[03] Binary Stars and H-R Diagrams (2/1/18)

Upcoming Items

1. Read Ch. 15.3 & 16 for next class and do the self-study quizzes.
2. Read jeans.pdf in Files/derivations on the ELMS class site
3. For derivations related to today's class, read twobody.pdf and massfunc.pdf from the same place

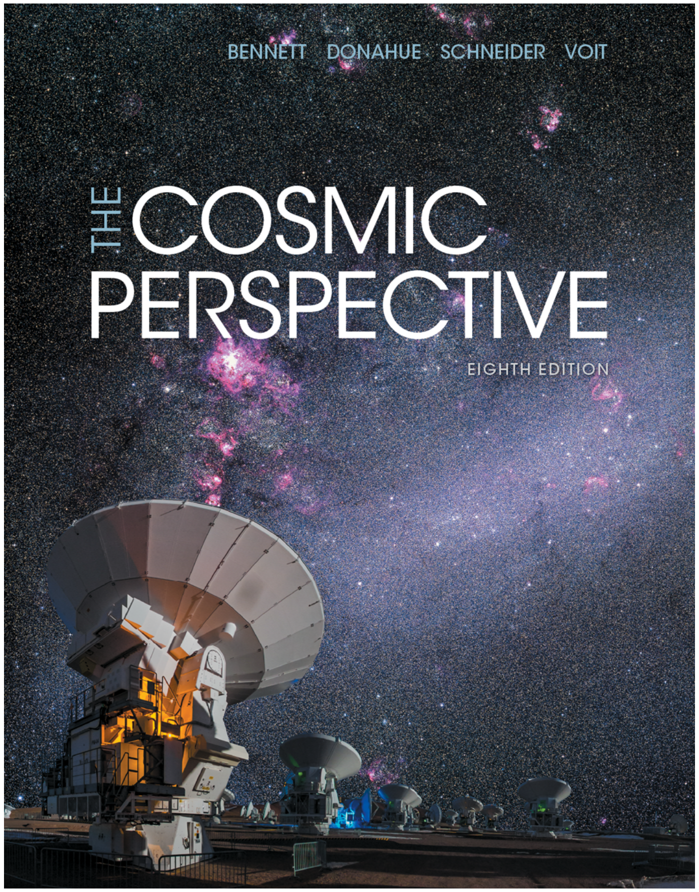
APOD 2/2/17: Collision Dust

LEARNING GOALS

Ch. 15.1–15.2

For this class, you should be able to…

- … *use Kepler's 3rd law in convenient units to derive star masses in binary systems (visual, eclipsing, spectroscopic);*
- … *infer the relative temperatures and radii of the stars in a binary viewed edge-on based on a light curve;*
- … *sketch an H-R (Hertzsprung-Russell) diagram showing the approximate locations of main sequence stars, giants and supergiants, and white dwarfs;*
- … *order stars on the main sequence by lifetime and by mass.*



Quick Review From Last Time

- Parallax: $d = 1/p$.
  - Which one is closer: $p = 1''$ or $p = 0.1''$?
- Magnitude system: $m_2 - m_1 = 2.5\log_{10}(F_1/F_2)$.
  - Which one is brighter in the sky: $m = 0$ or $m = 5$?
- Absolute magnitude: $M = m$ at 10 pc.
  - Which one is more luminous? $M = -5$ or $M = 10$?
- Distance modulus: $m - M = 5\log_{10}(d/10\ \mathrm{pc})$.
  - Which is closer? $m = 5$ & $M = 10$ or $m = 10$ & $M = 5$?
- Color: $\mathrm{B} - \mathrm{V} = m_\mathrm{B} - m_\mathrm{V}$.
  - Which is redder? $\mathrm{B} - \mathrm{V} = 0$ or $\mathrm{B} - \mathrm{V} = -5$?
  - How many times "redder" is it? $100\ (5\ \mathrm{mag} = 100\times)$.
  - Remember: blackbody color ⇔ temperature.

Binary Stars

- Three traditional ways to identify a binary:
  1. Visual.
  2. Spectroscopic.
  3. Eclipsing.
  4. But can also get from Doppler shifts of pulsars!
     - Can deduce a lot from light curves, including relative radii and temperatures.
     - For pulsars, can test general relativity!
- Combine Kepler's 3rd law with mass balance to derive stellar masses, sometimes individually:

$$\frac{m_1 + m_2}{\mathrm{M}_\odot} = \left(\frac{a}{\mathrm{AU}}\right)^3 \Big/ \left(\frac{P}{\mathrm{yr}}\right)^2$$

$$m_1 r_1 = m_2 r_2, m_1 v_1 = m_2 v_2$$

- Find star masses range from >100 to $0.08\ \mathrm{M}_\odot$.

In a visual binary, the individual mass components can be determined if

A. the relative distance of each star to their common barycenter can be measured.
B. the relative speeds of each star can be measured.
C. the physical radii of the stars can be measured.
D. A & B.
E. A, B, & C.

Stellar Properties, Continued

- We know how to get the following stellar properties:
  - Distance
  - Luminosity
  - Temperature

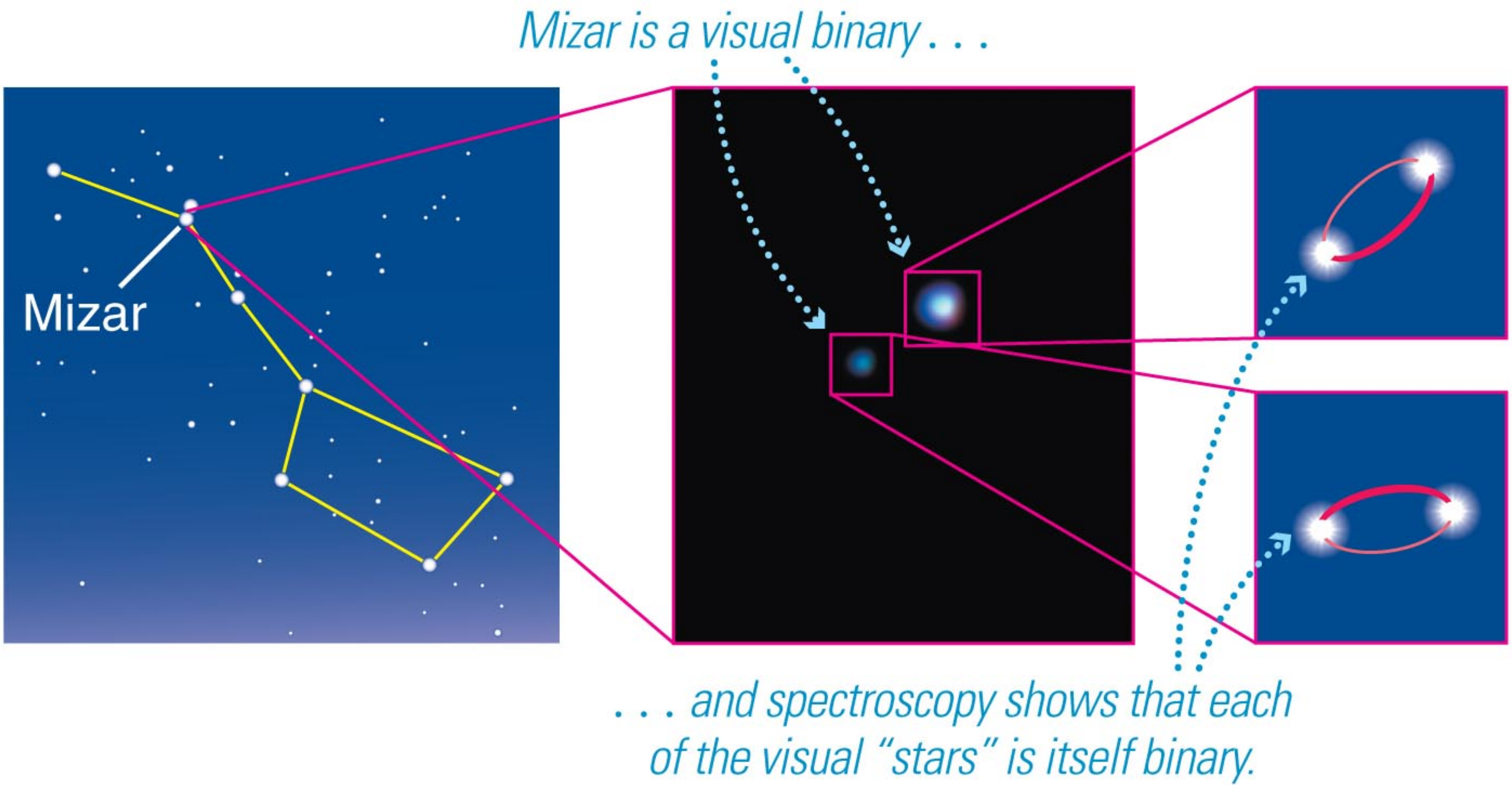
- What about mass?

Mass

- Stellar masses are measured by observing *binaries*.
- About half of all stars are in binary systems (but at least 80-90% of the most massive stars; what does that say)?
- For the most massive stars, >10% are actually in triple or higher-order systems! A complicated dance...
- How do we get masses? Observation of the stars' orbits.
- One can show (see massfunc.pdf) that if you can get the period P of an orbit, and the maximum orbital speed you see from star 1 is K_1, then for inclination i

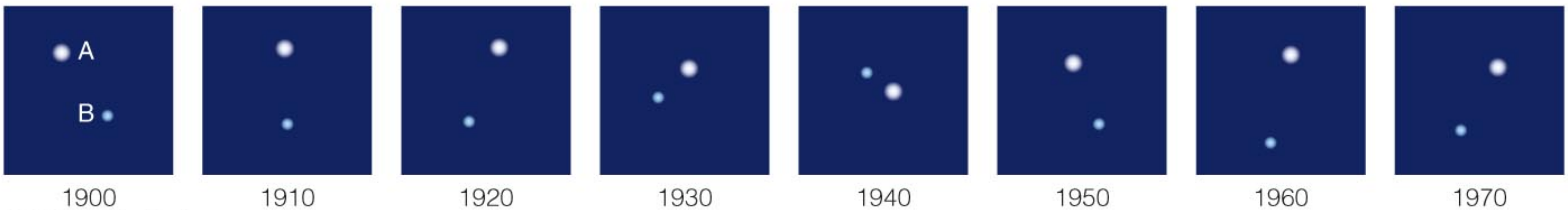
  $$f = PK_1^3/(2\pi G) = M_2^3 \sin^3 i/(M_1+M_2)^2$$

- Does this give an upper or lower limit to the mass M_2 of star 2? How many more numbers do we need for a measurement rather than a limit? How do we get them?



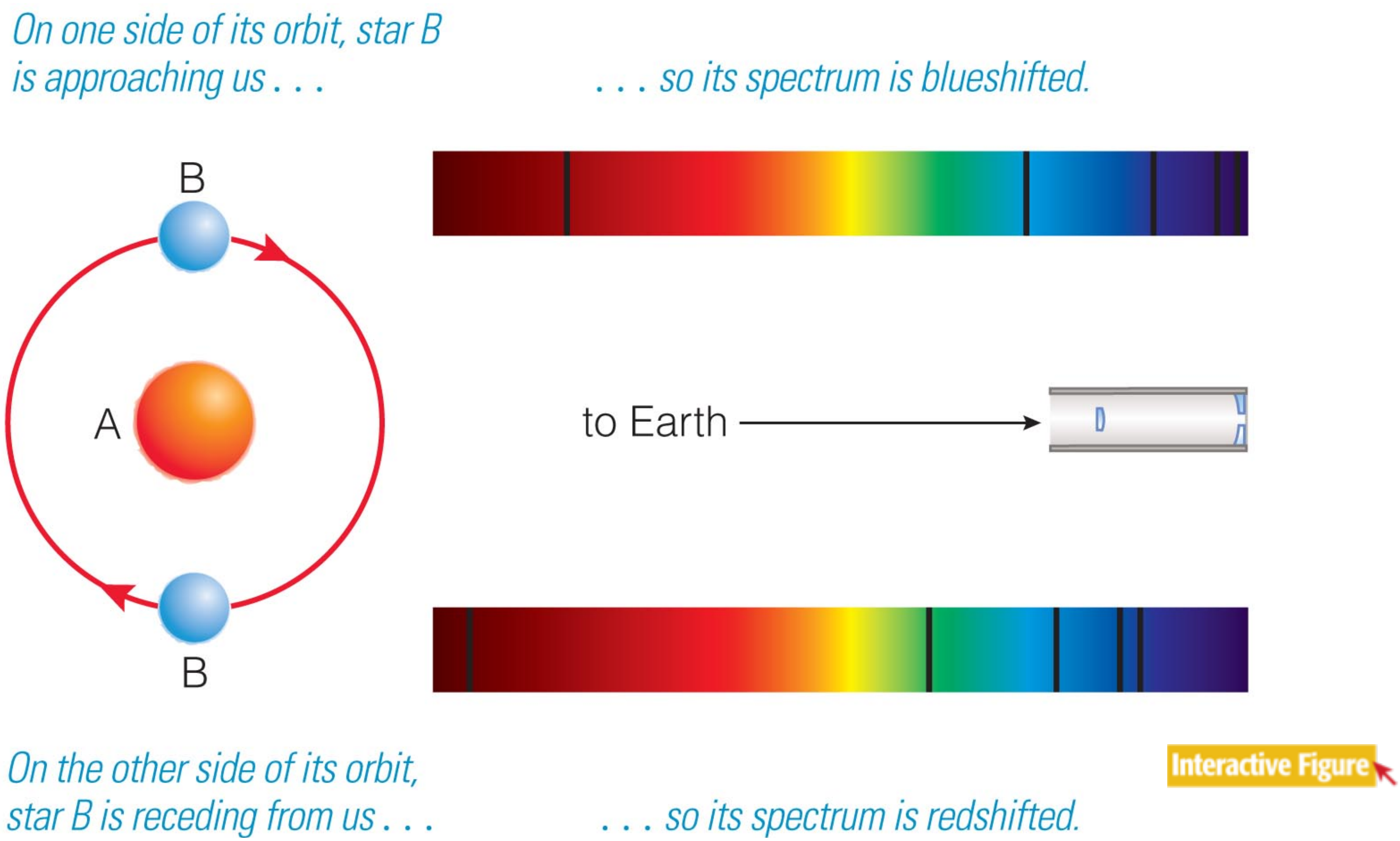
- The orbit of a binary star system depends on strength of gravity.

Visual Binary



We can directly observe the orbital motions of these stars.

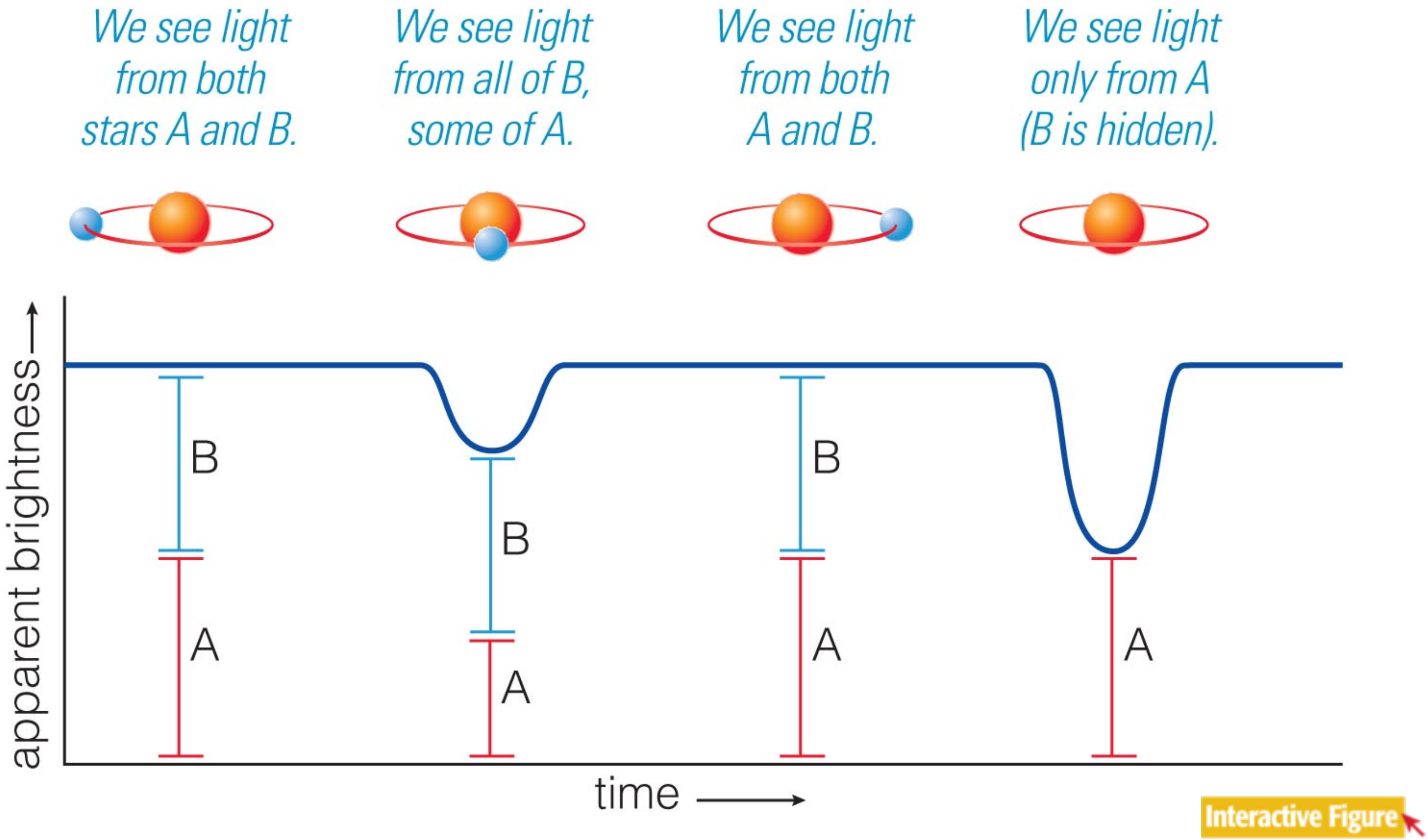
Spectroscopic Binary



We can determine the orbit by measuring Doppler shifts.

Eclipsing Binary

Study this carefully! Can you explain why the dips look the way they do?



We can measure periodic eclipses.

Most massive stars:

>100 $M_\odot$

Least massive stars:

0.08 $M_\odot$

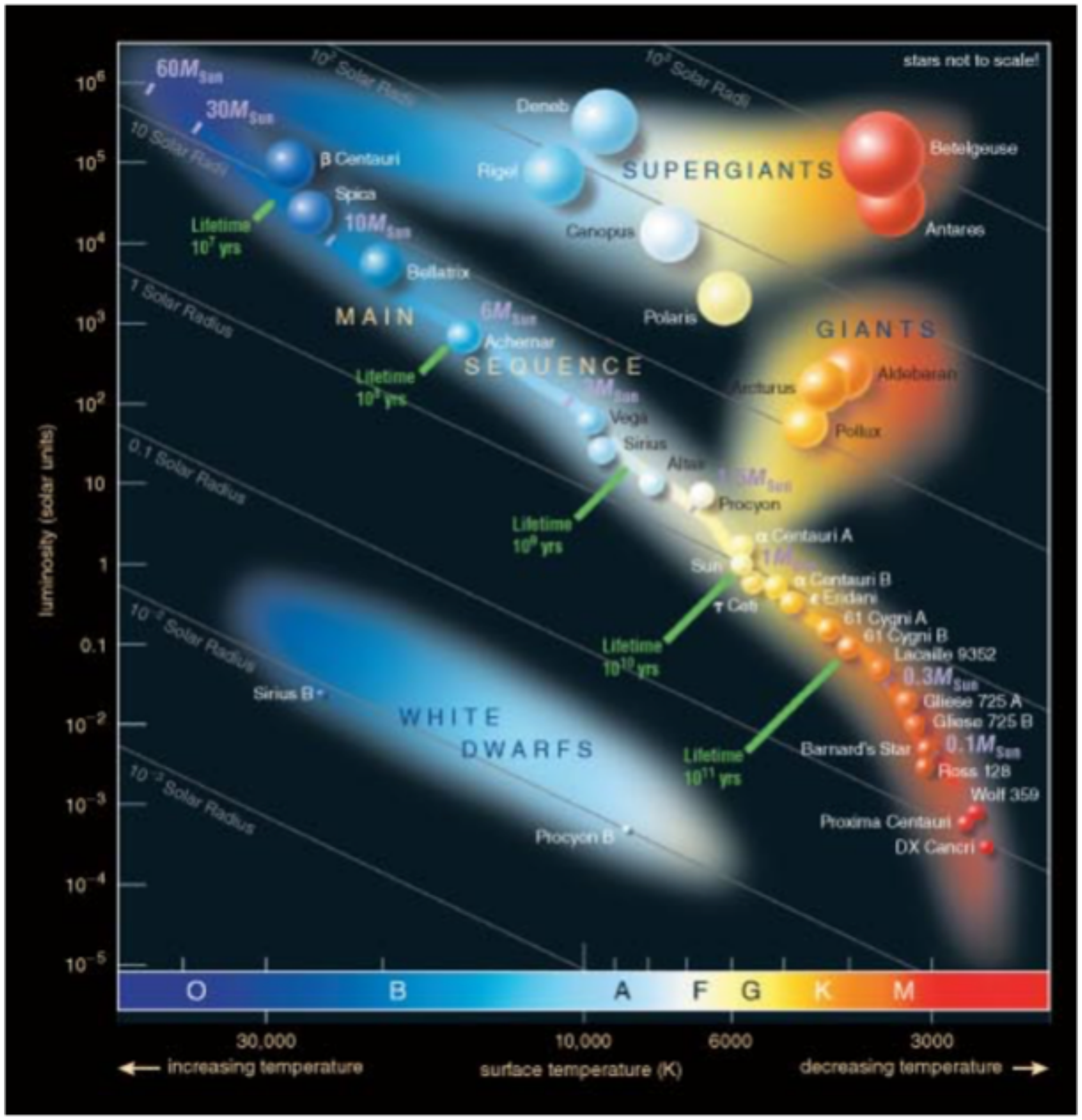
(**$M_\odot$** is mass of Sun)

Stellar Properties Summary

- We have discussed 5 ways to find 4 stellar properties:
  1. **Distance**
     - Use stellar parallax. [other methods possible, but root is parallax]
  2. **Luminosity**
     - Use distance and apparent brightness (inverse square law).
  3. **Temperature**
     - Use color (thermal radiation law; red = cool, blue = hot).
     - Use spectral type (O–M) from absorption spectrum (ionization level).
  4. **Mass**
     - Use binary stars (visual, eclipsing, and/or spectroscopic).
- Now we need to put these together to look at stellar populations as a whole. Brute force method: plot everything against everything else, look for patterns!

Hertzsprung-Russell (H-R) Diagrams

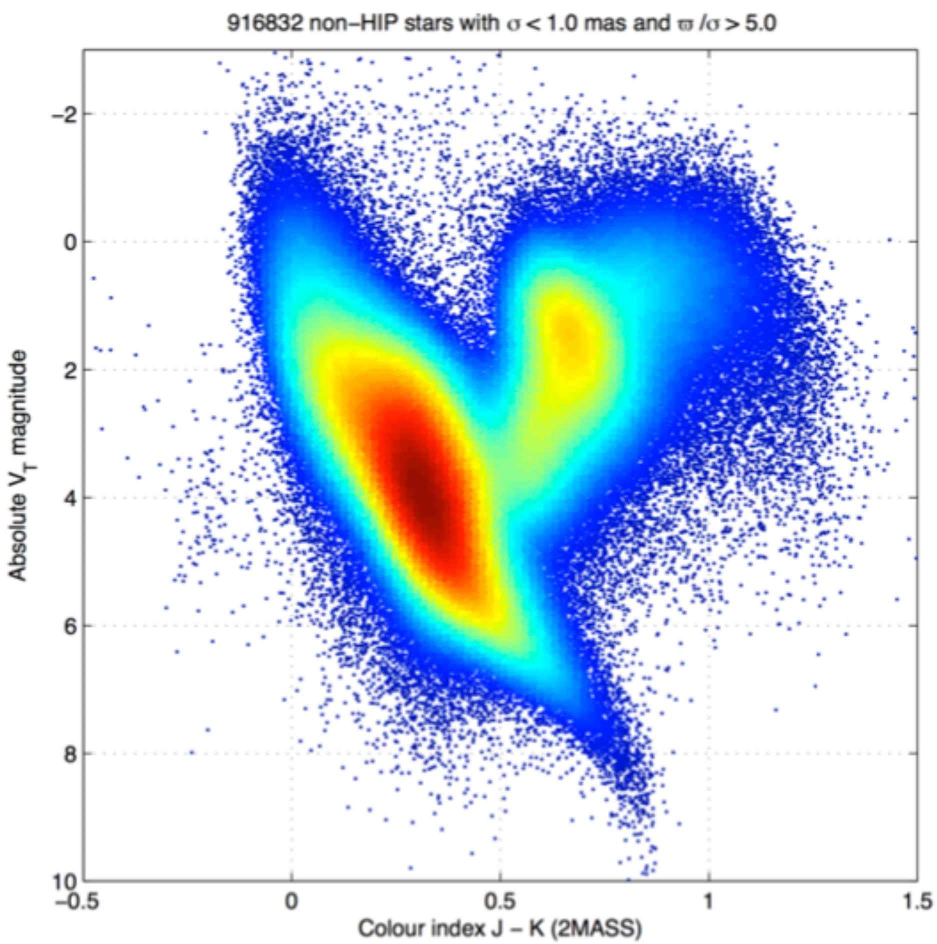
- Now that we have measured stellar properties (summary), we can look for important correlations.
- E.g., plot temperature versus luminosity or brightness.
  - This is called a Hertzsprung-Russell (H-R) diagram.
  - Most stars lie on the main sequence.
  - Stars at same temperature but different luminosities must be different size: giant and supergiants in one corner, white dwarfs in the other.
  - Add luminosity class to fully characterize a star.
- On main sequence, the most luminous stars are more massive and shorter lived, and vice versa.
- Some stars are truly gigantic.



Luminosity

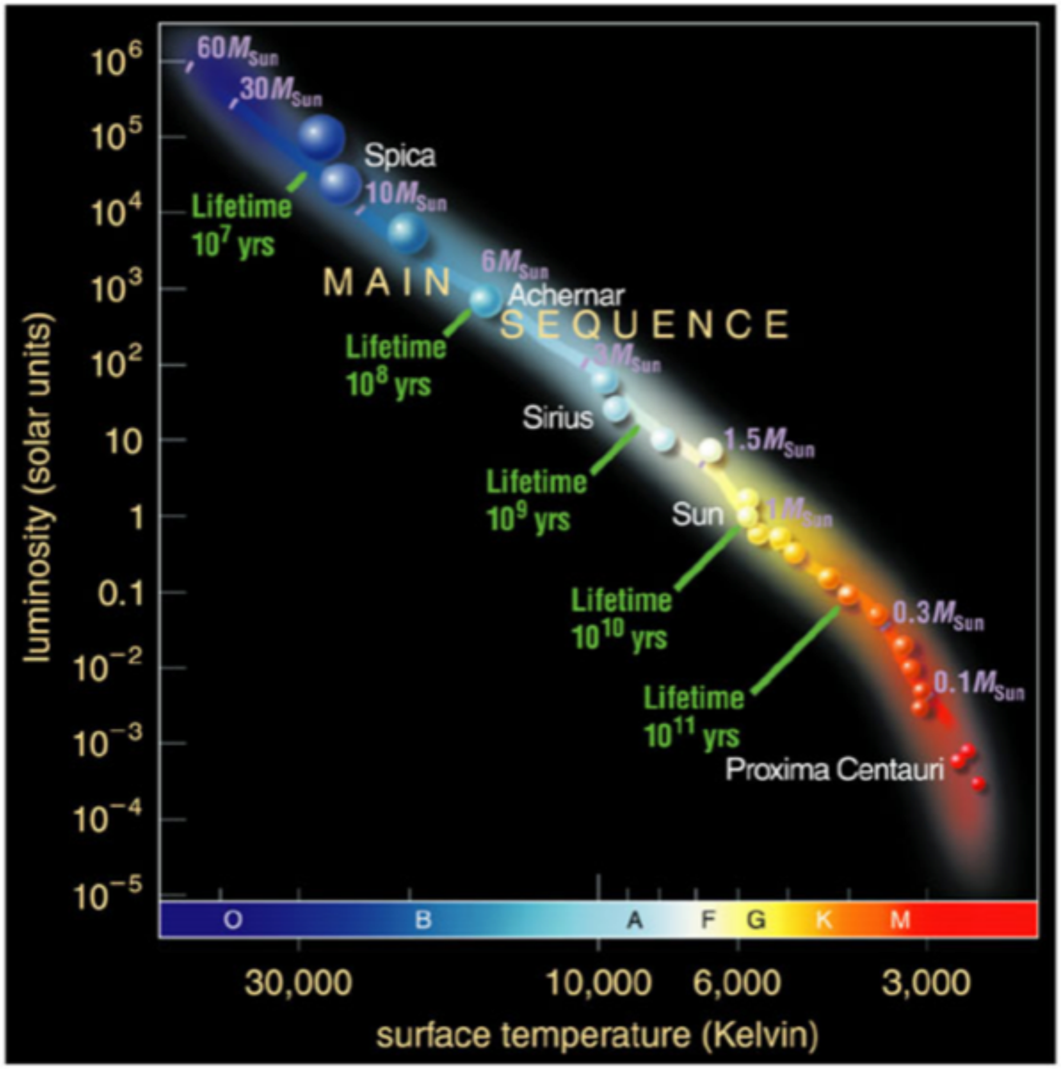
Temperature

- An H-R diagram plots luminosities & temperatures of stars.



- An H-R diagram plots luminosities & temperatures of stars.

GAIA first results for 1 million stars (August 2015)



- Most stars fall somewhere on the ***main sequence*** of the H-R diagram.

Stellar luminosity depends on temperature and radius

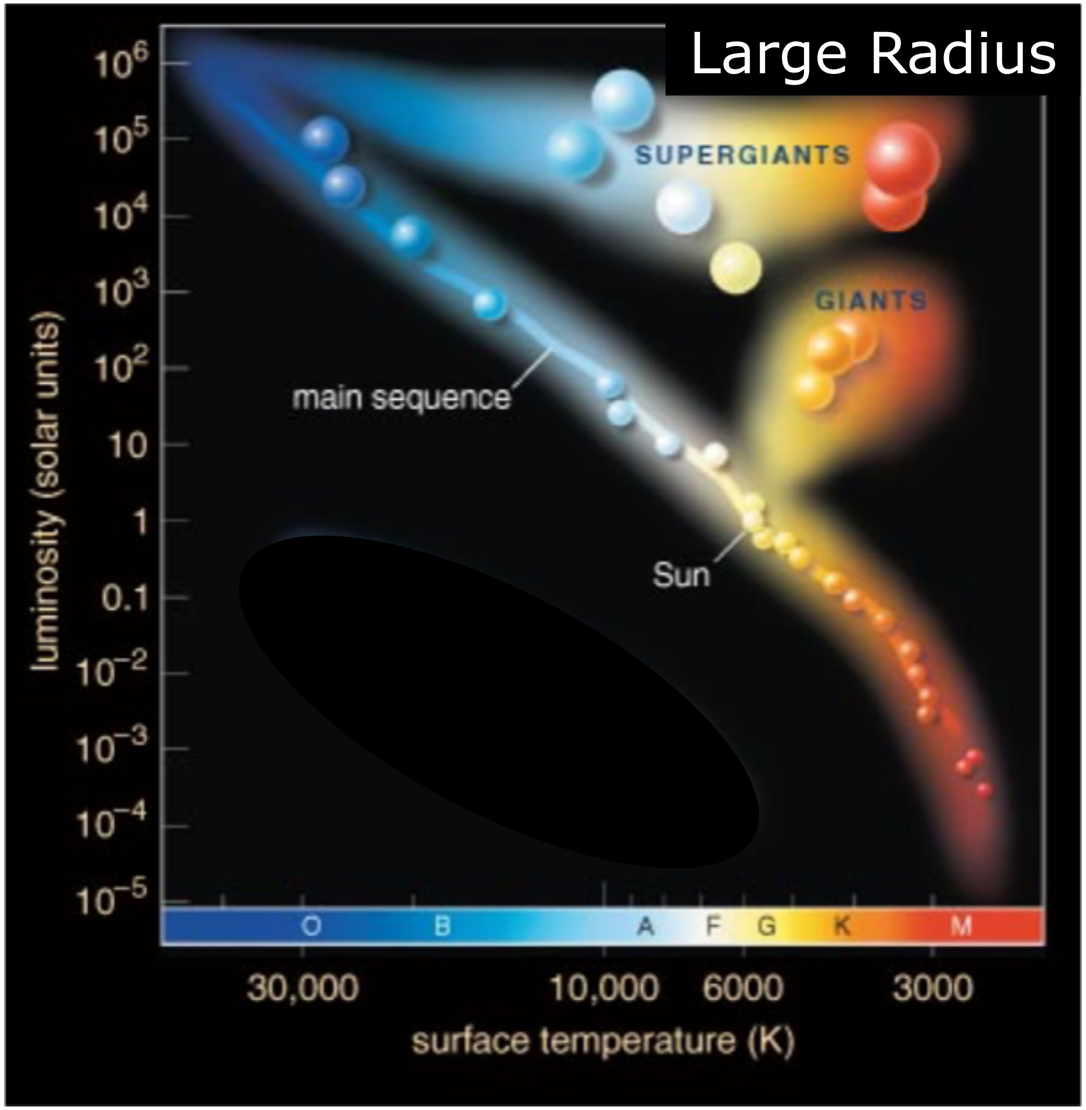
- Recall for blackbody radiation, emitted flux (power per unit radiating area) depends on temperature: $F_{\text{emit}} = \sigma T^4$.

- For a spherical object like a star, the emitting area is the sphere's surface area, $4\pi R^2$.

- So the luminosity of a star is given by

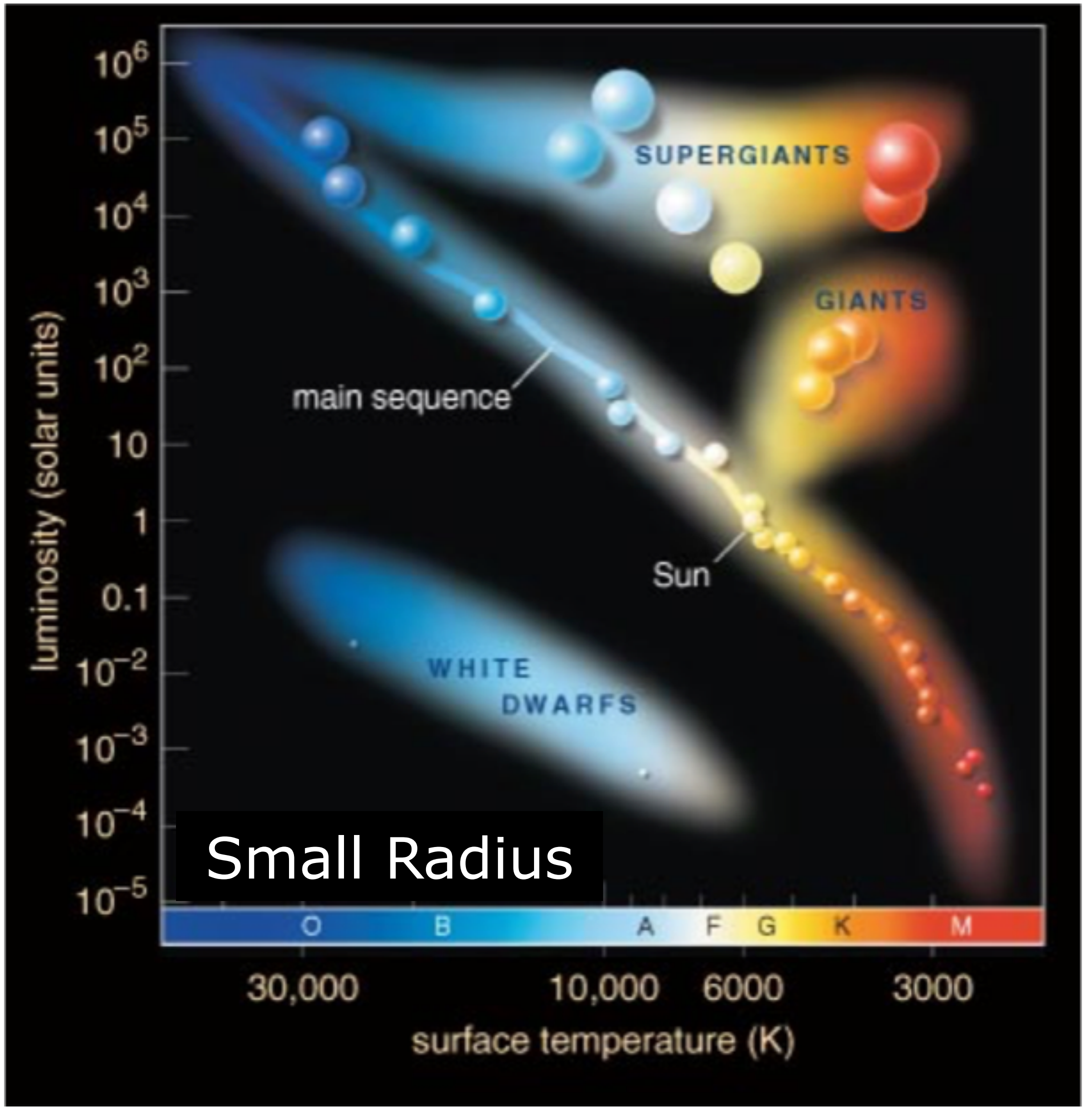
$$\boxed{L = 4\pi R^2 \sigma T^4.}$$

- This has important implications for the H-R diagram!

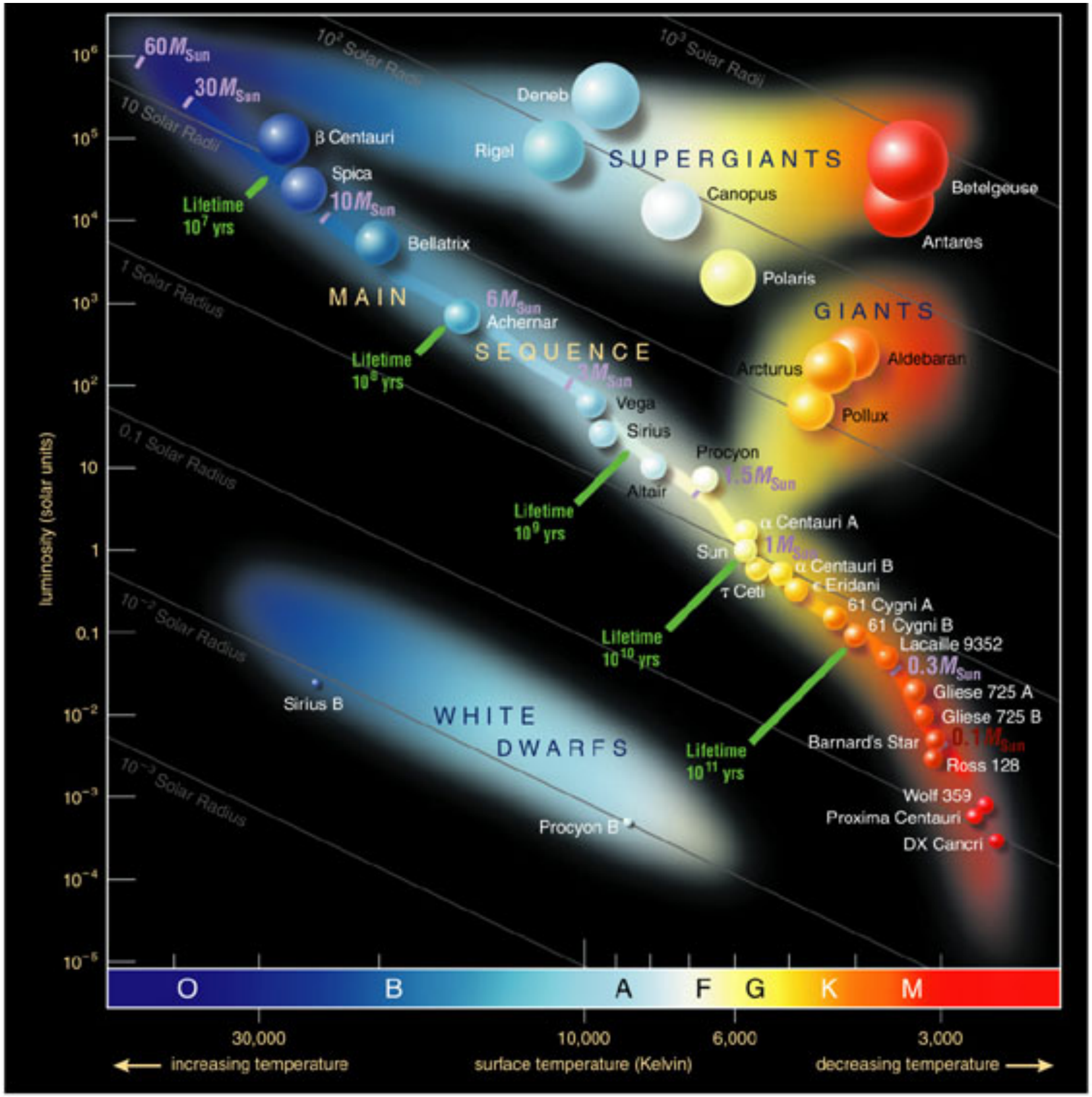


- Stars with lower T and higher L must have larger radius R: ***giants*** & ***supergiants***.

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



- Stars with higher T and lower L must have smaller radius R: ***white dwarfs***.



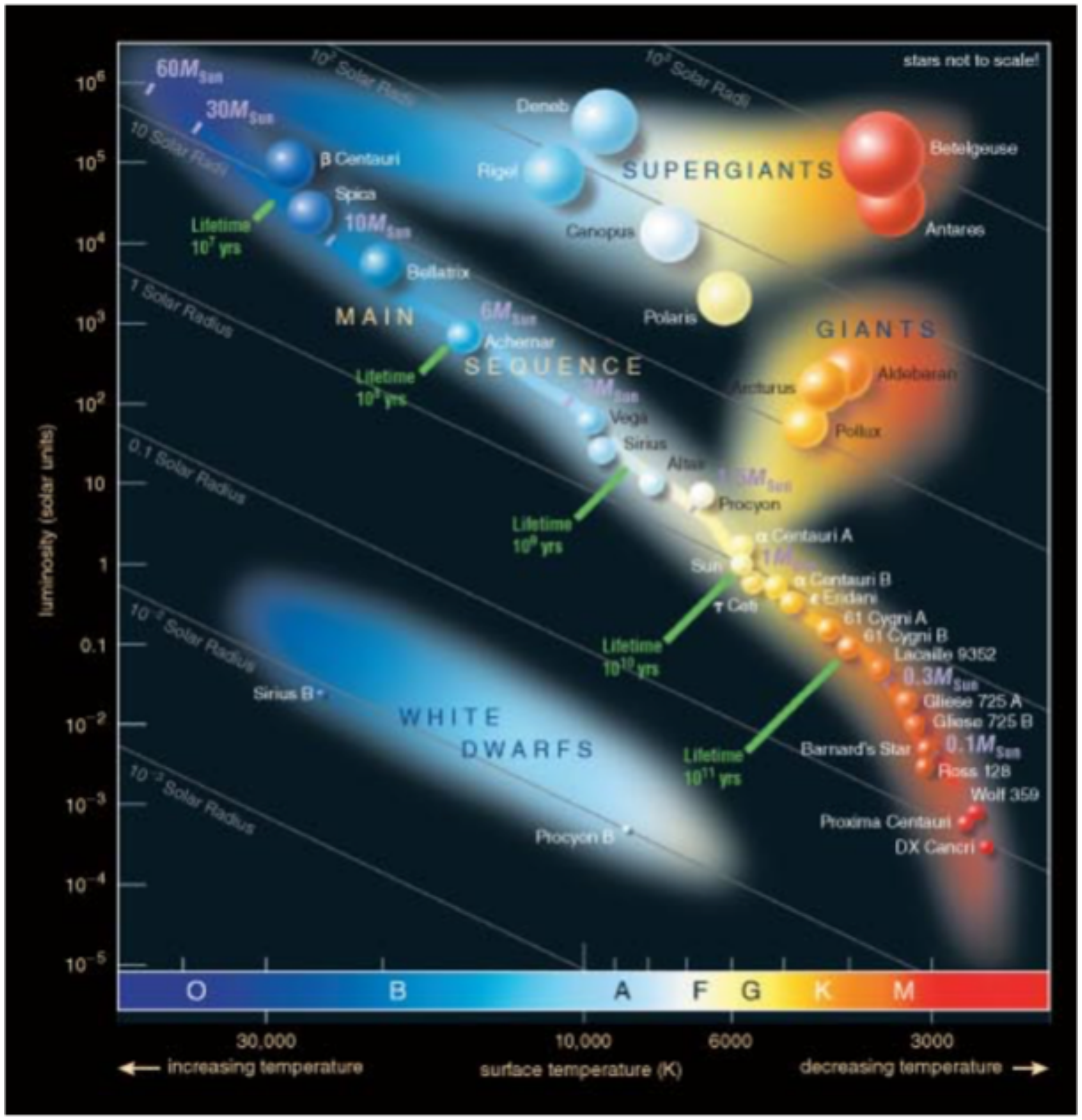
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Canopus
Betelgeuse
Antares
Polaris
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
10^3 Solar Radii
10^2 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O B A F G K M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Luminosity & Spectral Class

Add *luminosity class* (I–V) to spectral class (O–M):

I	— supergiant
II	— bright giant
III	— giant
IV	— subgiant
V	— main sequence

Examples:
Sun – G2 V
Sirius – A1 V
Proxima Centauri – M5.5 V
Betelgeuse – M2 I



Luminosity →

← Temperature

H-R diagram depicts:

- Temperature
- Color
- Spectral Type
- Luminosity
- Radius