ASTR702: Stellar Structure and Evolution

Prof. Loren Anderson

MWF 9:30-10:20

Recommended Text:

Theory of Stellar Structure and Evolution by Prialnik

Logistics

- I will use a mix of powerpoints and written notes (nearly all written notes).

- All class materials available on my website:
https://lorenanderson.faculty.wvu.edu/astr702-stellar-structure

- Homework assigned roughly weekly to be turned in one week after.

- Lowest homework is dropped.

- 50% homework, 15% each midterm, 20% final.

What I hope you will learn in this course

- What are the observed properties of stars?
- Why are stars stable?
- What governs basic stellar properties?
- How do stars generate energy?
- How do stars transport energy?
- What are the different states of matter inside stars?
- How do we make simple stellar models?
- How do different types of stars form, evolve and die?
- What are the different end-points of stellar evolution?
- Special topics: compact objects, binaries, astroseismology
- How do we simplify and understand very complicated problems?

Course Outline

1) What are our astronomical observables? Overview of the HR diagram and the properties of stars. What simplifying assumptions can we make? (1 week)
2) Basic underlying principles such as hydrostatic equilibrium, perfect gas equation of state, virial theorum, stability of self-gravitating spheres. (1 week)
3) Characteristic timescales of evolution, maximum mass of planets and minimum mass for nuclear fusion ignition, maximum stellar mass, dimensional analysis and homology relations. (1 week)
4) Energy generation, nuclear reactions, tunneling, p-p chain, CNO cycle, neutrinos. (2 weeks)
5) Basic physical processes of the gas and radiation inside stars, chemical compositions, equations of state, radiation pressure, degeneracy pressure, Saha equation. (1 week)
6) Heat transfer through radiation, conduction and convection, blackbody radiation, opacity, Rosseland mean. (2 weeks)
7) Equations of stellar structure, polytropes, Chandrasekhar mass, Eddington luminosity, boundary conditions, Lane-Emden equation. (2 weeks)
8) Pre-main sequence evolution, Hayashi track, observations and theories. (1 week)
9) End-points of low-mass, intermediate mass and high-mass stars. (1 week)
10) General relativity, black holes and neutron stars. (1 week)
11) Astroseismology and pulsations (1 week)

What is a star?

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A star is any object which satisfies two conditions:

a) bound by self-gravity

b) radiates energy supplied by an internal source

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Therefore,

1) Stars evolve
2) Stars die

We will start with stars that satisfy a and b and then see how 1) and 2) happen. We'll look at star birth later!

What are our observables?

What are our observables?

1. Mass (in binaries)
2. Distance
3. Spectral Type
4. Luminosity
5. Radius
6. Temperature
7. Composition

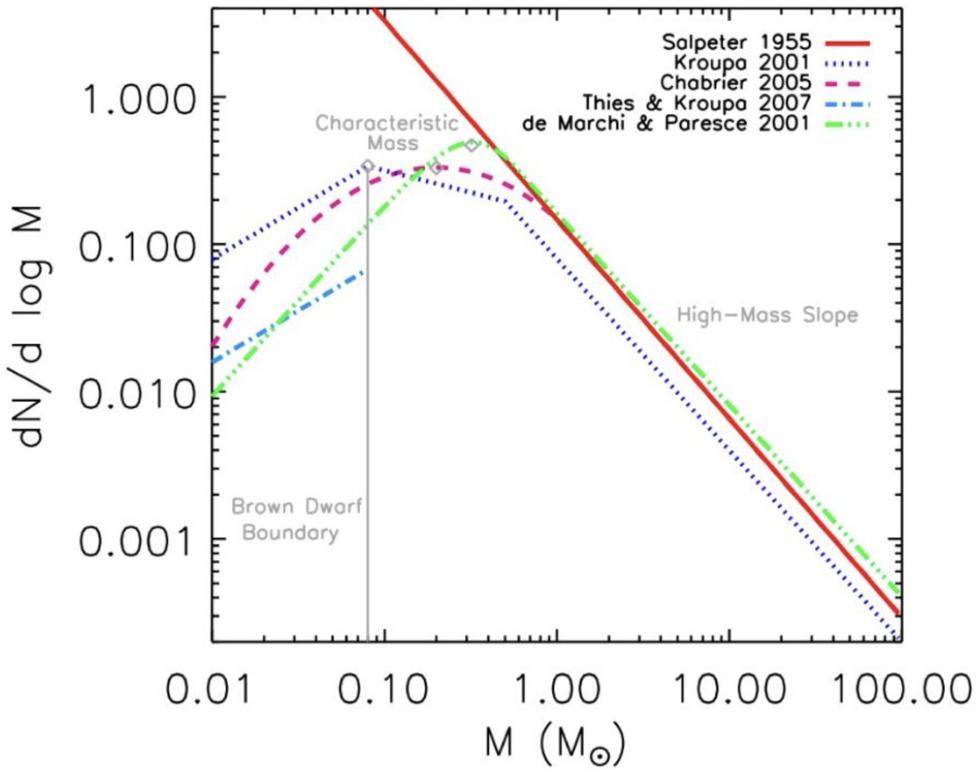


Figure 1: The initial mass function as derived by various authors.

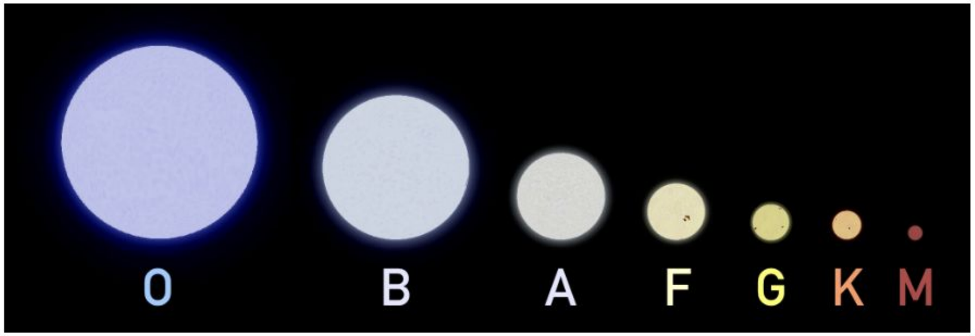
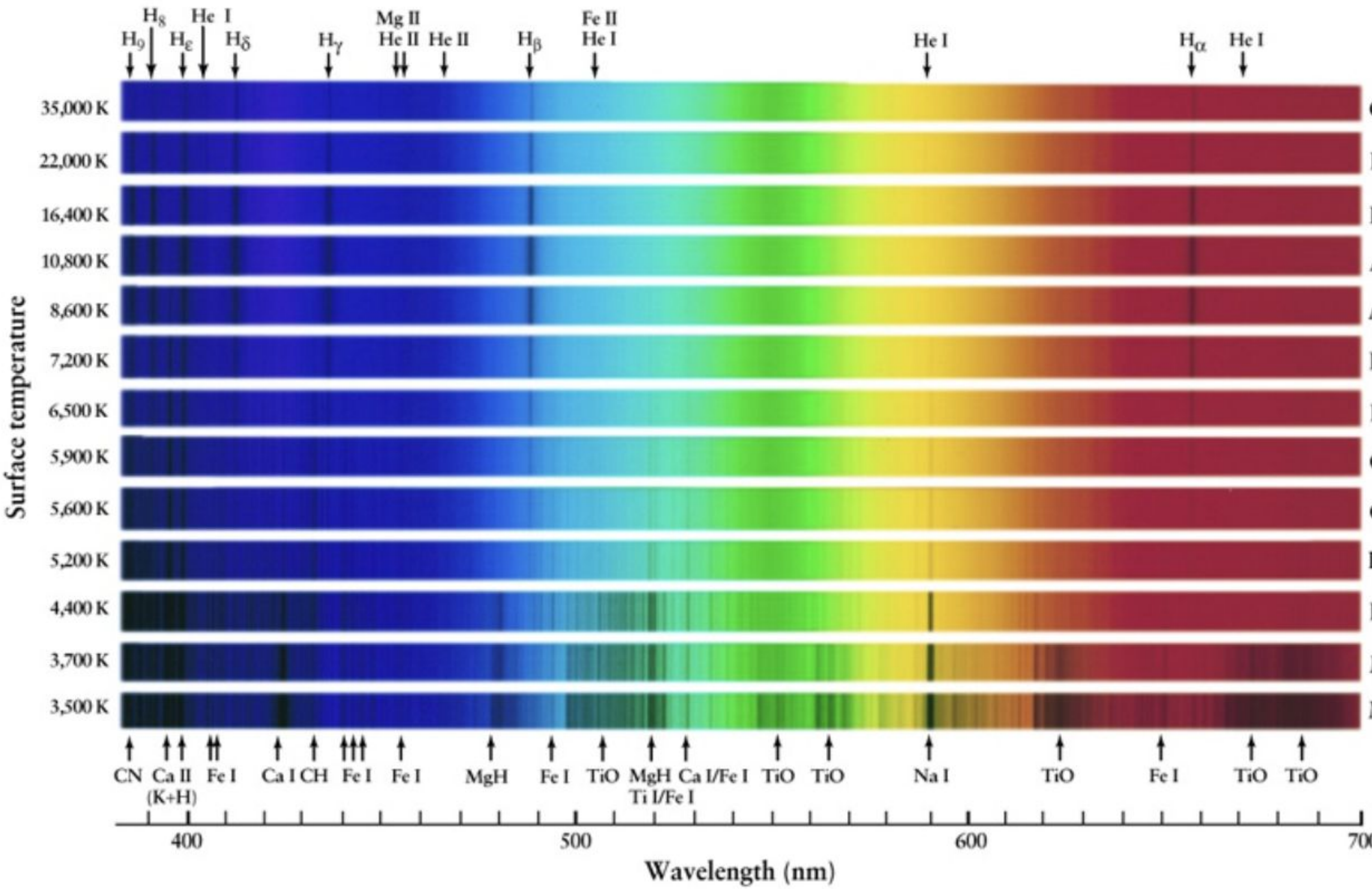


Figure 2: Relative sizes of spectral types.


Surface temperature
Wavelength (nm)
35,000 K
22,000 K
16,400 K
10,800 K
8,600 K
7,200 K
6,500 K
5,900 K
5,600 K
5,200 K
4,400 K
3,700 K
3,500 K
O
B2
B5
A0
A5
F0
F5
G0
G5
K0
K5
M0
M2
400
500
600
700
H9 H8 Hε He I Hδ Hγ Mg II He II He II Hβ Fe II He I He I Hα He I
CN Ca II (K+H) Fe I Ca I CH Fe I Fe I MgH Fe I TiO MgH Ti I/Fe I Ca I/Fe I TiO TiO Na I TiO Fe I TiO TiO

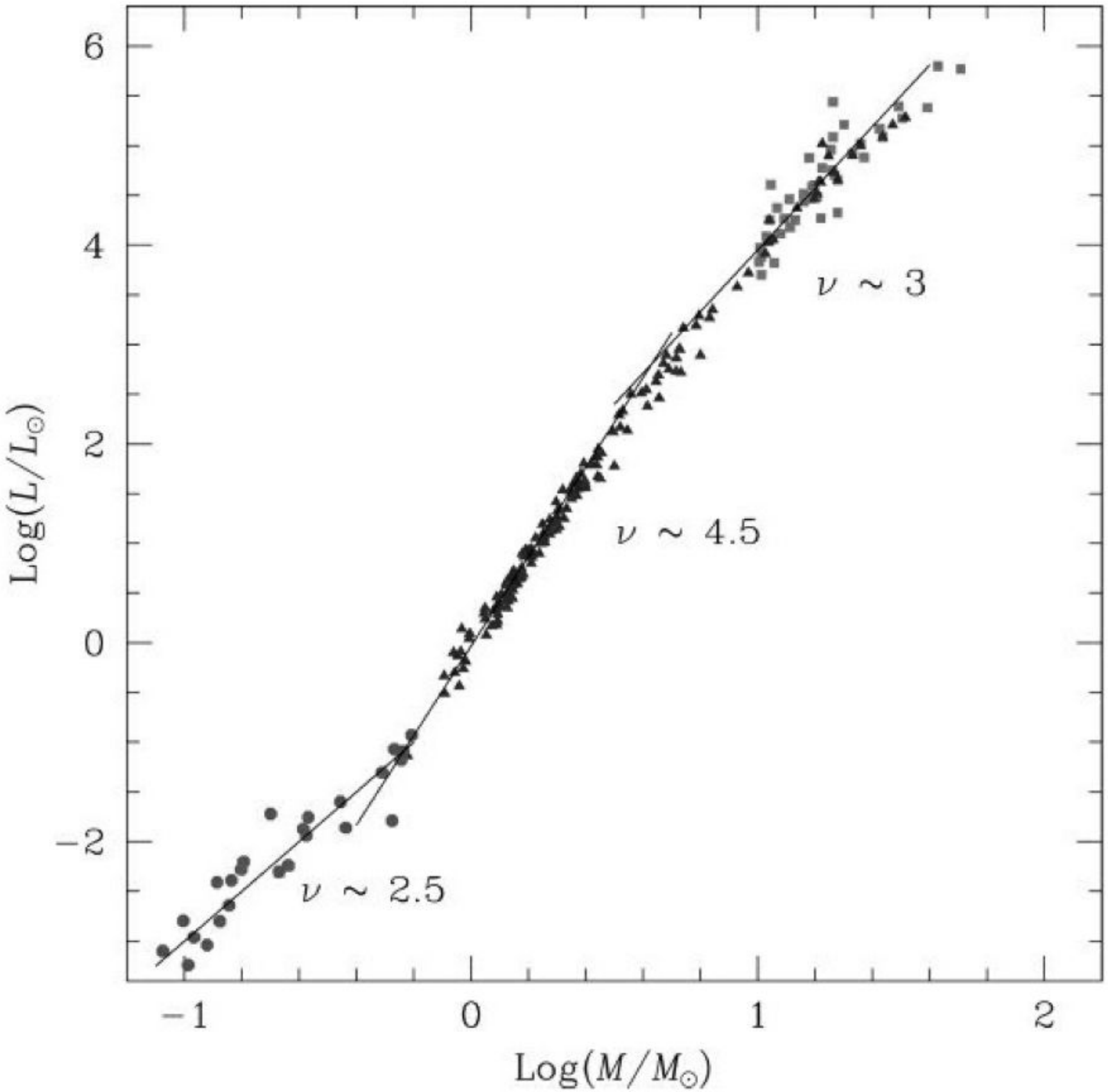


Figure 1.6 The mass-luminosity relation for main-sequence stars. Data from O. Yu. Malkov (2007), *Mon. Not. Roy. Astron. Soc.*, 382, based on detached main-sequence eclipsing binaries (triangles), E. A. Vitrichenko, D. K. Nadyozhin and T. L. Razinkova (2007), *Astron. Lett.*, 33 (squares) and from the compilation by O. Yu. Malkov, A. E. Piskunov and D. A. Shpil'kina (1997), *Astron. Astrophys.*, 320 (dots).

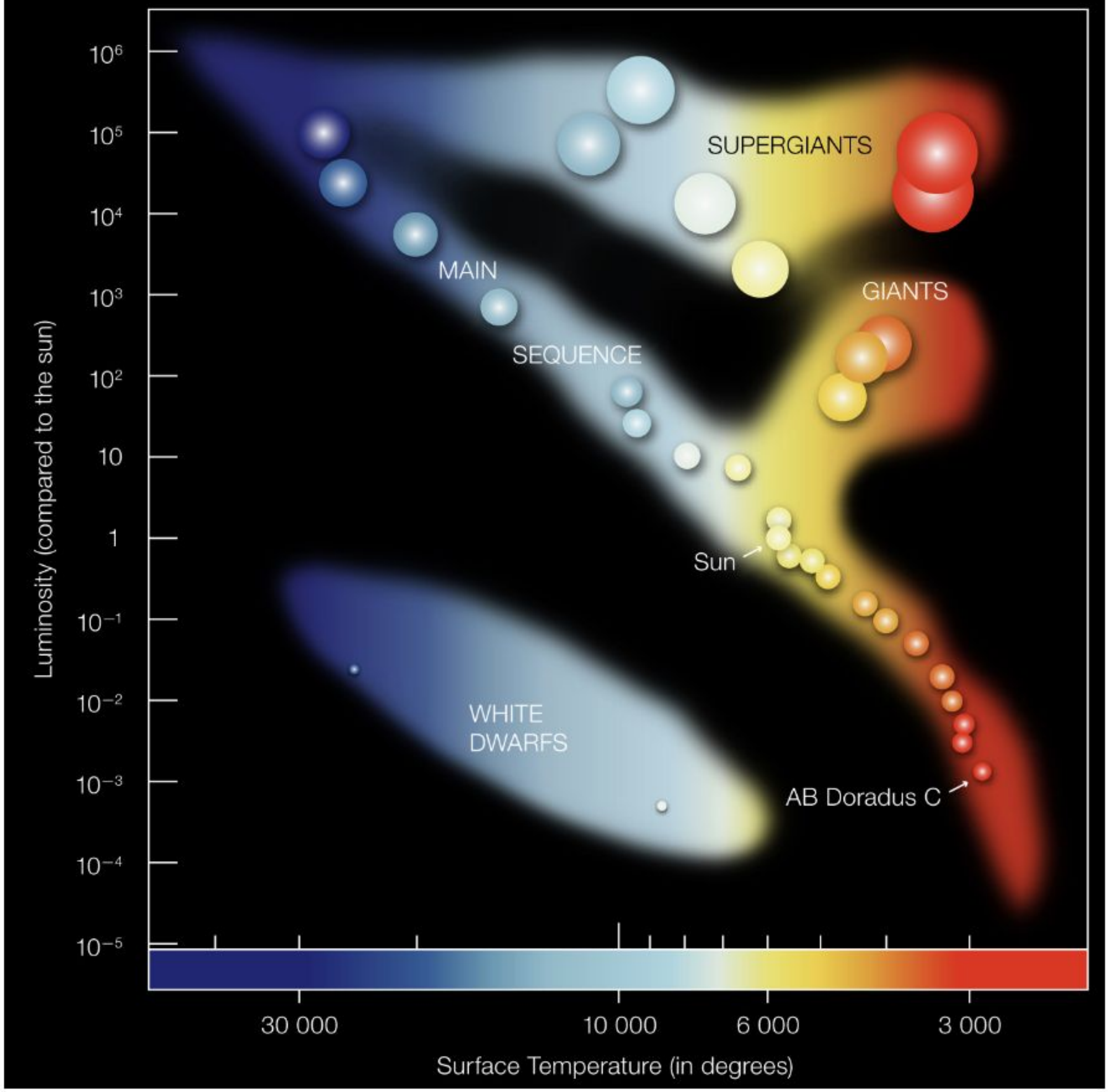


Figure 5: H-R diagram

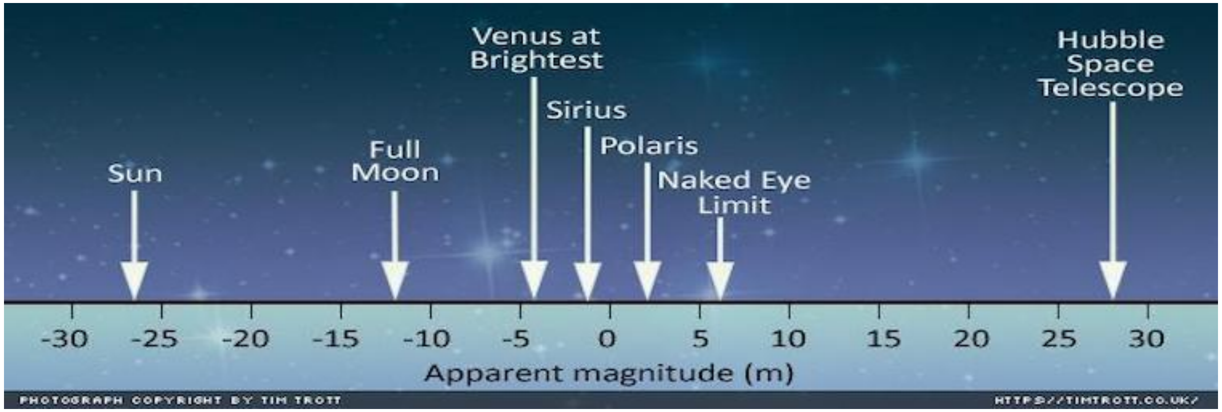
Brightness

We measure *apparent brightness*, or *flux F* (ergs cm^{-2} s^{-1}). This is the amount of energy falling per unit time per unit area on an eye or telescope.

Astronomical brightnesses are often measured in *magnitudes.*

$$m_1 - m_2 = -2.5\log_{10}(F_1/F_2)$$

i.e. an arithmetic difference of 5 means a factor of 100 difference in brightness or flux.



See Stellar Glossary at end of HKT.

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What we really care about is *luminosity*, the amount of energy per unit time.

Solar luminosity is 4×10^{33} erg/s.

See Stellar Glossary at end of HKT.

Distance

Distance

Only direct method is *parallax.*

1 AU = 1.5 x 10^{13} cm.

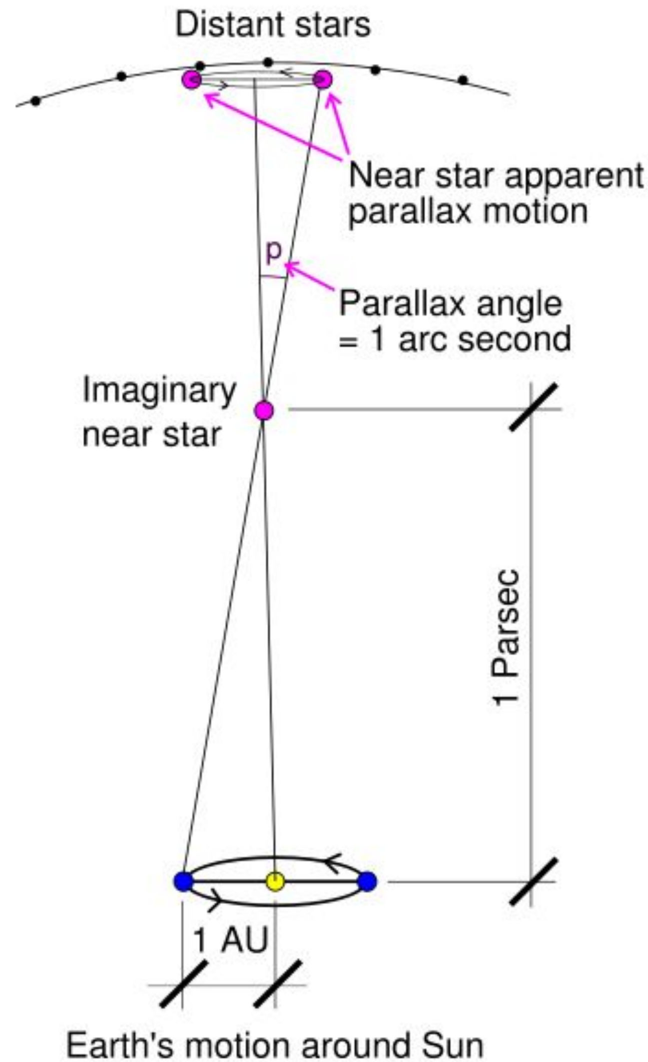
A parsec is the distance corresponding to a parallax angle of 1 arcsecond.

D(pc) = 1/p(arcseconds)

1 pc = 3 x 10^{18} cm = 3.23 ly

1 ly = 9.5 x 10^{17} cm

Proxima Centauri has p = 0.”76 or distance of ____ pc (____ ly).



GAIA will determine the position, parallax, and annual proper motion of 1 billion stars with an accuracy of about 20 µas at 15 mag, and 200 µas at 20 mag.

The distance to about 20 million stars will thus be measured with a precision of 1% or better, and about 200 million distances will be measured to better than 10%. Distances accurate to 10% will be achieved as far away as the Galactic center.

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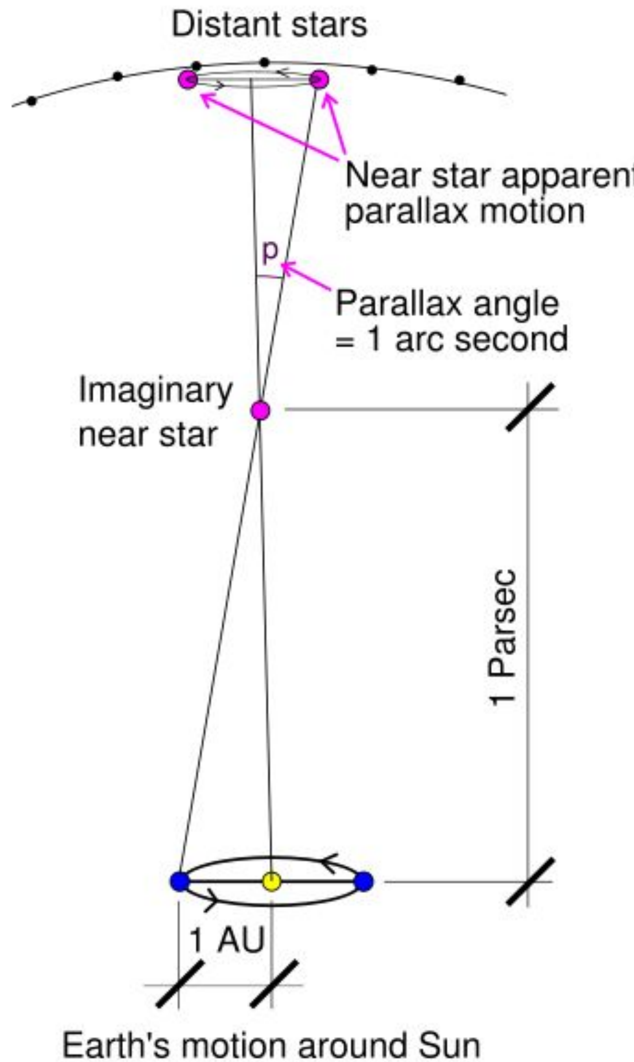
Proxima Centauri has p = 0.”76 or distance of 1.3 pc (4.3 ly).



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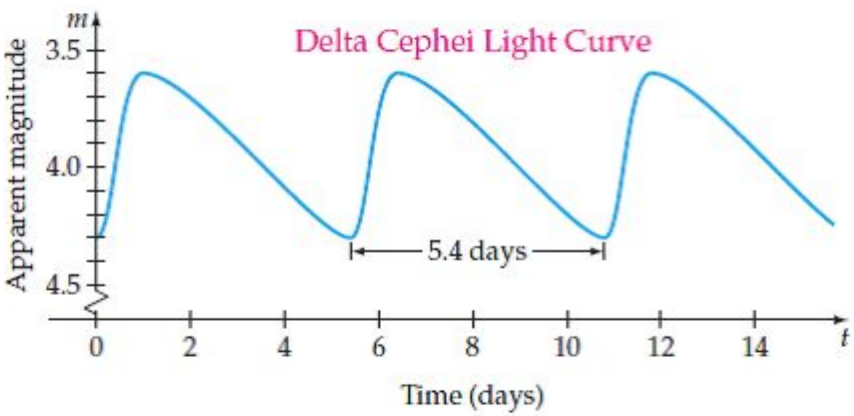
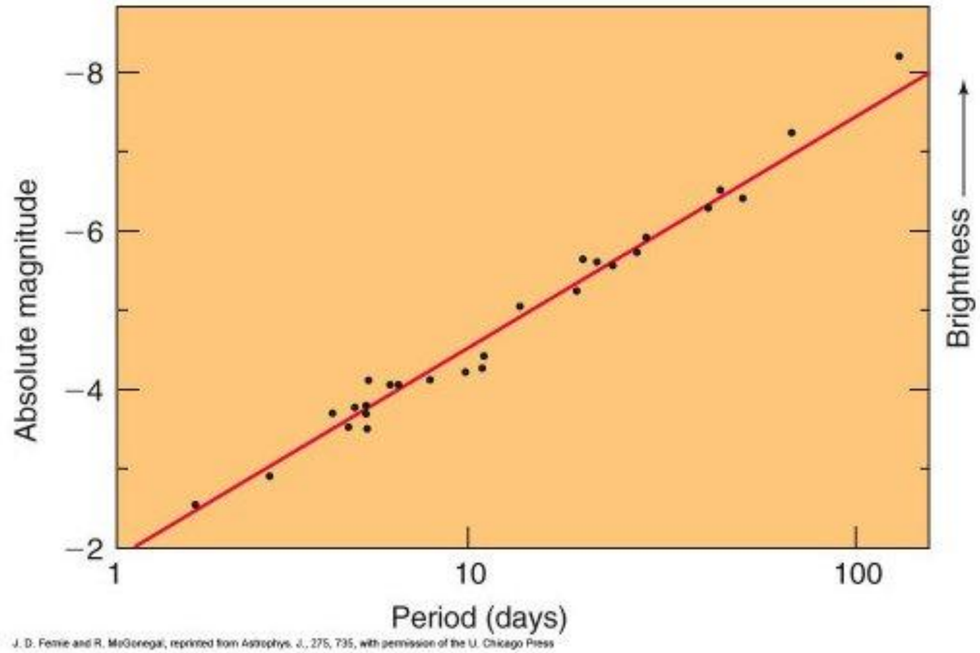
Distance

Most accurate indirect method is through using *Cepheid Variables.* These are bright stars which can be used as *standard candles*.





$$M = -2.8\log_{10}(P) - 1.4$$

Absolute Magnitude

Apparent magnitude a star would have at 10 pc.

$$M = m - 5(\log_{10}d - 1)$$

Absolute magnitude of Sun is 4.83. These generally range from -10 to 17. The *distance modulus* μ is m – M.

The absolute bolometric magnitude M_{bol} (energy over all wavelengths) of the Sun is 4.75.

$M_{bol} = M_v + BC$, where M_v is the absolute visual magnitude and BC is the *bolometric correction.*

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Q: What sign will bolometric corrections have?

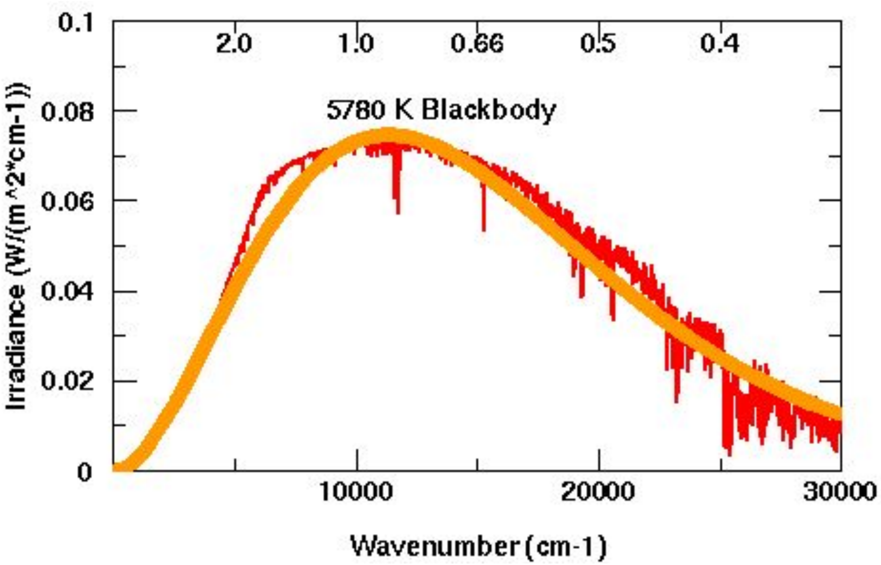
Temperatures

Temperatures

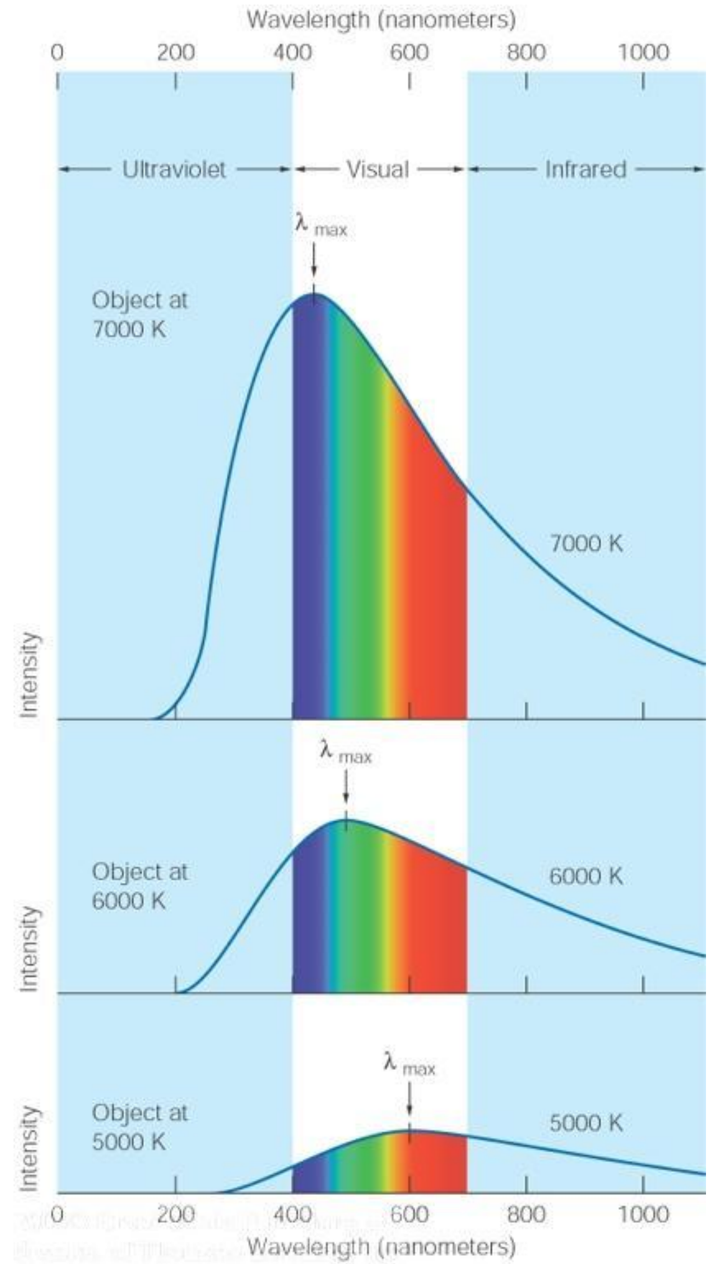
The spectrum of a star's light, or its *continuum,* is very close to a blackbody.

Effective temperature, T_{eff}, is the temperature of a blackbody that would radiate the same flux.

This is a good approximation to temperature of outermost layer, the *photosphere,* where the bulk of emitted radiation originates.



http://cseligman.com/text/sun/blackbody.htm



Colors

The color of a star is measured by comparing its brightness in two different wavelength bands.

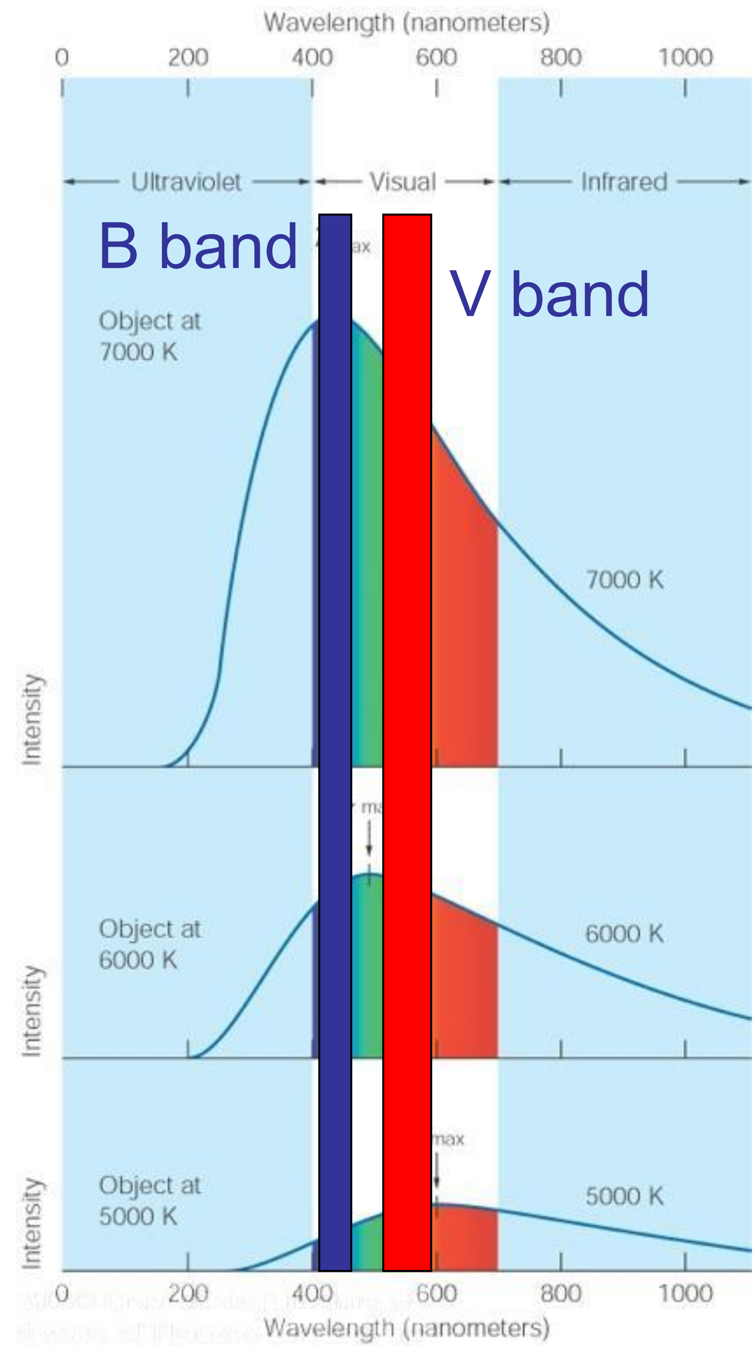
U = ultraviolet = 365 nm

B = blue = 440 nm

V = visual = 550 nm

The *bluer* a star appears, the _____ the color index B – V.

The *hotter* a star is, the _____ its color index B – V.



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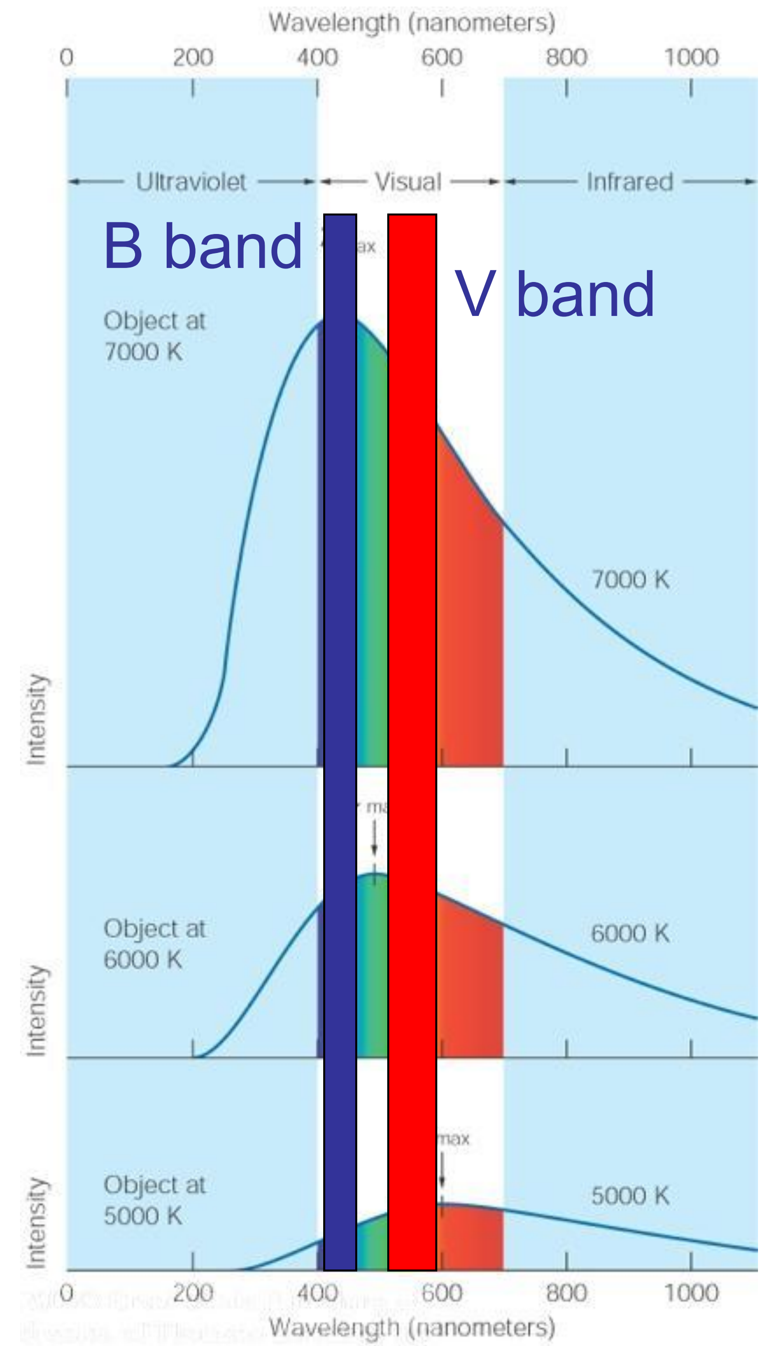

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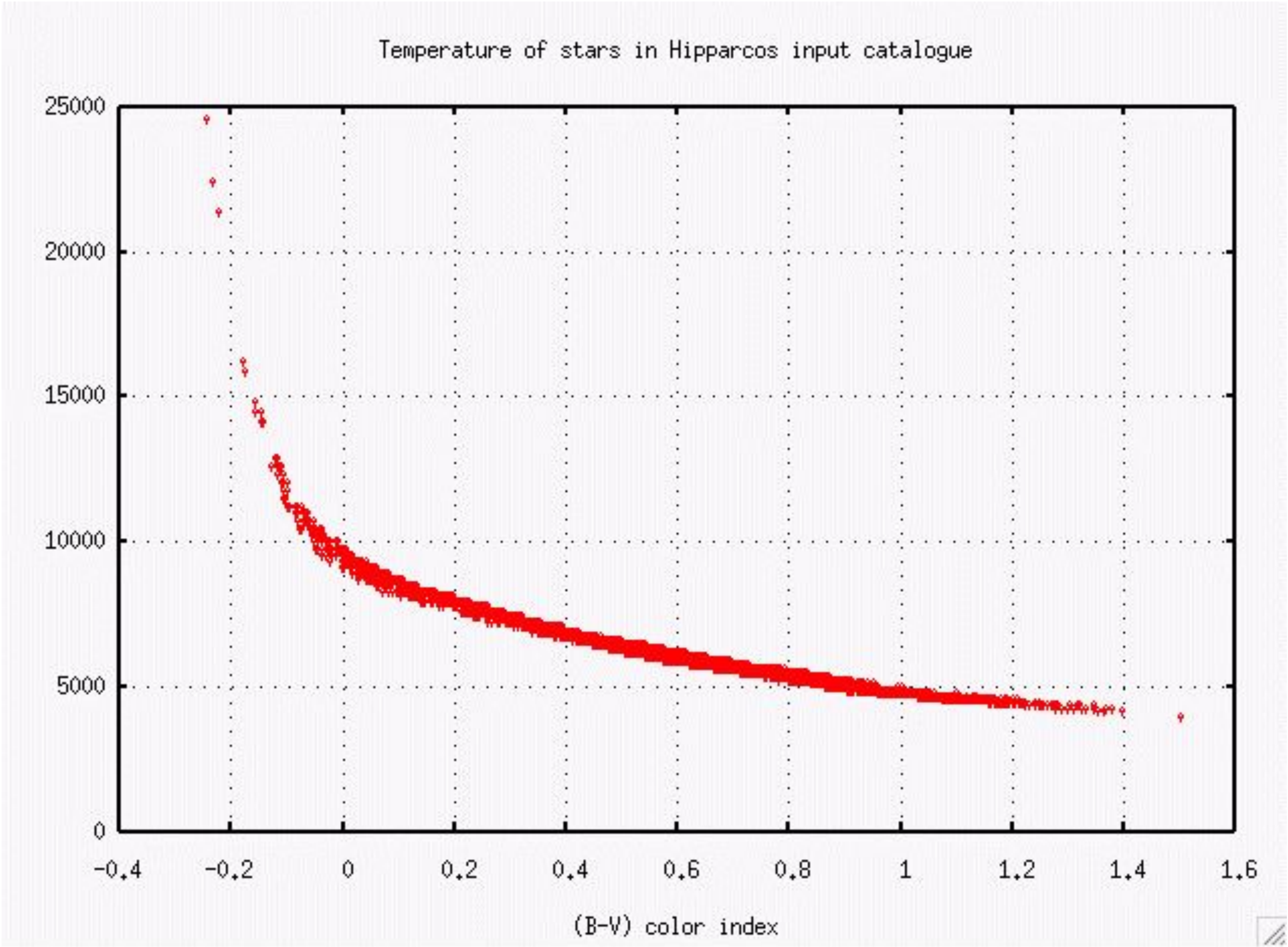
Sun has B-V of 0.65.

Rigel has B-V of -0.03.

Betelgeuse has B-V of 1.86.

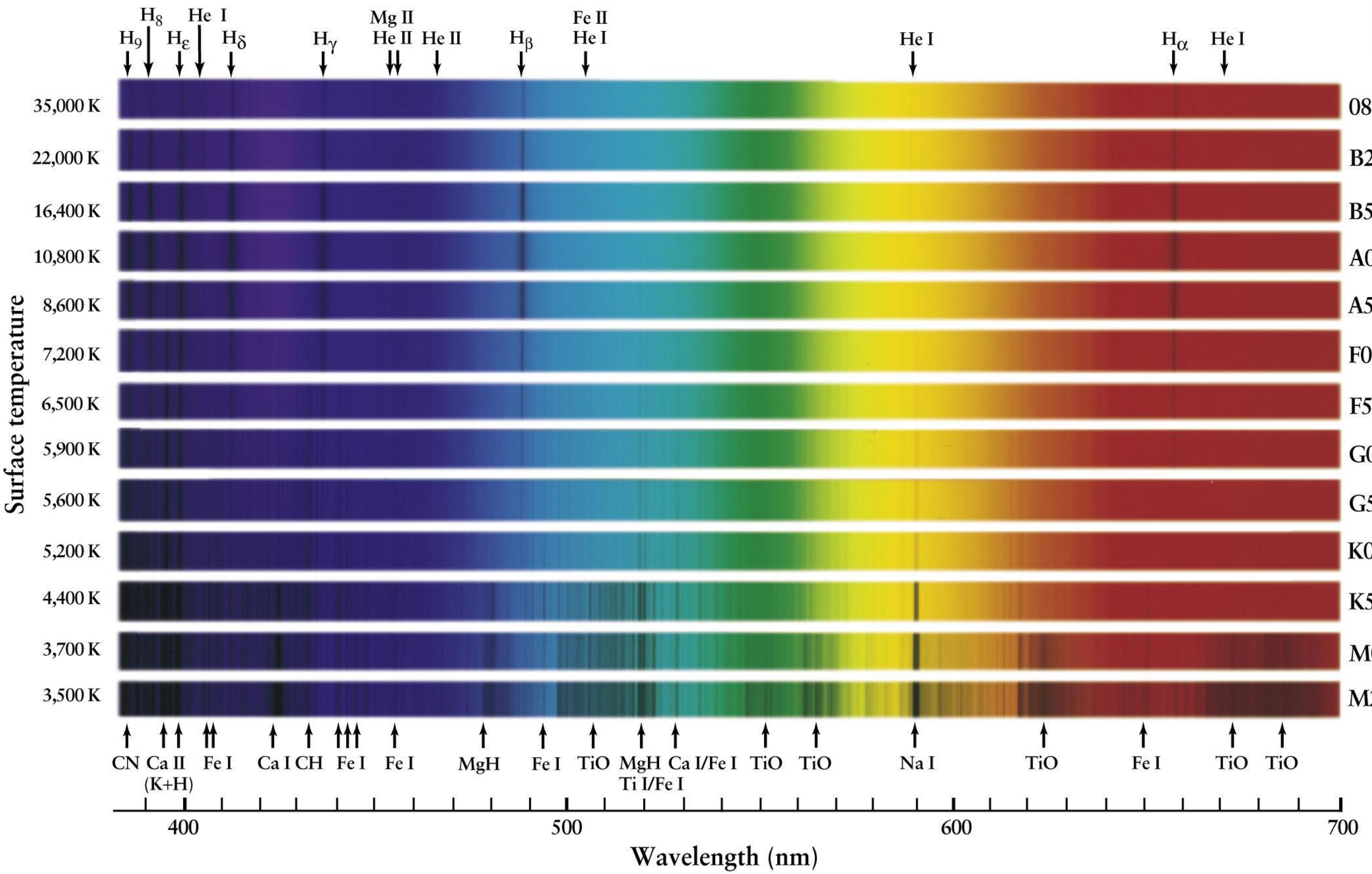

Temperature of stars in Hipparcos input catalogue
25000
20000
15000
10000
5000
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
(B-V) color index

Compositions

Compositions

Balmer Series

n	λ, air (nm)
3	656.3
4	486.1
5	434.0
6	410.2
7	397.0
∞	364.6

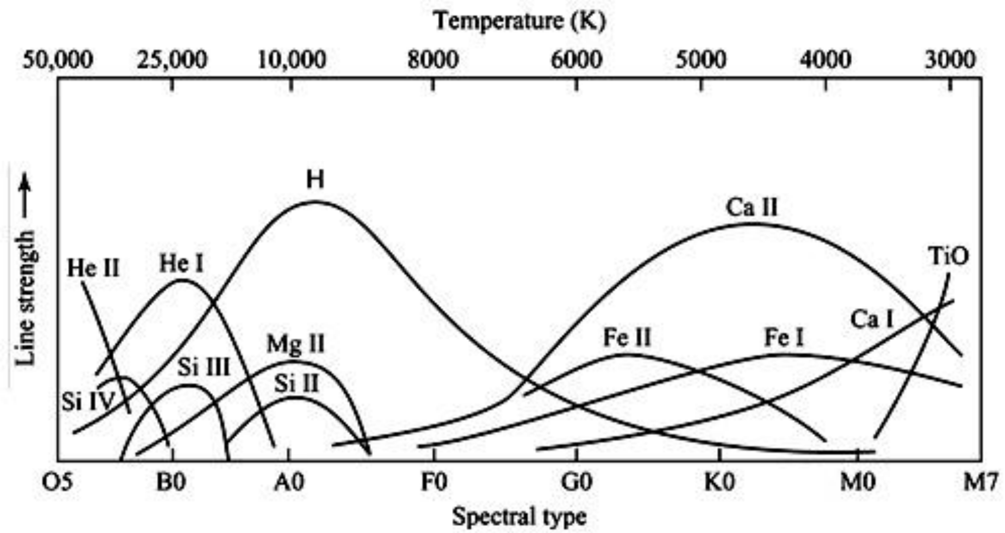


Compositions

Often we will talk about *abundances*. The abundance of iron in a star

is $[Fe/H] = \log[n(Fe)/n(H)]_{star} - \log[n(Fe)/n(H)]_{sun}$

where n(Fe) and n(H) are the number densities of Iron and Hydrogen.



We'll also use *mass fractions*. Canonical mass fractions of hydrogen, helium, and "metals" will be taken as X = 0.73, Y = 0.25, Z = 0.02.

Table 7. Present-day solar mass fractions and He abundance

Present-Day:	Z/X	X	Y	Z	A(He)
this work	0.0191	0.7390	0.2469	0.0141	10.925
[05A1], [07G]	0.0165	0.7392	0.2486	0.0122	10.93
[98G]	0.0231	0.7347	0.2483	0.0169	10.93

Lodders et al. 2009

Spectral Classes

Class	Temperature	Conventional color	Apparent color[7][8]	Mass (solar masses)	Radius (solar radii)	Luminosity	Hydrogen lines	% of all Main Sequence Stars[9]
O	30,000–60,000 K	blue	blue	64 $M_\odot$	16 $R_\odot$	1,400,000 $L_\odot$	Weak	~0.00003%
B	10,000–30,000 K	blue to blue white	blue white	18 $M_\odot$	7 $R_\odot$	20,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	white	3.1 $M_\odot$	2.1 $R_\odot$	40 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellowish white	white	1.7 $M_\odot$	1.4 $R_\odot$	6 $L_\odot$	Medium	3%
G	5,000–6,000 K	yellow	yellowish white	1.1 $M_\odot$	1.1 $R_\odot$	1.2 $L_\odot$	Weak	7.6%
K	3,500–5,000 K	orange	yellow orange	0.8 $M_\odot$	0.9 $R_\odot$	0.4 $L_\odot$	Very weak	12.1%
M	2,000–3,500 K	red	orange red	0.4 $M_\odot$	0.5 $R_\odot$	0.04 $L_\odot$	Very weak	76.45%

Subclasses within each type from 0-9 in order of decreasing temperature. Sun is a G2 star.

Only bad astronomers forget generally known mnemonics

Radii

Radii

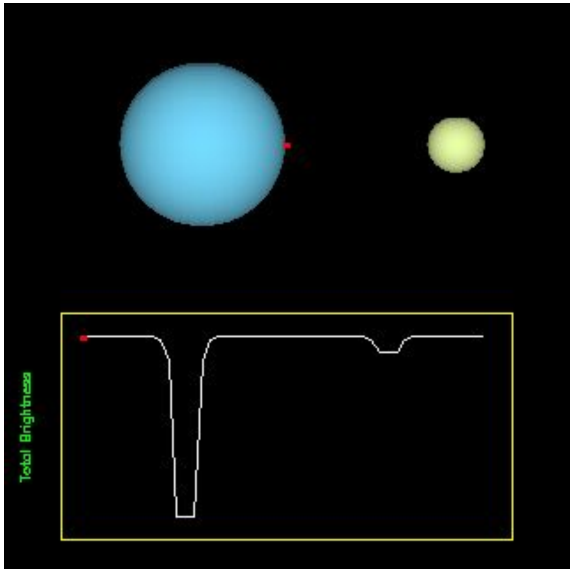
1) For two stars of same spectral type and known distances, make use of Stephan-Boltzmann Law.

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

2) For binary stars, can use eclipses.

3) Can measure directly through optical interferometry for the brightest stars.

Radius of Sun is 7×10^{10} cm.



Masses

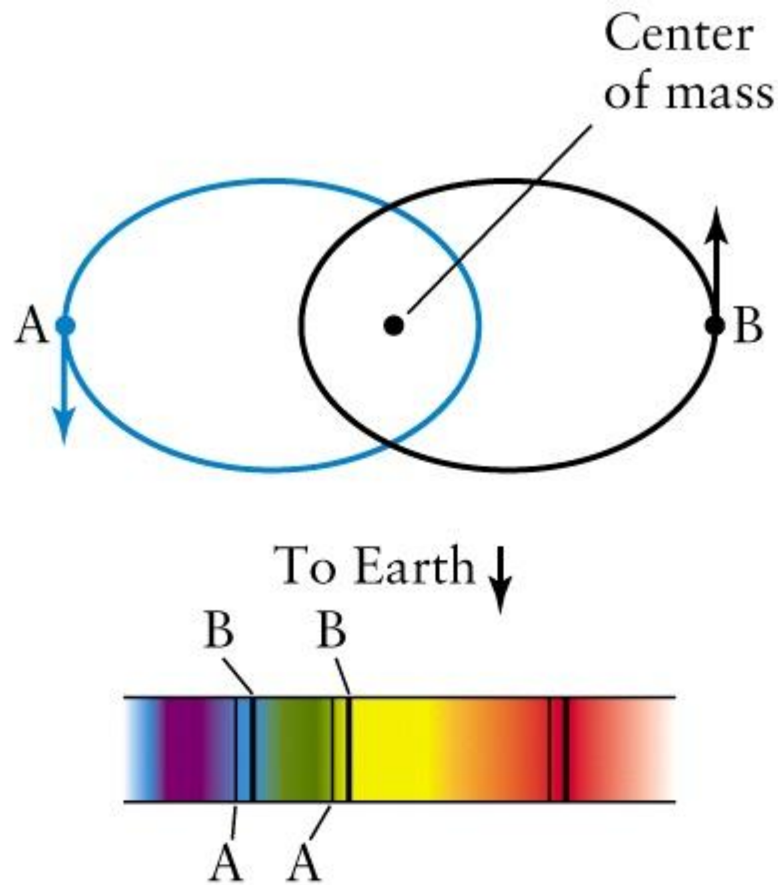
Masses

$$M_A + M_B = \frac{a_{AU}^3}{P_y^2} \qquad M_A a_A = M_B a_B \qquad (M_A \text{ and } M_B \text{ in units of solar masses})$$

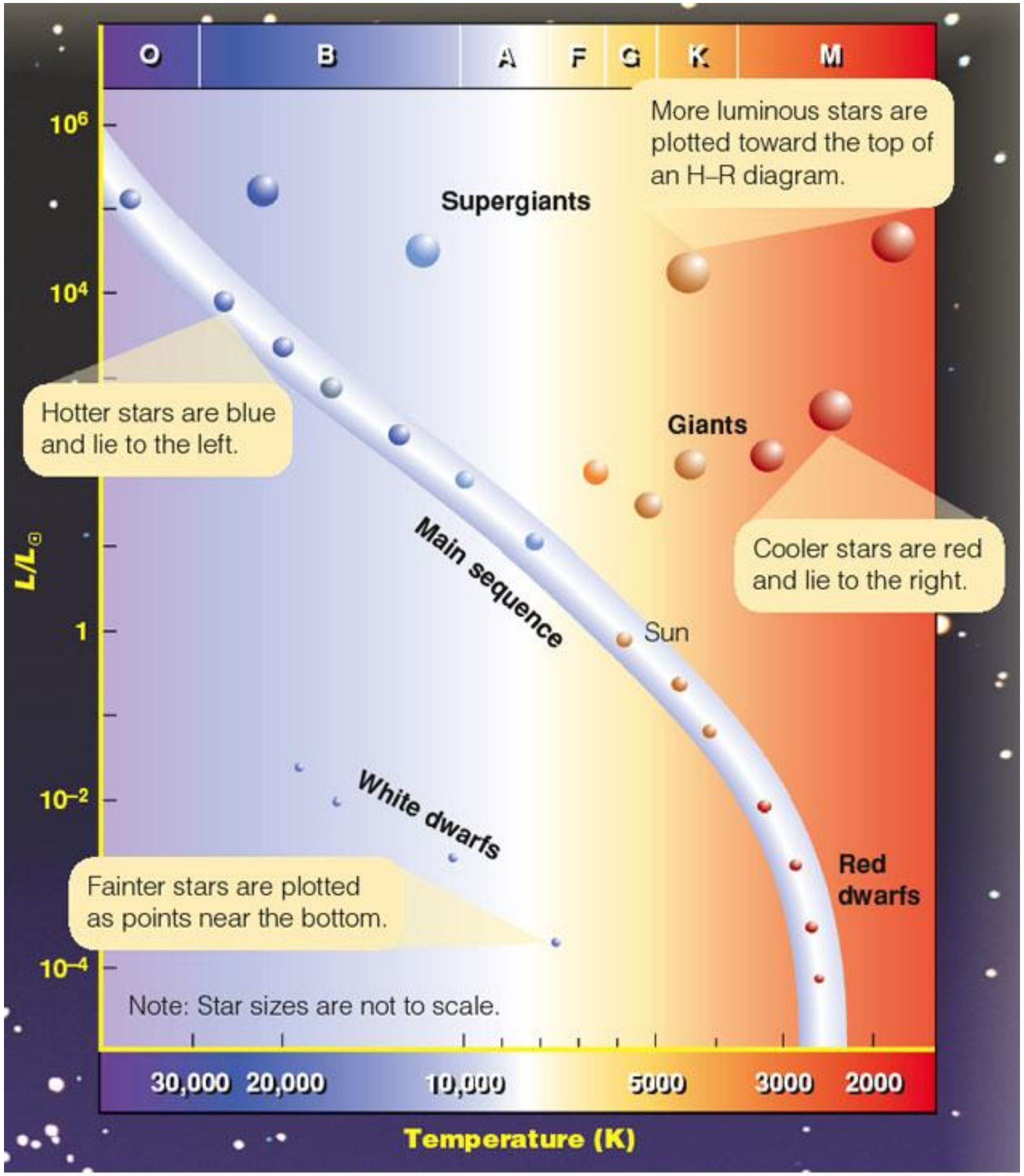
Many thousands of spectroscopic binaries, thousands of visual binaries and 50 eclipsing binaries.

Best measurements for eclipsing binaries, as we know orbit orientation.

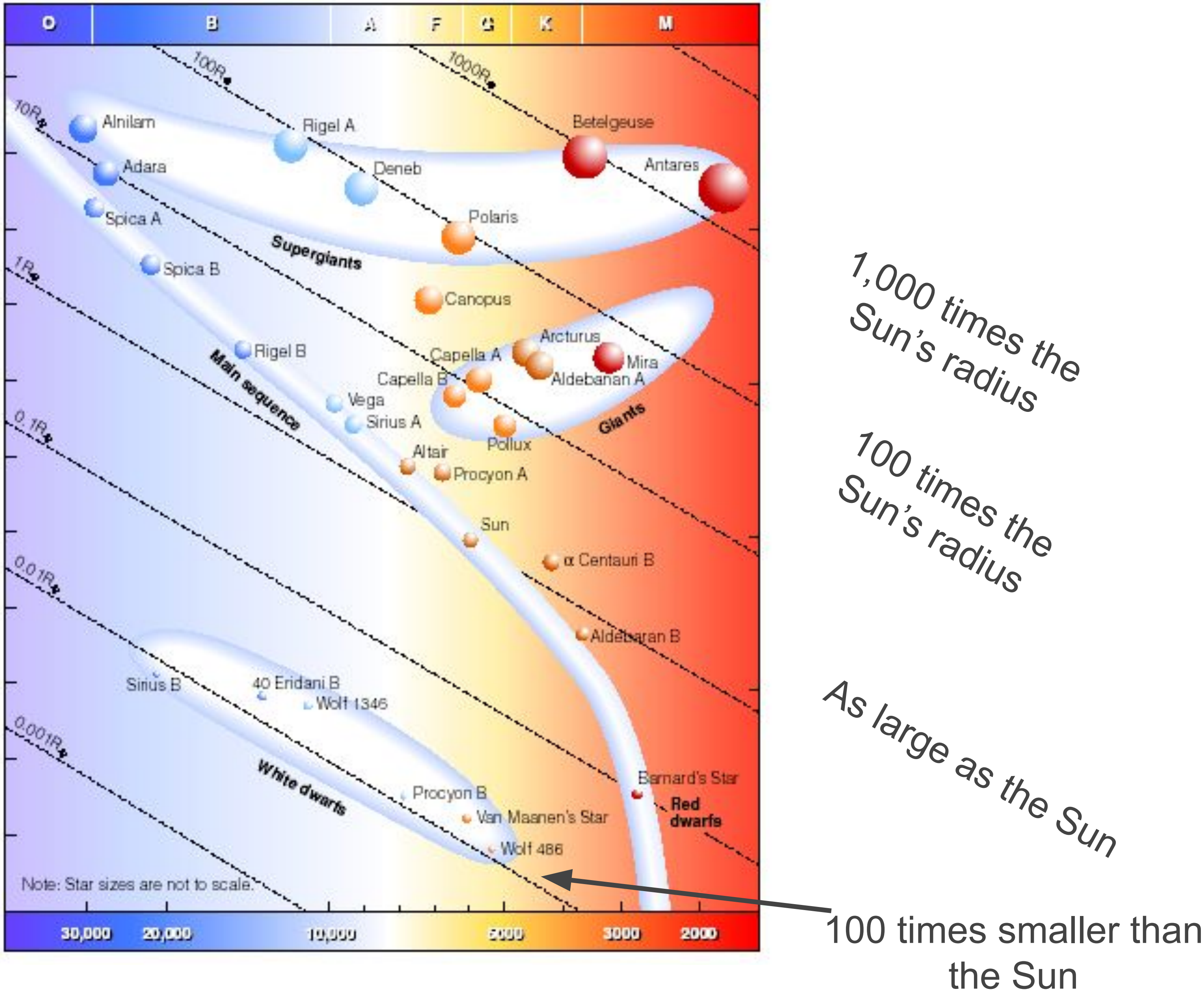
Mass of Sun is 2×10^{33} g.



The Hertzsprung Russell Diagram



Radii of Stars in the HR Diagram



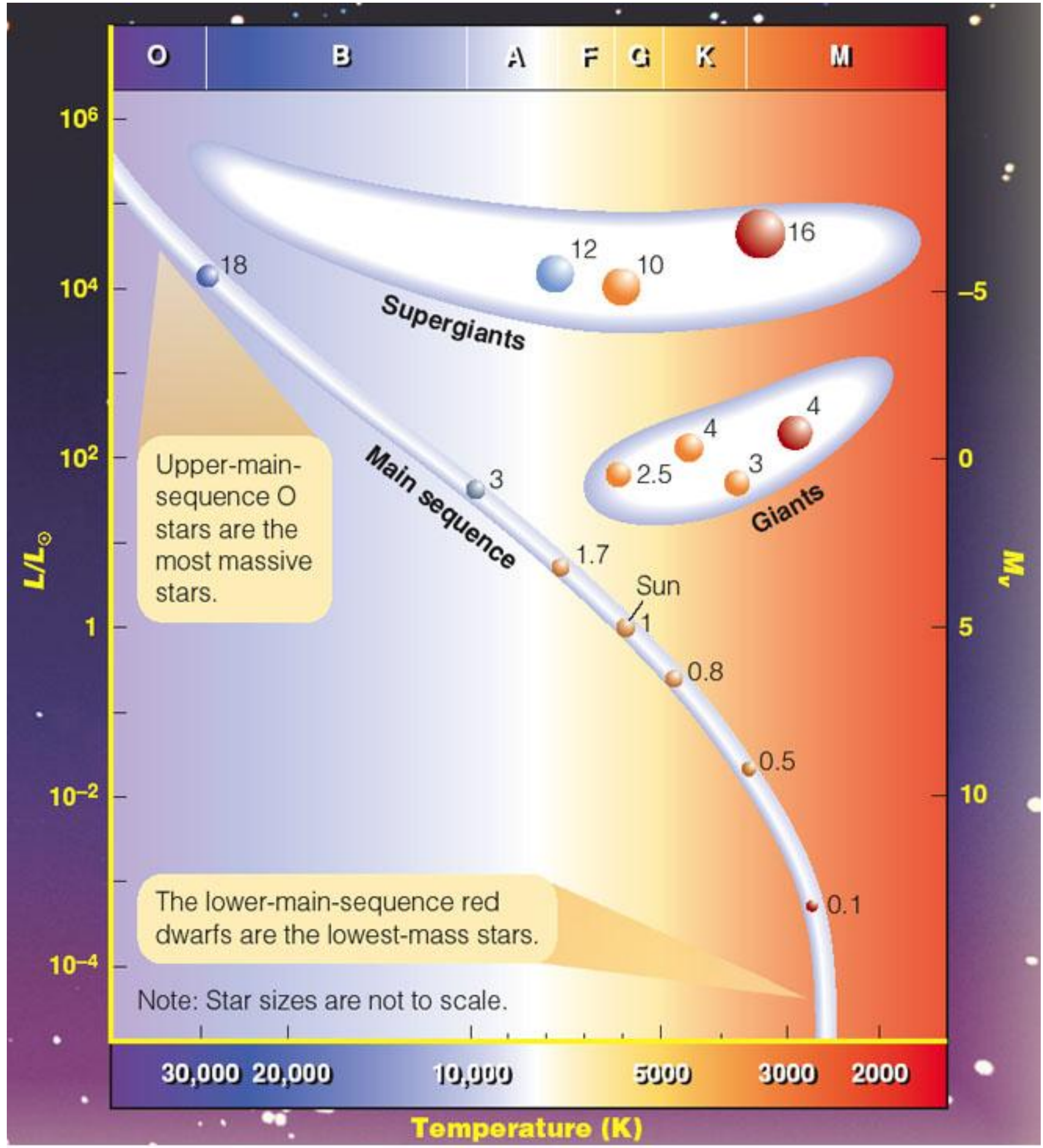
Masses of Stars in the HR Diagram

The higher a star's mass, the more luminous it is:

$$L \sim M^{3.5}$$

Q: How will stellar lifetime depend on mass?

$$t_{life} \sim M^{?}$$



Masses of Stars in the HR Diagram

The higher a star's mass, the more luminous (brighter) it is:

$$L \sim M^{3.5}$$

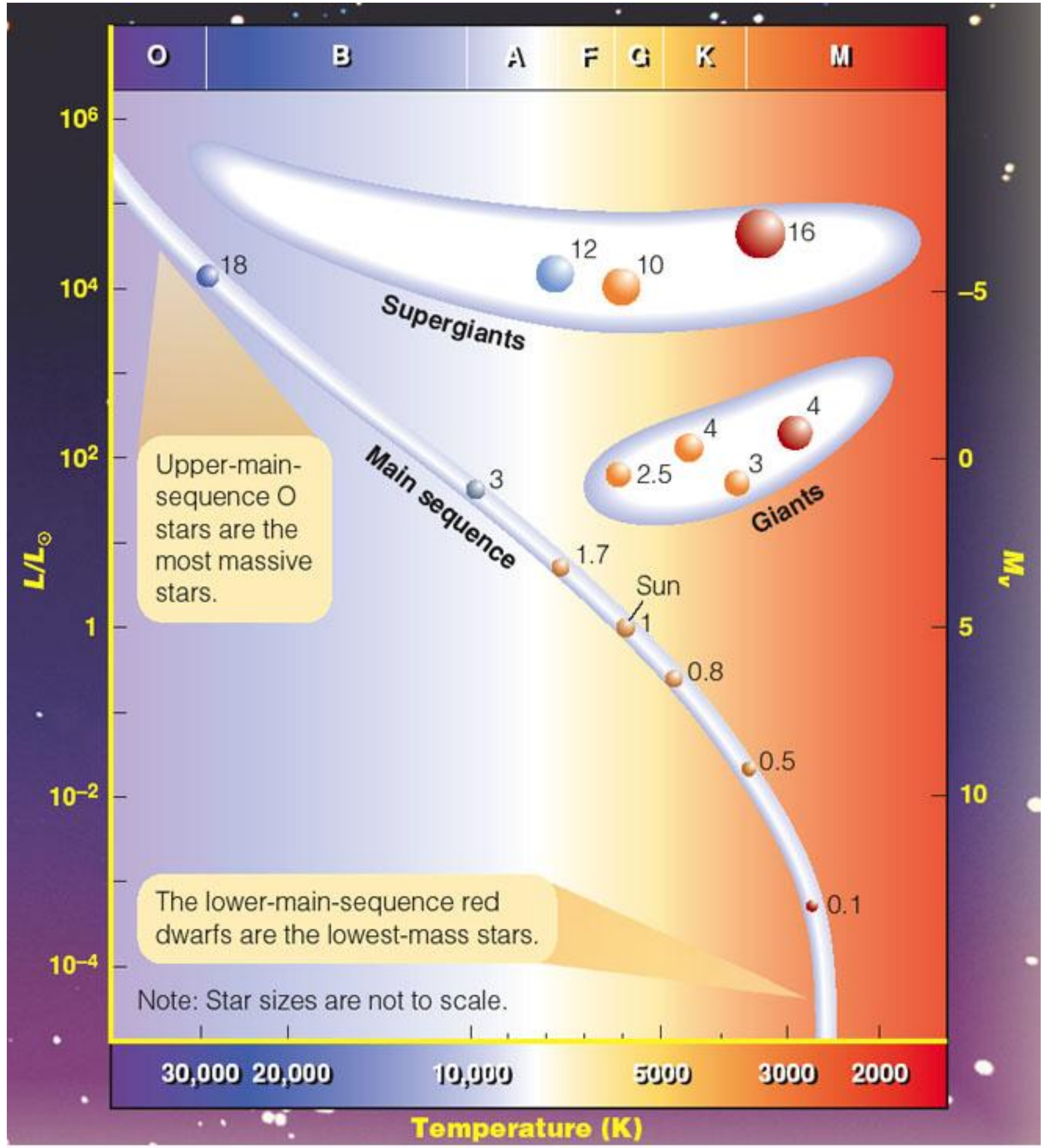
High-mass stars have much shorter lives than low-mass stars:

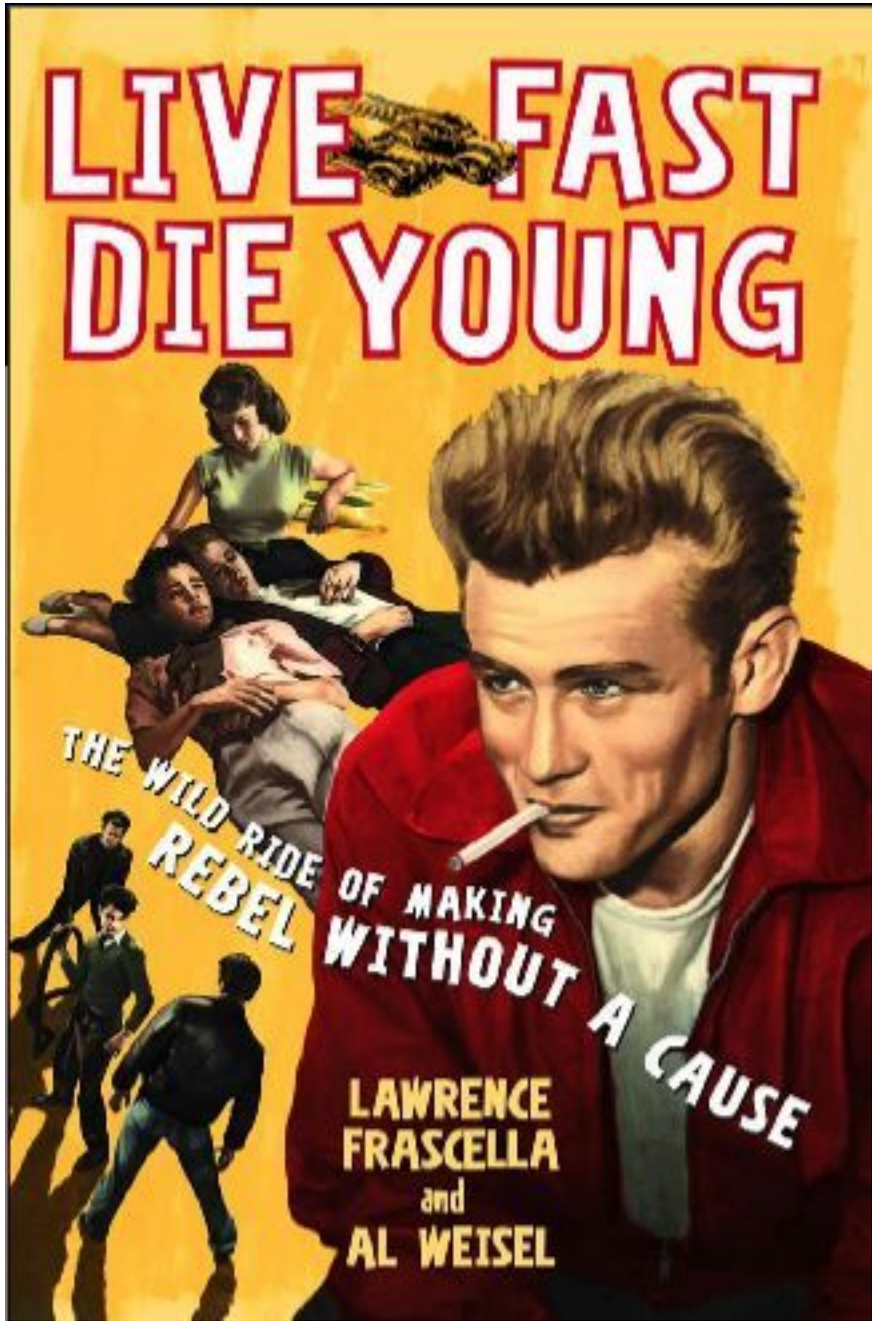
$$t_{life} \sim M^{-2.9}$$

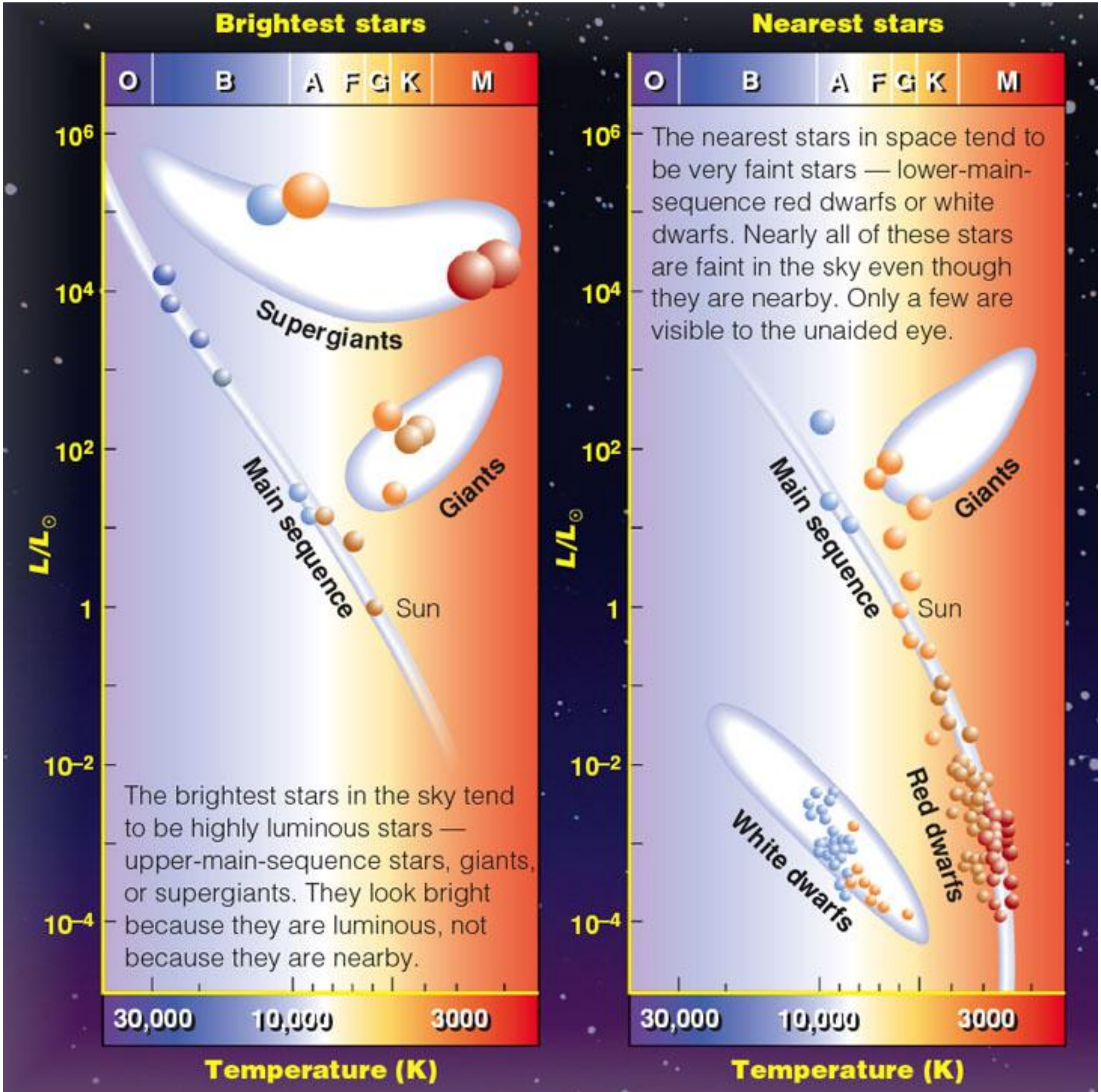
Sun: ~ 10 billion yr.

10 M_{sun}: ~ 30 million yr.

0.1 M_{sun}: ~ 3 trillion yr.

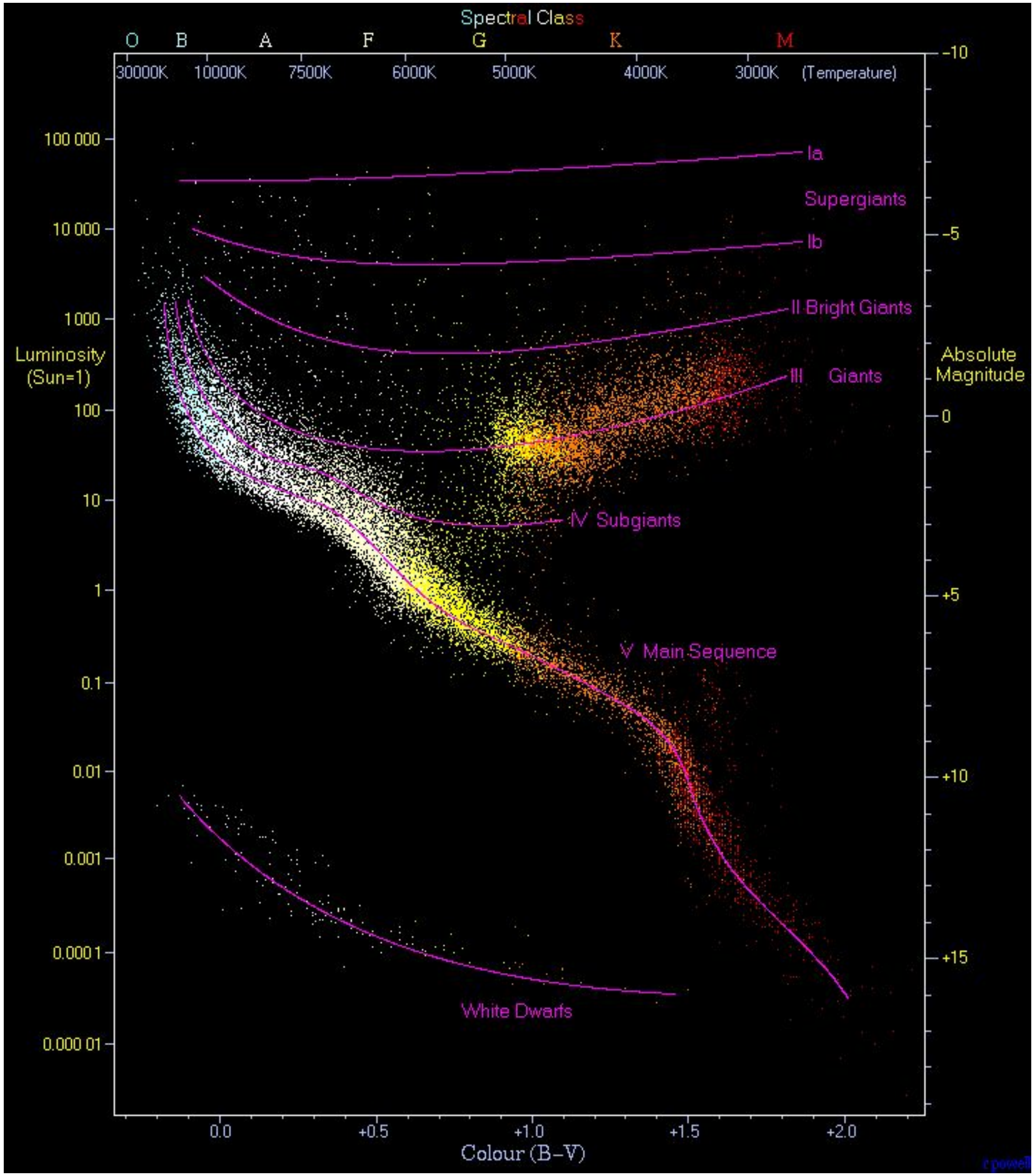



LIVE FAST
DIE YOUNG
THE WILD RIDE OF MAKING
REBEL WITHOUT A CAUSE
LAWRENCE
FRASCELLA
and
AL WEISEL



Brightest stars
Nearest stars
O B A F G K M
O B A F G K M
10^6
10^4
10^2
1
10^-2
10^-4
L/L⊙
Supergiants
Giants
Main sequence
Sun
The brightest stars in the sky tend to be highly luminous stars — upper-main-sequence stars, giants, or supergiants. They look bright because they are luminous, not because they are nearby.
The nearest stars in space tend to be very faint stars — lower-main-sequence red dwarfs or white dwarfs. Nearly all of these stars are faint in the sky even though they are nearby. Only a few are visible to the unaided eye.
Giants
Main sequence
Sun
Red dwarfs
White dwarfs
30,000
10,000
3000
30,000
10,000
3000
Temperature (K)
Temperature (K)

Color-Magnitude Diagram from Hipparcos



Some stars of the same spectral type may have very different luminosities.

Note the stellar *luminosity classes.*

Sun is a G2V star.

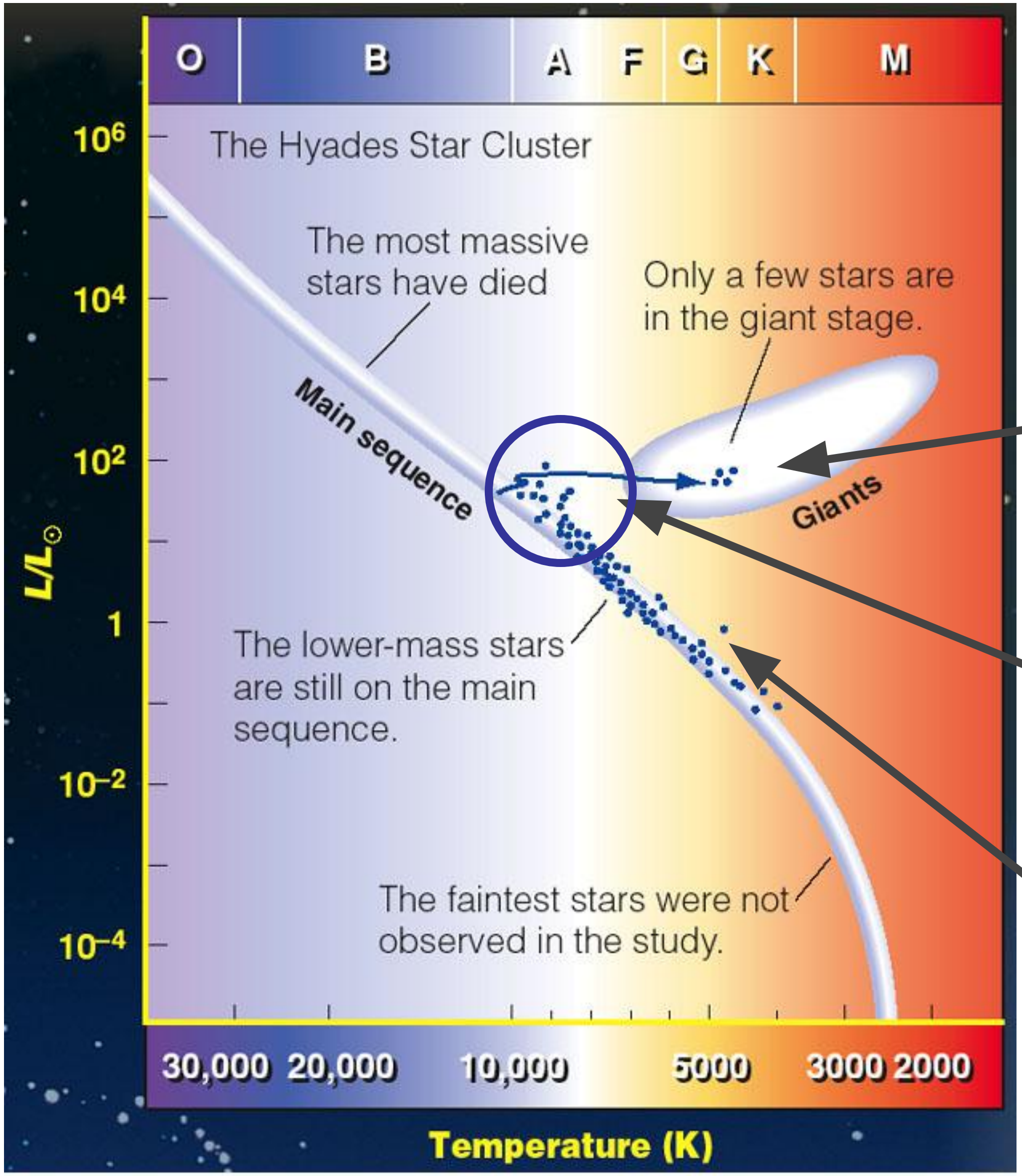
Star Clusters

Open clusters: 100-1000 stars. Young (Population I) stars. 10s-100s of pc away. In Galactic plane.

Globular clusters: 10^6 stars. Old (Population II) stars. Kpc - Mpc away. Distributed around Galactic center.

Provide useful snapshots of populations.

HR Diagram of Hyades



High-mass stars evolved onto the giant branch

Turn-off point

Low-mass stars still on the main sequence