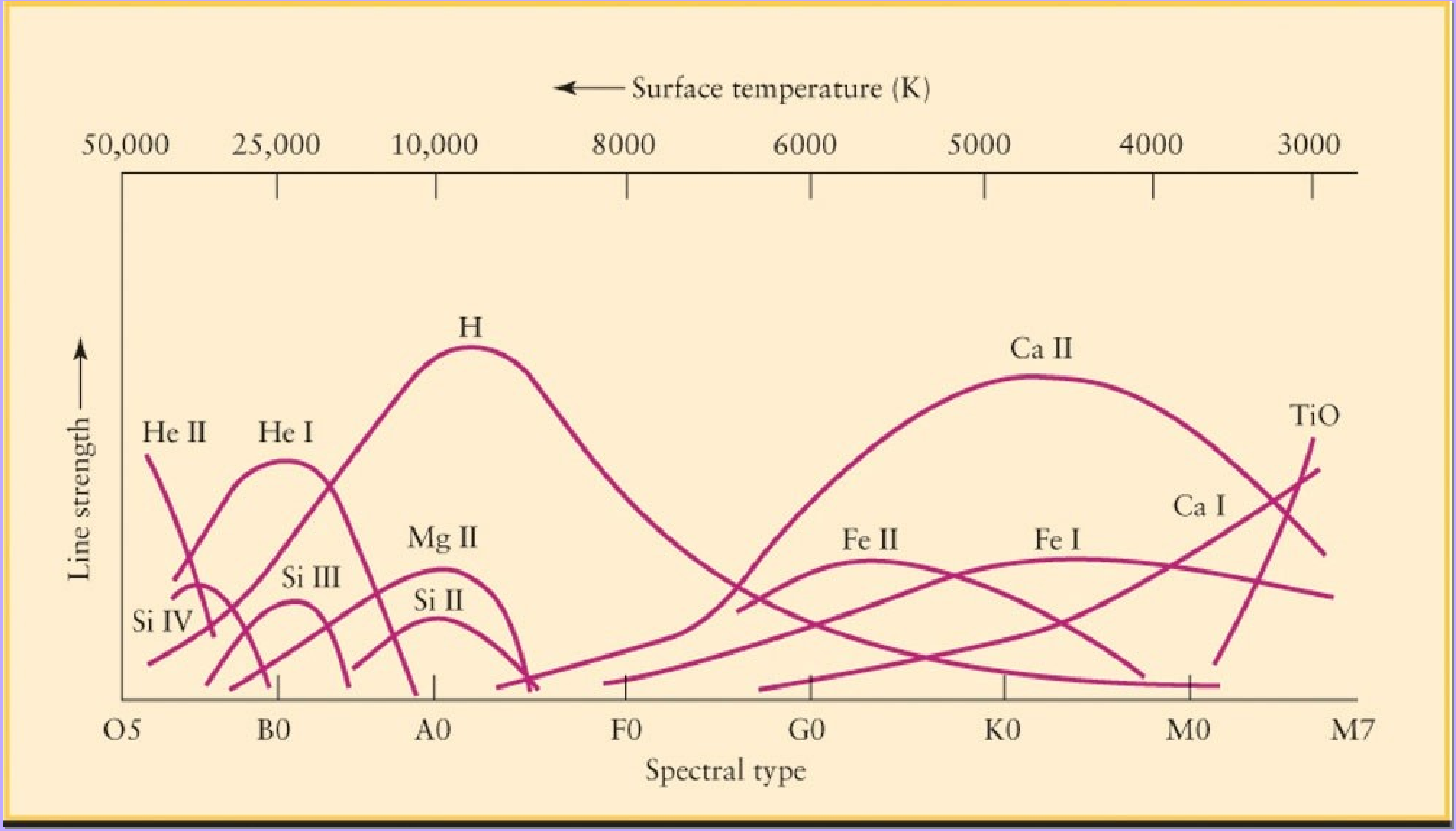
Consider the Hydrogen atom: although the most abundant element in the universe, Balmer (n=2) lines do not show in the spectrum of every star.

- If a star is much hotter than 10,000 K, the photons have such a high energy that they ionize the H atom. With only one electron torn away, H can not produce absorption lines.

- If a star is much cooler than 10,000 K, almost all H atoms are in the lowest energy state (n=1), therefore weak or no Balmer lines.

Spectra and Spectral Classification of Stars

Every type of atom or molecule has a characteristic temperature range in which it produces prominent absorption lines in the visible part of the spectrum.



Spectra and Spectral Classification of Stars

The absorption line spectrum of a star is primarily determined by the blackbody (surface) temperature of the star. The OBAFGKM is a temperature sequence.

Analyzing Absorption Spectra

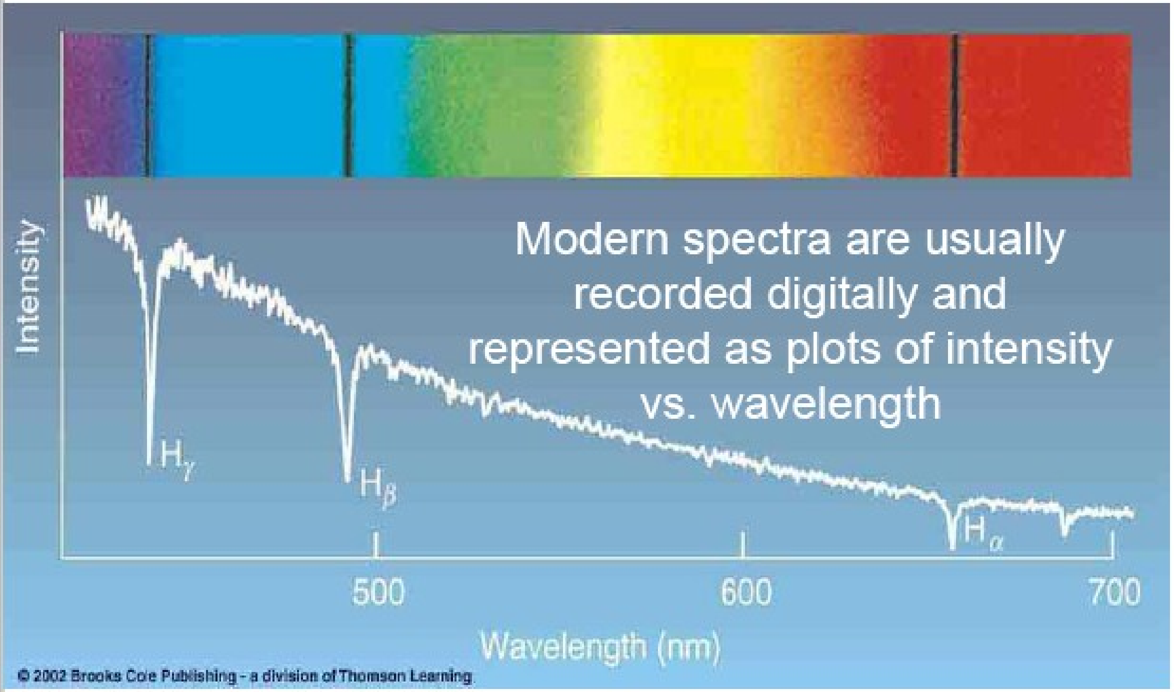
- Each element produces a specific set of absorption (and emission) lines.
- Comparing the relative strengths of these sets of lines, we can study the composition of gases.

TABLE 7-2
The Most Abundant Elements in the Sun

Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	91.0	70.9
Helium	8.9	27.4
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.07	0.8
Neon	0.01	0.2
Magnesium	0.003	0.06
Silicon	0.003	0.07
Sulfur	0.002	0.04
Iron	0.003	0.1

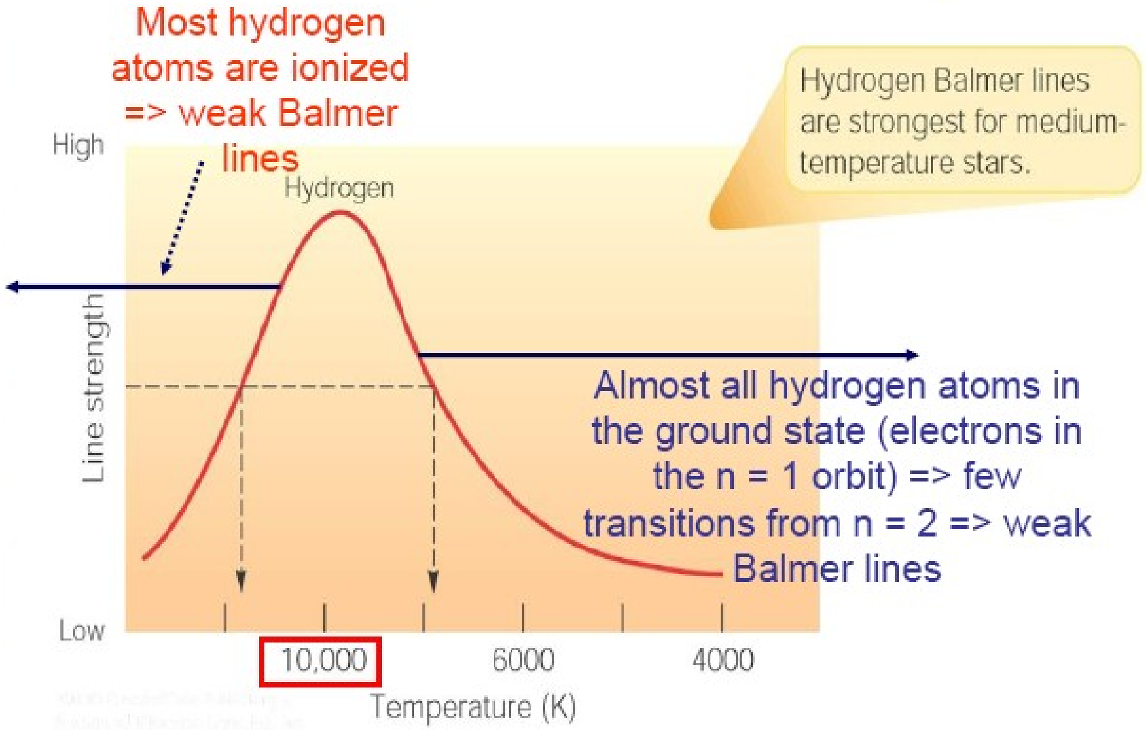
By far the most abundant elements in the Universe

Absorption Spectrum Dominated by Balmer Lines



The Balmer Thermometer

Balmer line strength is sensitive to temperature:



Spectral Classification of Stars (2)

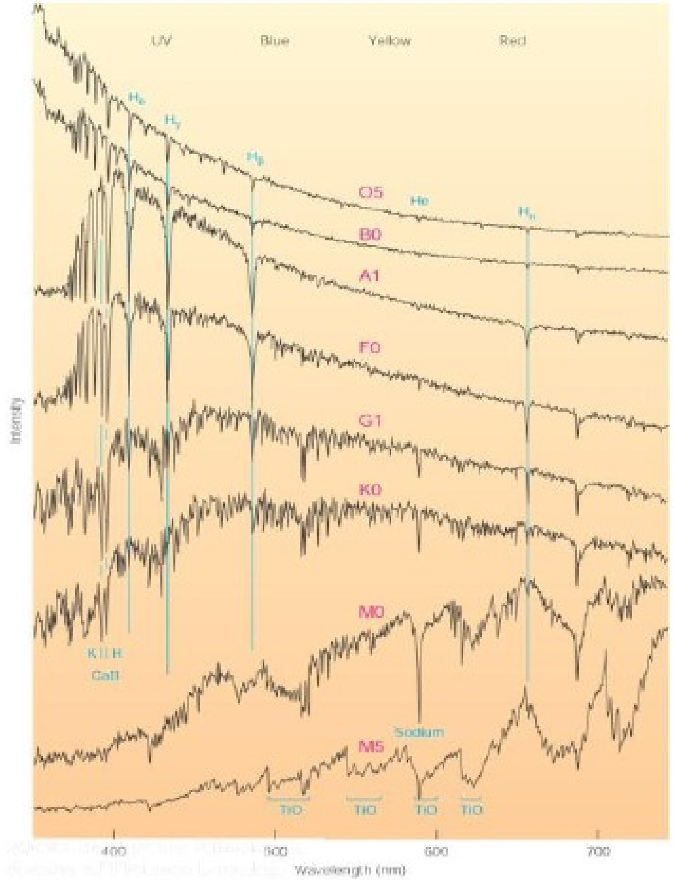
TABLE 7-1
Spectral Classes

Spectral Class	Approximate Temperature (K)	Hydrogen Balmer Lines	Other Spectral Features	Naked-Eye Example
O	40,000	Weak	Ionized helium	Meissa (O8)
B	20,000	Medium	Neutral helium	Achernar (B3)
A	10,000	Strong	Ionized calcium weak	Sirius (A1)
F	7,500	Medium	Ionized calcium weak	Canopus (F0)
G	5,500	Weak	Ionized calcium medium	Sun (G2)
K	4,500	Very weak	Ionized calcium strong	Arcturus (K2)
M	3,000	Very weak	TiO strong	Betelgeuse (M2)

Mnemonics to remember the spectral sequence:

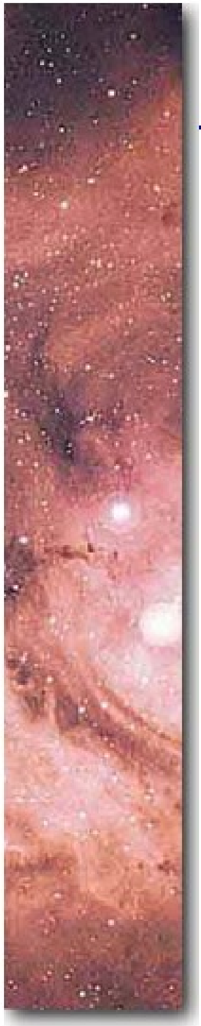
Oh	Oh	Only
Be	Boy,	Bad
A	An	Astronomers
Fine	F	Forget
Girl/Guy	Grade	Generally
Kiss	Kills	Known
Me	Me	Mnemonics

Stellar Spectra

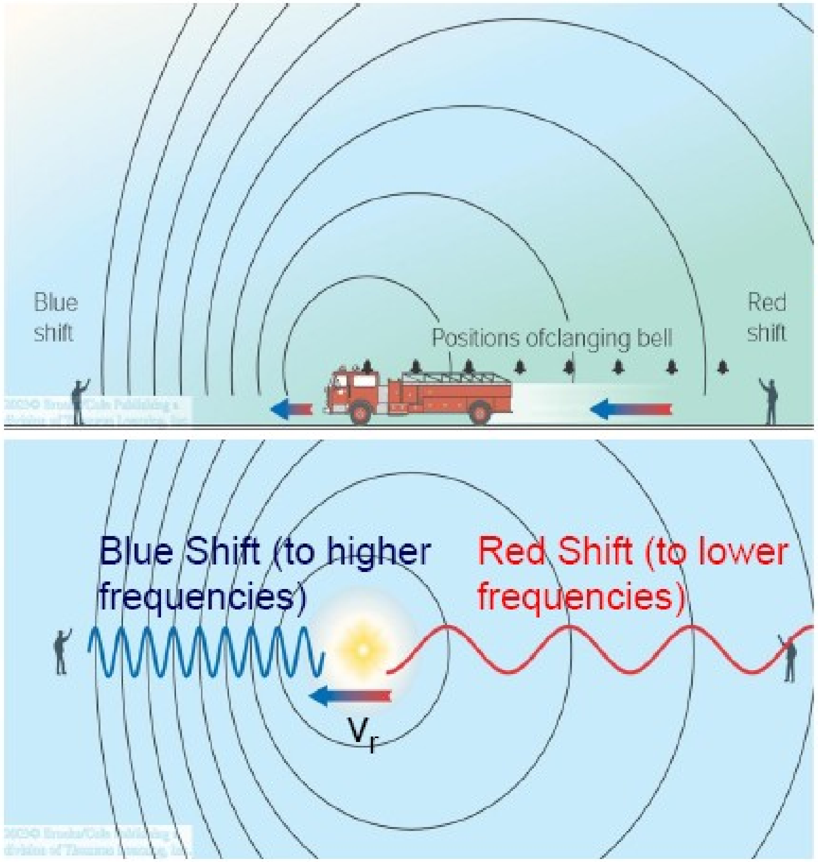


O
B
A
F
G
K
M

Surface temperature



The Doppler Effect (1)



The light of a *moving source* is blue/red shifted by

$$\Delta\lambda/\lambda_0 = v_r/c$$

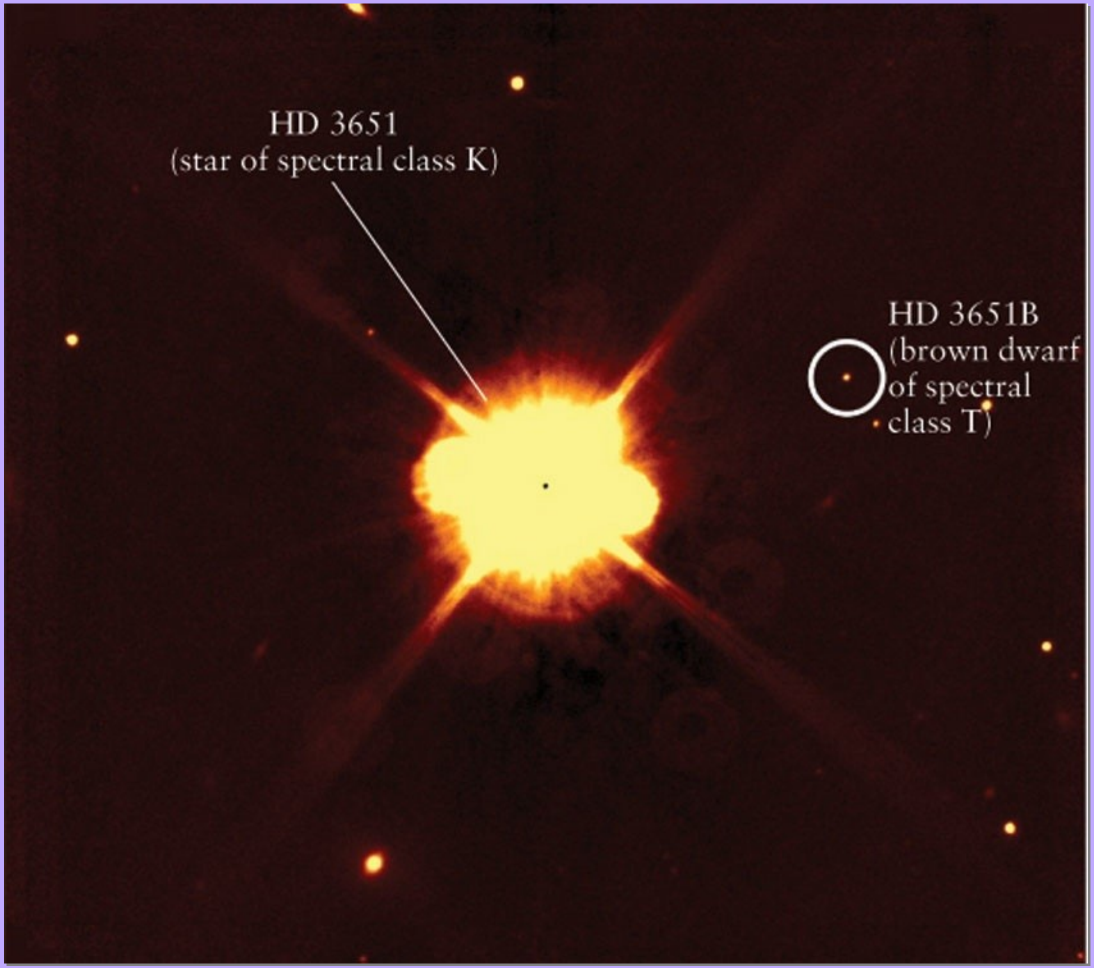
λ_0 = actual wavelength emitted by the source

$\Delta\lambda$ = Wavelength change due to Doppler effect

v_r = radial velocity

Spectra and Spectral Classification of Stars

Two new types have been added to this sequence: L (1300-2500K) and T (below 1300 K) for brown dwarfs: OBAFGKMLT.



CONCLUSIONS:

We can determine the blackbody temperature of a star from:

1) UBV photometry - color indices are related to T

2) From spectra of stars - the OBAFGKM is a temperature sequence.

Stellar Radii

L - luminosity, the amount of light (energy) emitted in the unit of time (J/s = W). In astronomy, we use as a unit $L_{\odot}$ (Sun's luminosity).

b, (F) - apparent brightness, or light flux (W/m^2); the amount of light emitted in the unit of time, per unit area.

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

L - luminosity (W)

d - distance to star (m)

b - brightness (flux) (W/m^2)

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

L - luminosity (W)

R - star's radius (m)

f - flux (W/m^2)

Stellar Radii

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

L - luminosity (W)

R - star's radius (m)

f - flux (W/m^2)

Stefan-Boltzmann law: $f = \sigma T^4$

Therefore:

$$\boldsymbol{L = 4\,\pi\,R^2\,\sigma\,T^4}$$

T - star's surface temperature (K)

σ - Stefan-Boltzmann constant ($5.67\ 10^{-8}\ W\ m^{-2}\ K^{-4}$)

Stellar Radii

Therefore, if we know the luminosity and the surface temperature of a star, we can determine its radius.

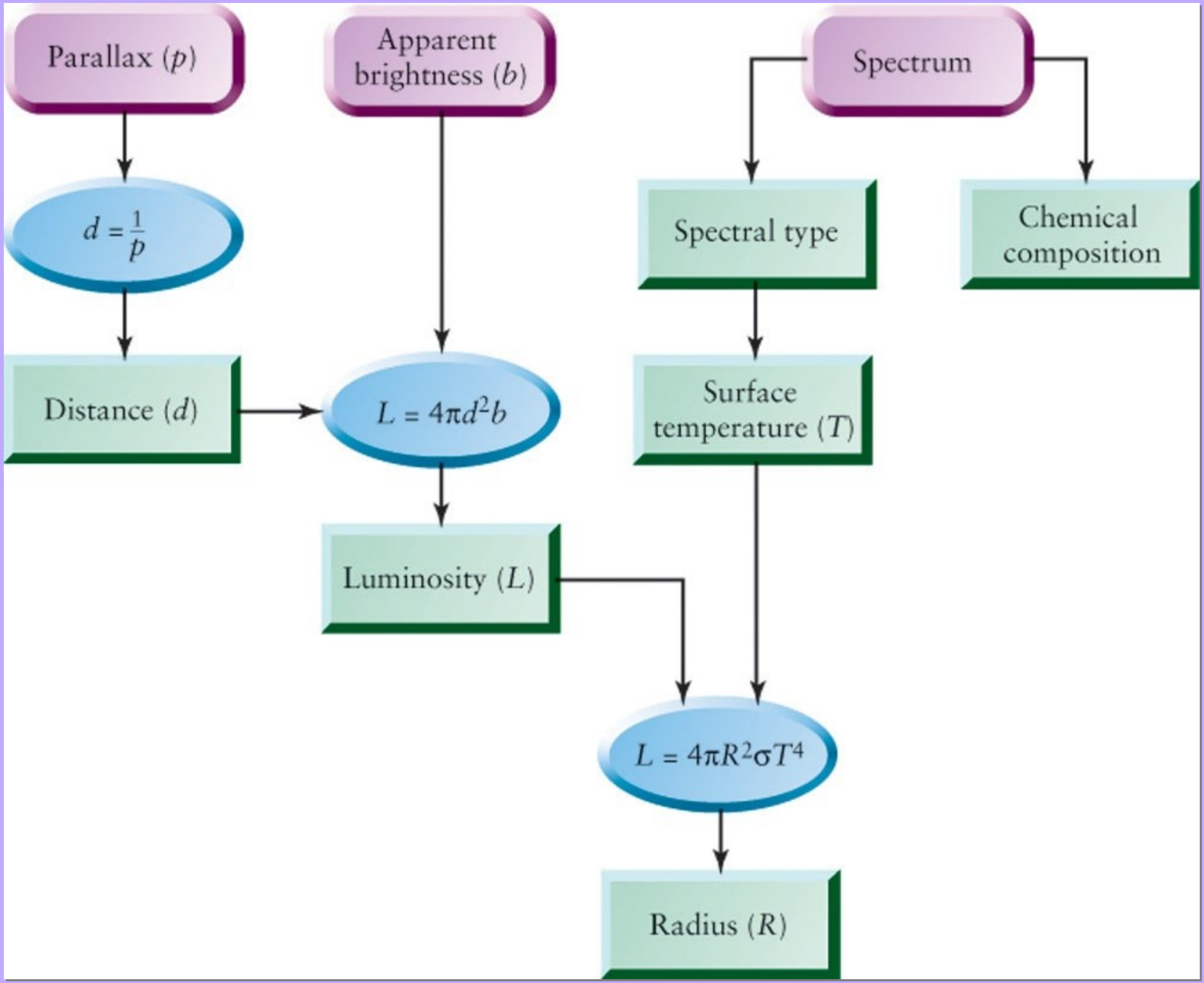
Measuring stellar radii directly is very difficult, because stars are mainly point sources. The apparent sizes we see on an image have to do with the seeing disk and the star's apparent magnitude rather than the intrinsic radius.

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

- a relatively cool star, can nonetheless be quite luminous if it has a large enough radius.

- a relatively hot star, can have very low luminosity, if its radius is very small (i.e., the surface area is small).

From Observed Quantities to Physical Quantities of the Stars



The Hertzsprung-Russel (H-R) Diagram

The most important stellar quantities are the luminosity and the surface temperature. If these are plotted for a collection of stars, they show various sequences. The H-R diagram is a plot of stellar luminosities (absolute magnitudes) versus surface temperatures (spectral type).

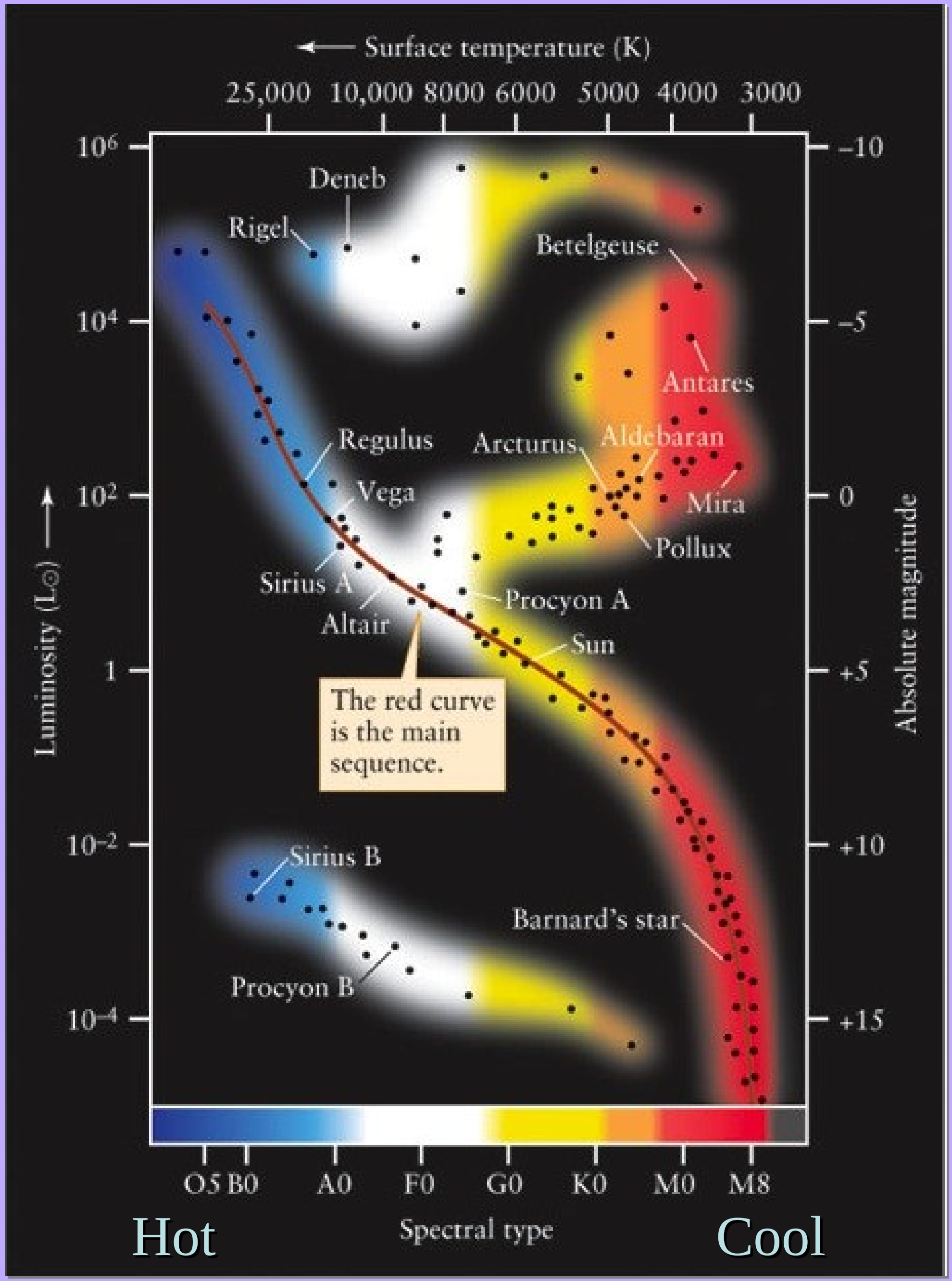
The H-R diagram was introduced - independently - by the Dutch astronomer Ejnar Hertzsprung (1911) and by the American astronomer Henry Norris Russell (1913).

- Hertzsprung used B-V colors as a measure of the surface temperature.

- Russell used spectral types (OBAFGKM) as a measure of the surface temperature.

The H-R Diagram

Bright



Faint

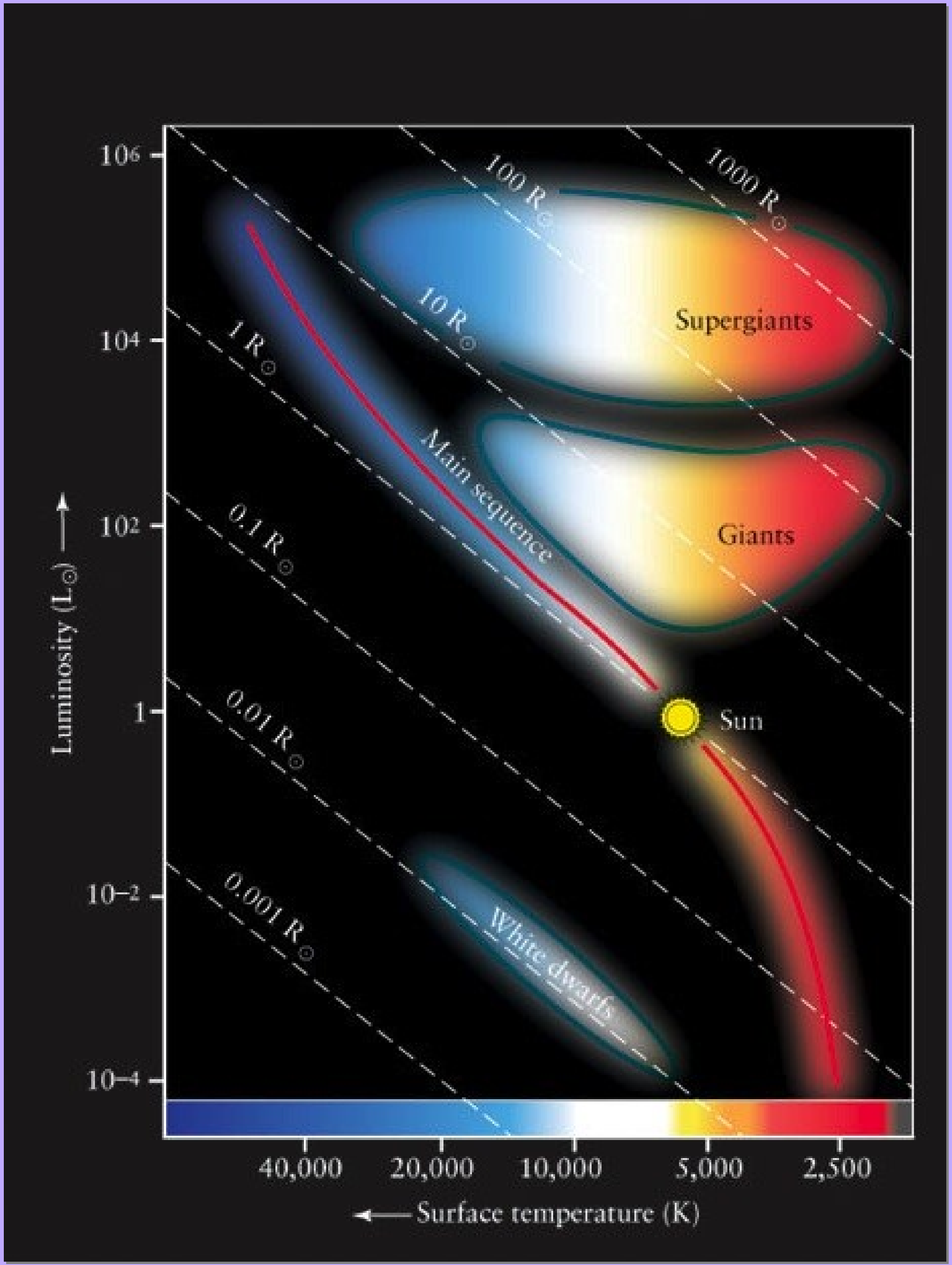
- main sequence (90% of the stars); hydrogen fusion phase

- Sun: main-sequence G2 star with M = +4.8

The H-R Diagram: Radii

- Some stars are very luminous, but cool: therefore they have to have large radii. These are the giants (10-100 $R_{\odot}$) and supergiants (1000 $R_{\odot}$); about 1% of the stars.

- Some stars are underluminous (compared to the main sequence) but very hot; therefore they have to have small radii. These are white dwarfs (0.01 $R_{\odot}$, size of the Earth); about 9% of the stars.



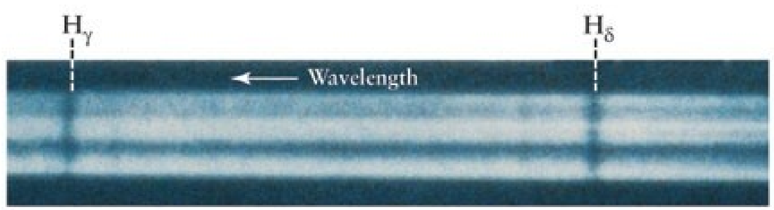
Stellar Spectra Contain Information About A Star's Size

Stars of the same surface temperature can have very different luminosities.

By comparing the spectra of stars of same surface temperature but of different luminosities, one can see:

- a giant star has narrow Balmer absorption lines
- a main-sequence star has broad Balmer absorption lines

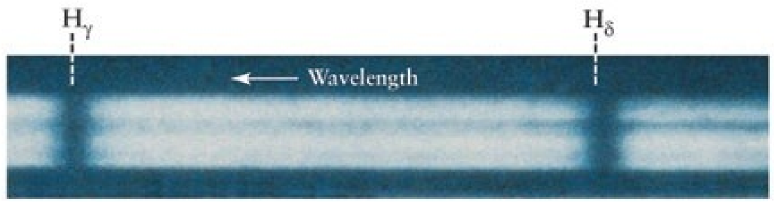
B8



Supergiant

(a) A supergiant star has a low-density, low-pressure atmosphere: its spectrum has narrow absorption lines

B8



Main-sequence

(b) A main-sequence star has a denser, higher-pressure atmosphere: its spectrum has broad absorption lines

Stellar Spectra Contain Information About A Star's Size

Hydrogen lines are affected by the pressure and density of the gas in the atmosphere of the star. The higher the pressure and the density, the more frequently atoms collide and interact with other atoms and ions. These collisions shift the energy levels in the hydrogen atom, and thus broaden the hydrogen spectral lines.

The density of a star's atmosphere is determined by the star's surface gravity ($g = GM/R^2$).

Therefore, the larger the surface gravity, the broader the spectral lines. Main-sequence stars have larger surface gravities than giants: thus their Hydrogen lines are broader.

Stellar Spectra Contain Information About A Star’s Size

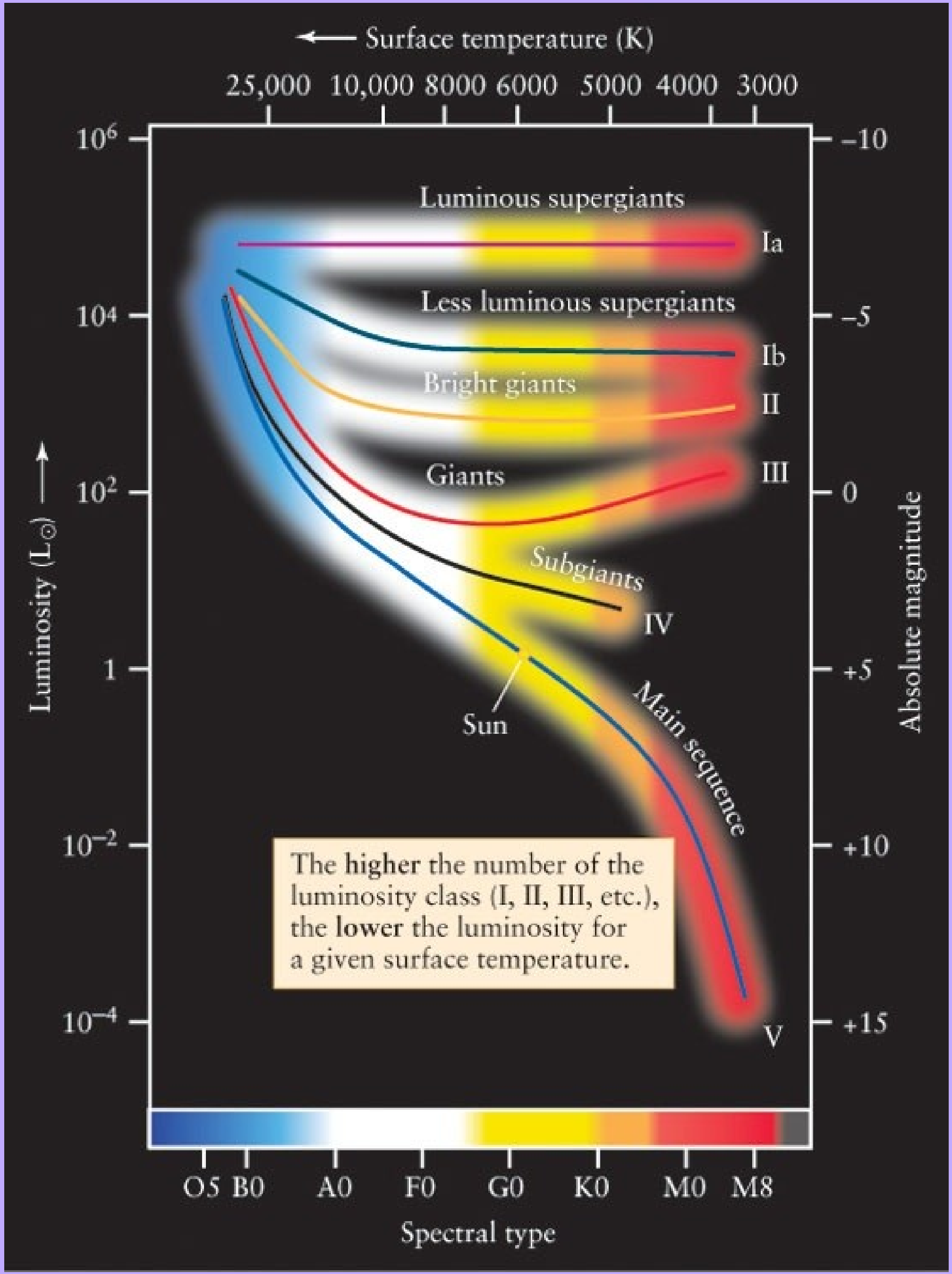
The Luminosity Class

In 1930, W.W. Morgan and P. C. Keenan of the Yerkes Observatory developed a system of luminosity classes based on subtle differences in the spectral lines.

The luminosity class added to the OBAFGKM spectral classification forms the Morgan-Keenan (MK) spectral classification system.

The H-R Diagram: The Luminosity Class

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



The MK Spectral System

The MK system has two dimensions: one for the surface temperature (OBAFGKM) and the other for luminosity (Ia, Ib, II, III, IV, V).

Examples:

- The Sun is a G2 V star
- The Albirio system (β Cygni): K3 II and B8 V

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

- surface temperature - strengths of specific spectral lines

- luminosity class (via surface gravity, and radius) - the broadening of spectral lines

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