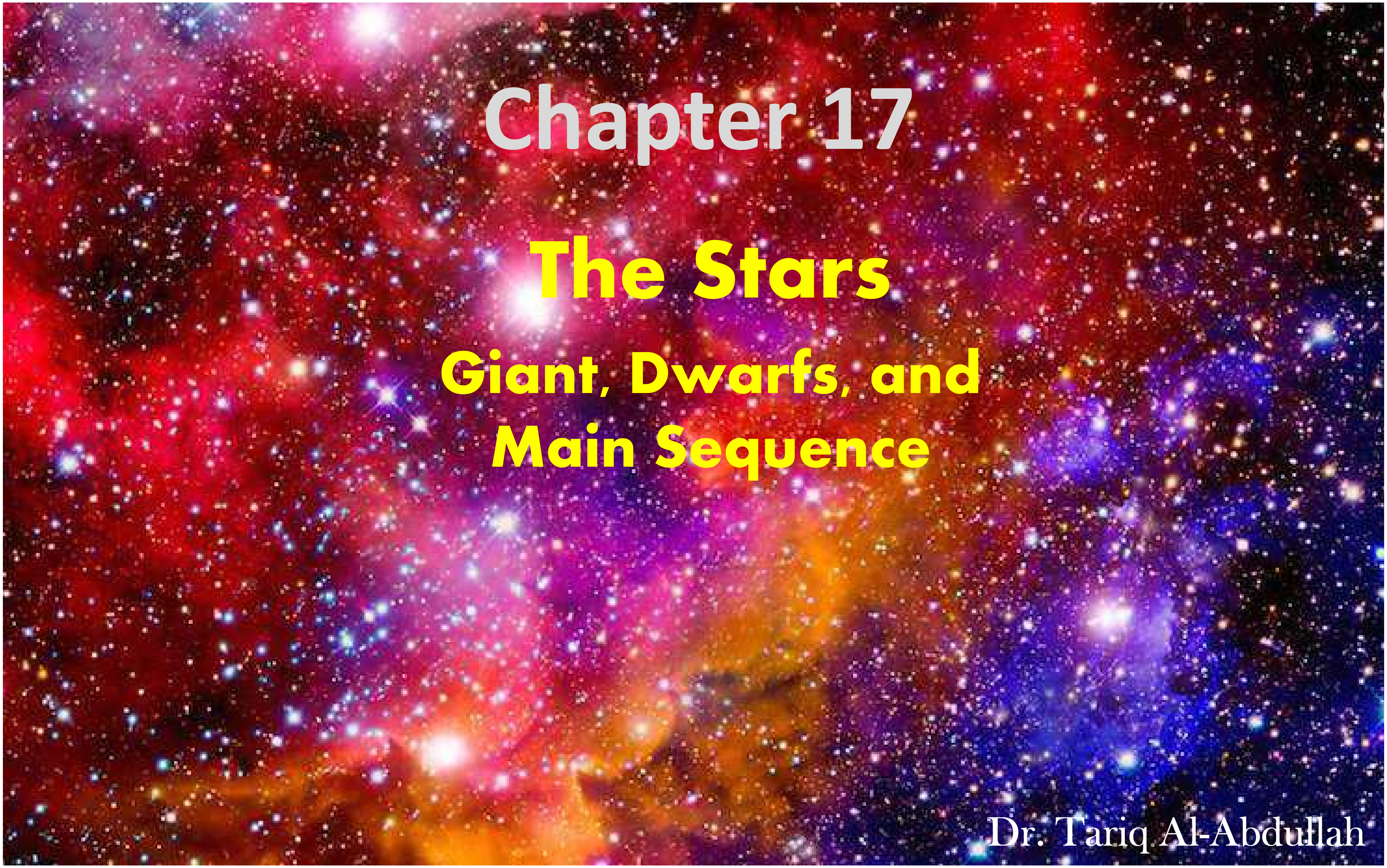

Chapter 17
The Stars
Giant, Dwarfs, and
Main Sequence
Dr. Tariq Al-Abdullah

Learning Goals:

17.1 The Solar Neighborhood

17.2 Luminosity and Apparent Brightness

17.3 Stellar Temperatures

17.4 Stellar Sizes

17.5 The Hertzsprung-Russel Diagram

17.6 Extending the Cosmic Distance Scale

17.7 Stellar Masses

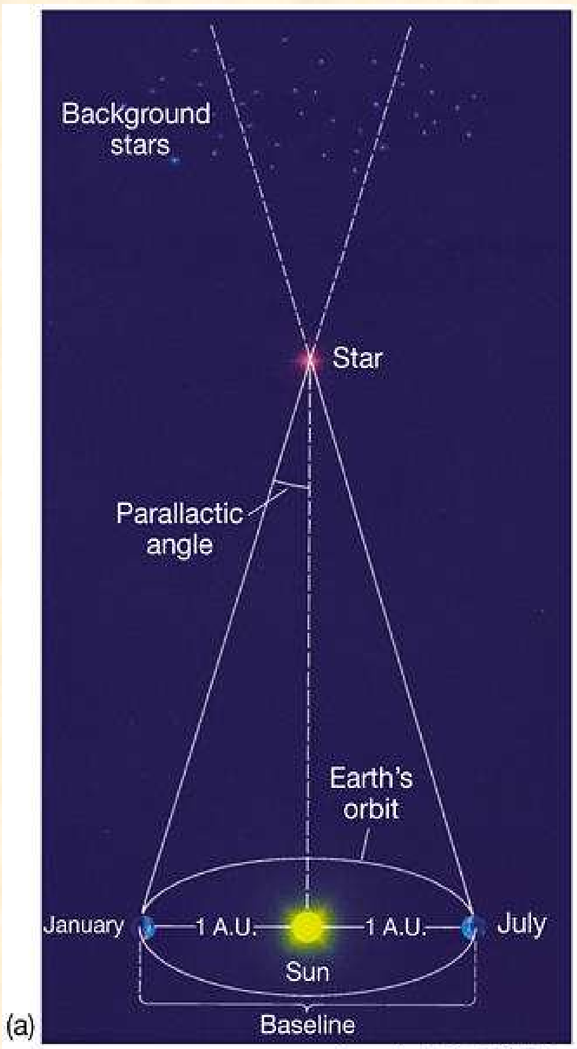
17.8 Mass and Other Stellar Properties

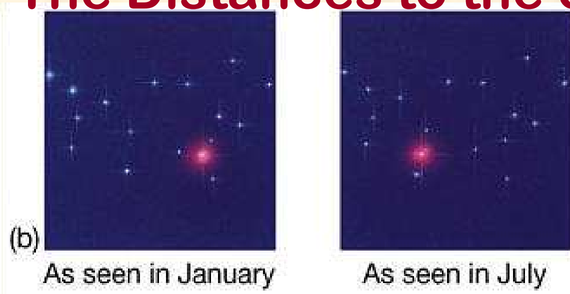
17.1 The Solar Neighborhood

- ✓ **The Milky-Way galaxy contains an enormous amount of stars.**
- ✓ **100 billion stars, 100,000 ly diameter, 25000 ly its center.**
- ✓ **Knowing the distance to stars ➔ Discover their properties.**
- ✓ **Observable universe contains several tens of sextillion stars (10^{21})**

17.1 The Solar Neighborhood

The Distances to the Stars





- **Stellar Parallax:** actually this only works in determining stellar distances for nearby stars.
- **Astronomers usually use arc-seconds.**
- **1 parsec (parallax in arc seconds).**
- **Observed parallax 1'' = 206,265 A.U.**

$$\text{distance (parsec)} = \frac{1}{\text{parallax (arc second)}}$$

- **1pc = 3.27 light year**

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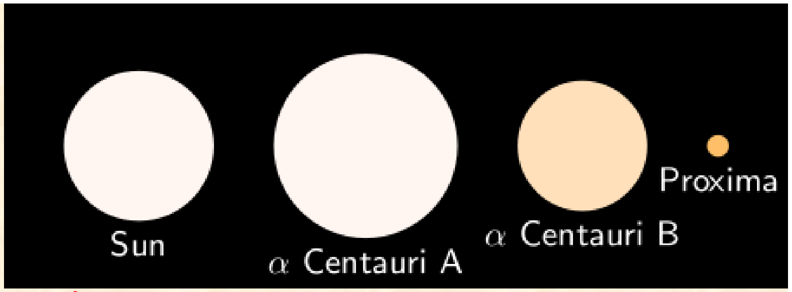
17.1 The Solar Neighborhood



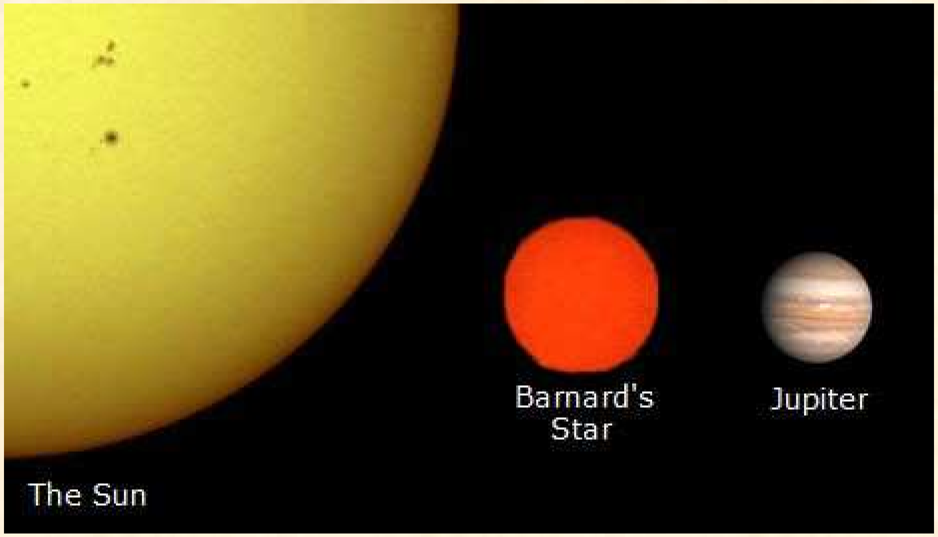
• **Our Nearest Stars:**

1- Alpha Centauri complex (triple-star system)

Proxima Centauri at 1.35 pc (4.2 ly, 270,000 A.U.) ≈ 0.77”

2- Barnard's Star, red dwarf, runaway

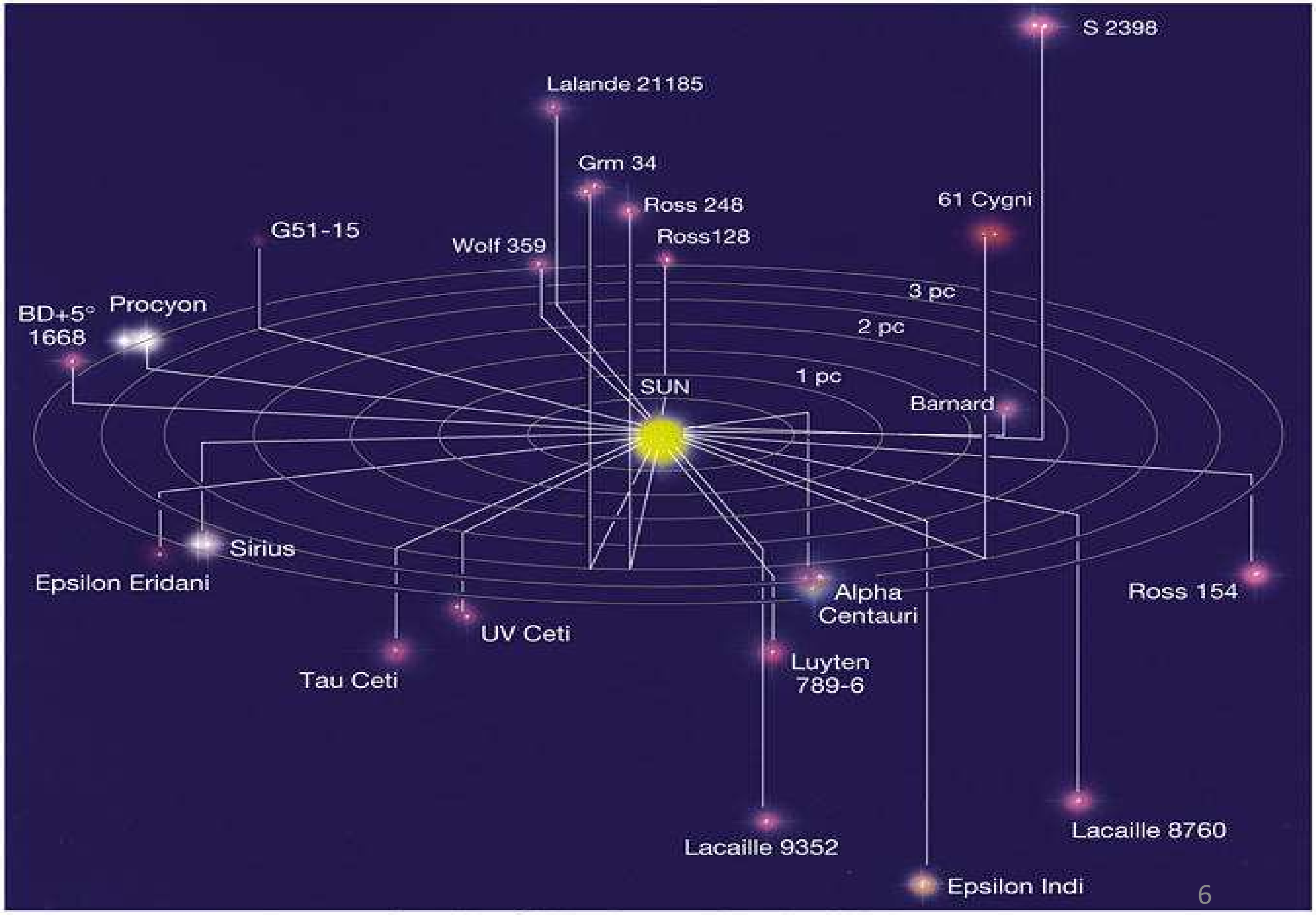
1.8 pc (6.0 ly) ≈ 0.55”



17.1 The Solar Neighborhood

The figure shows 30 nearest galactic neighbors

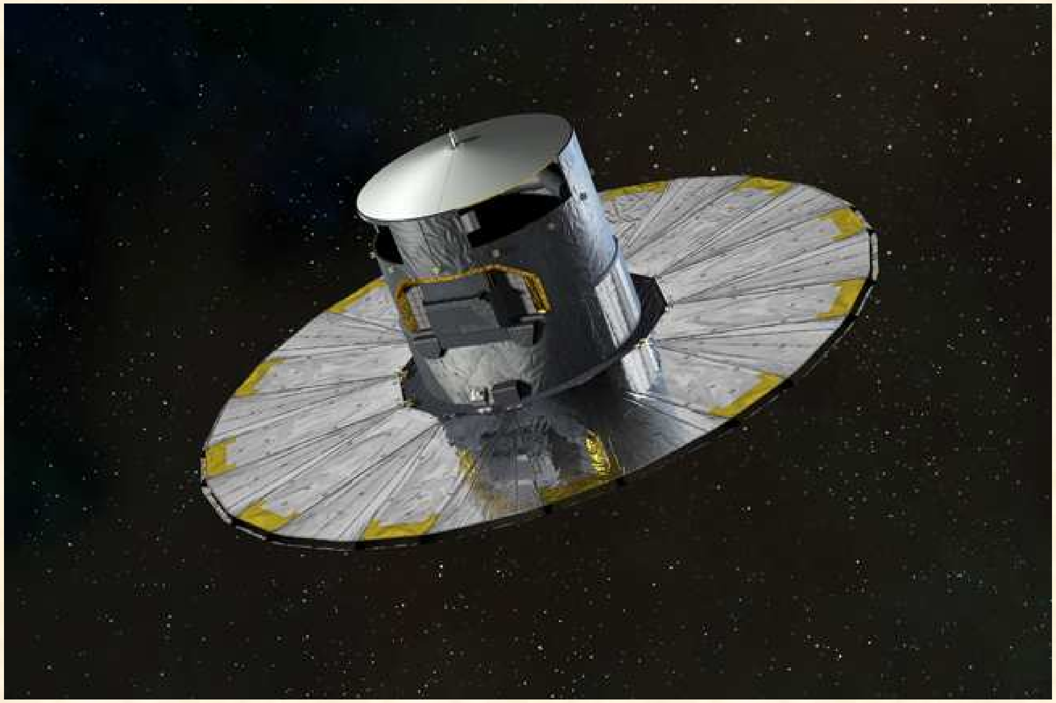
- Stellar Parallax
  - 0.03” == 30 pc
  - Several thousand stars, smaller than the sun (invisible)
- High Resolution
  - visibility 100-200 pc
- ESA’s GAIA project
  - 10,000 pc
  - 1 billion stars



17.1 The Solar Neighborhood

Inside GAIA's Billion Pixel Camera

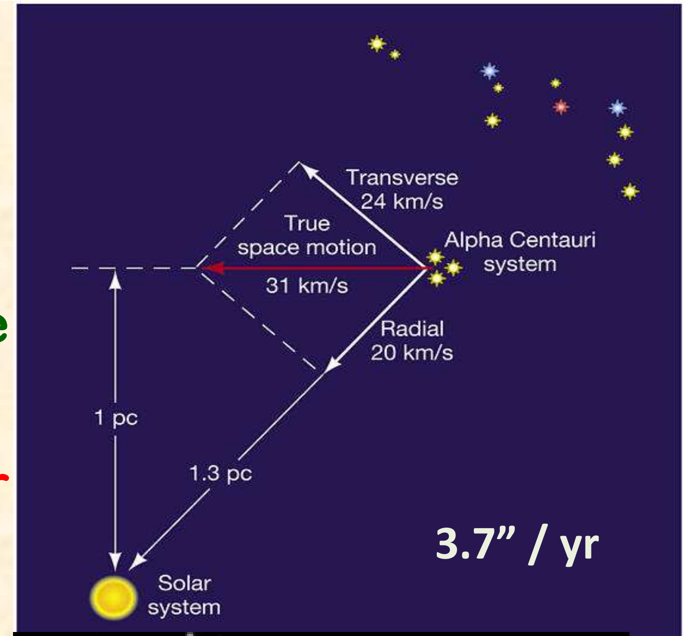
ESA's Gaia mission will produce an unprecedented 3D map of our Galaxy by mapping, with exquisite precision, the position and motion of a billion stars. The key to this is the billion-pixel camera at the heart of its dual telescope. This animation illustrates how the camera works.

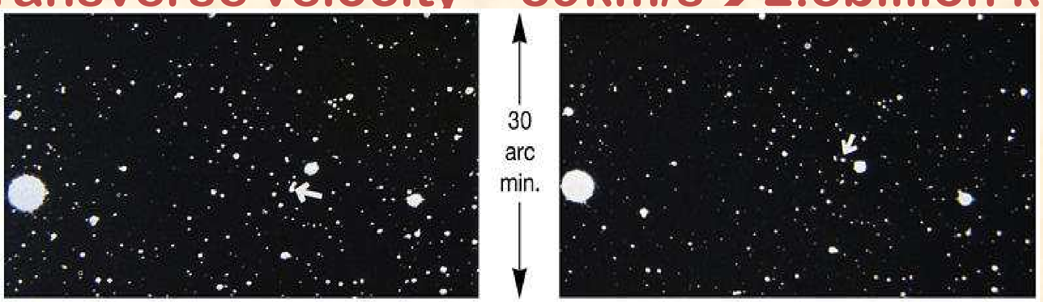


17.1 The Solar Neighborhood

→ **Stellar Motion (Bernard’s Star)**

- Radial velocity: **Doppler effect.**
- Transverse velocity, **perpendicular to our line of sighting.**
- Proper motion: **Annual movement of a star across the sky, as seen from the Earth.**
- Barnard’s Star moved 228” in 22 years.
- proper motion =10.4”/yr
- transverse velocity = 89km/s➔2.8billion km/yr





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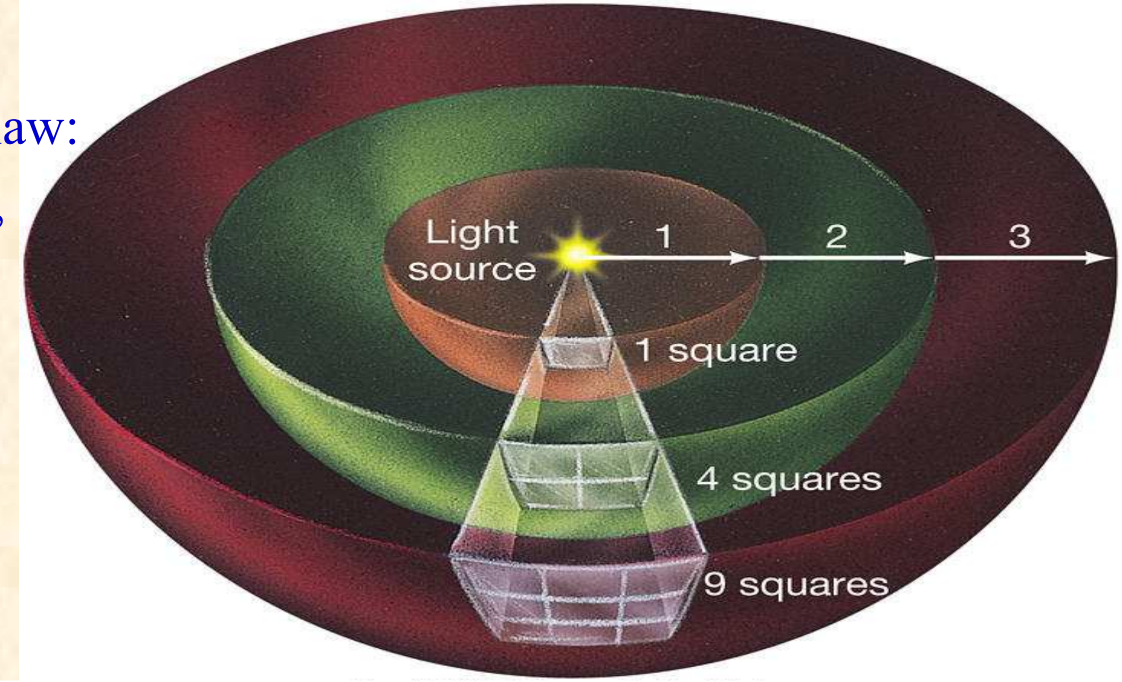
17.2 Luminosity and Apparent Brightness

- **Luminosity:** **Total rate at which radiative energy is given off by a celestial body. Sometimes referred to as *Absolute Brightness*.**
- **Apparent Brightness:** **The brightness that the star appears to have to an observer on the Earth.** **Amount of energy striking a unit area per unit time:** **Energy flux**



- This depends on how far away the object is by the inverse-square law:
- Knowing Brightness and Distance, we can determine Luminosity
- **Apparent brightness ~ luminosity / distance^2**
- Often expressed relative to the Sun's luminosity (L_{SUN}).

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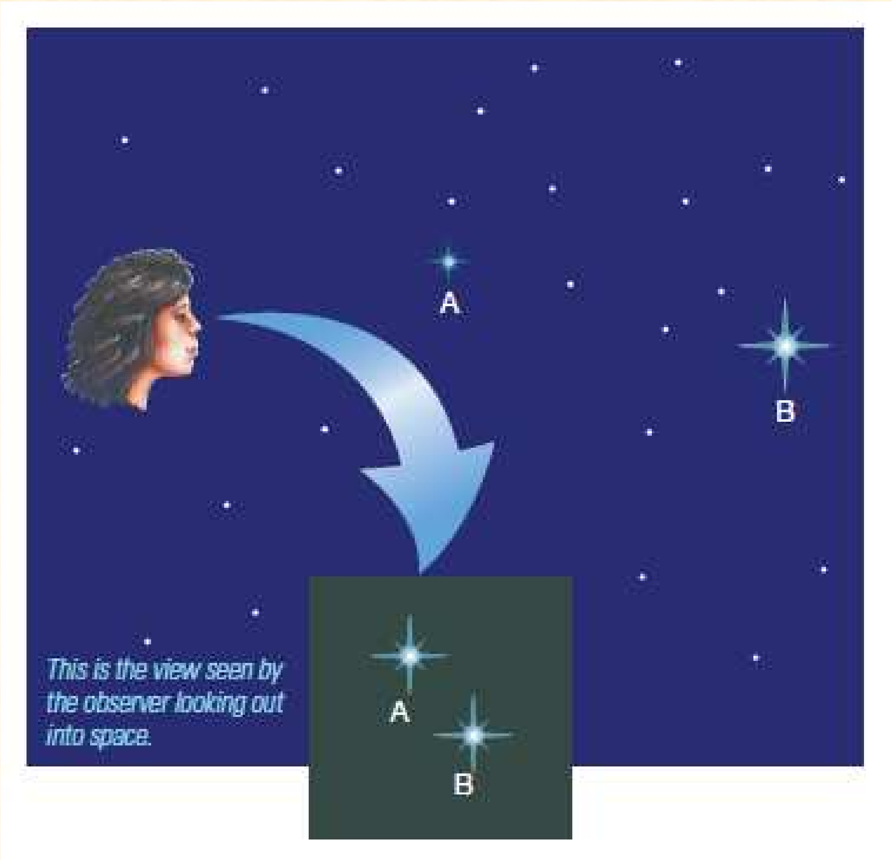
17.2 Luminosity and Apparent Brightness

- Two identical stars can have the same apparent brightness if they lie at the same distance

- Two non-identical stars can also have the same apparent brightness if the more luminous one lies farther away.



17.2 Luminosity and Apparent Brightness

The Magnitude Scale

- Instead of measuring apparent brightness in watts / sq. meter.
- Construct the Magnitude Scale since second century B.C.
- Greeks (Hipparchus) established scale called Apparent magnitude:
  - Brightest stars visible to unaided eye = Magnitude 1
  - Dimmest stars visible to unaided eye = Magnitude 6
  - "first magnitude" in astronomy means "bright"
  - Measurements show 1st magnitude stars are 100 times as bright as 6th magnitude stars.
  - So, a Magnitude difference of 1 corresponds to a factor of 2.5 in brightness. or $(2.51)^5 \approx 100$

The Magnitude Scale

- **Modern astronomers have modified and extended the scale:**

  a) **1→6 or 7→2 corresponds to a factor of 100 in apparent brightness.**

  b) **apparent magnitudes, old scale.**

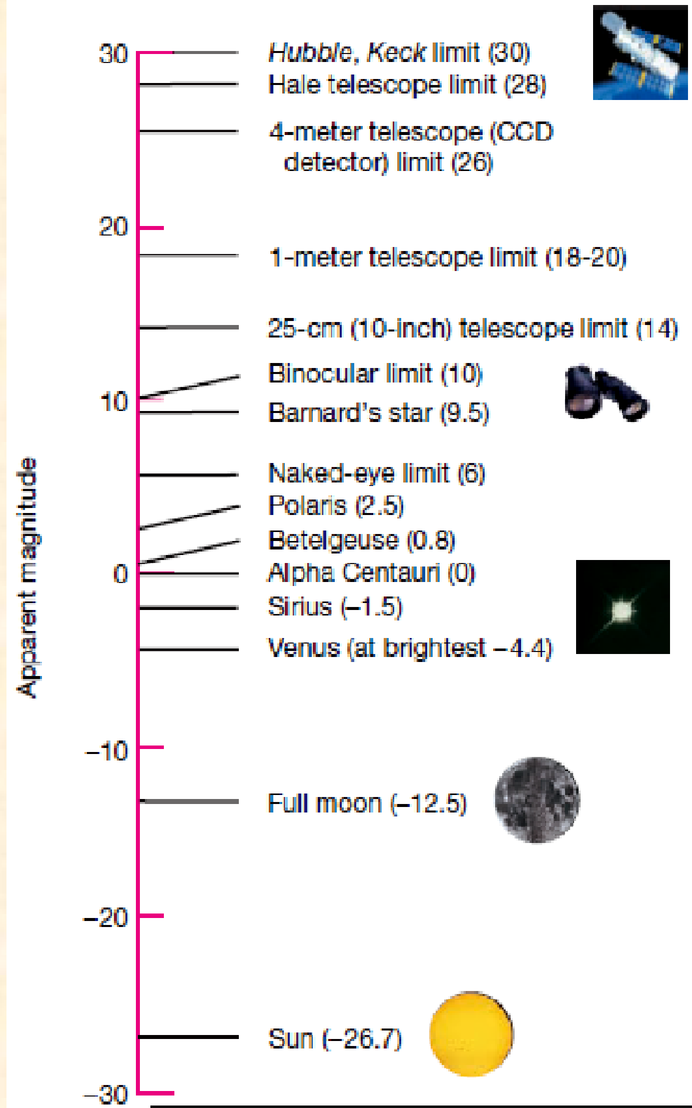
  c) **The scale can have real numbers.**

  d) **Magnitudes outside 1-6 are allowed.**

- **Apparent magnitude a star would have if it were exactly 10 pc from the Earth ≡ Absolute Magnitude**

- **Absolute Magnitude = Luminosity, although in different units.**

- **It is a logarithmic scale; a change of 5 in magnitude corresponds to a change of a factor of 100 in apparent brightness.**



Difference = 10^{22}

EXAMPLES

- **Luminosity and Brightness of the Sun:**
    - o **Sun's Brightness = 1370 Watts/m^2**
    - o **Sun's Distance (d) = 1.5×10^{11}m**
    - o **Therefore, Area of Sphere is $4\pi d^2$**

      $= 4\pi\,(1.5 \times 10^{11} m)^2 = 3 \times 10^{23}\ m^2$
    - o **Luminosity= (1370 Watts/m^2)x($3\times10^{23} m^2$) = 4×10^{26} Watts**

- **Sirius; Brightest Star in the Sky:**
    - o **Apparent Magnitude = -1.46**
    - o **Distance: parallax = 0.38'' ➔ (d) = 1/parallax = 2.5 pc**
    - o **3.26 l.y. in a parsec; So, d = 8.6 l.y.**
    - o **Luminosity= $22 \times L_{Sun}$**

$$\text{apparent brightness (energy flux)} \propto \frac{\text{luminosity}}{\text{distance}^2}$$

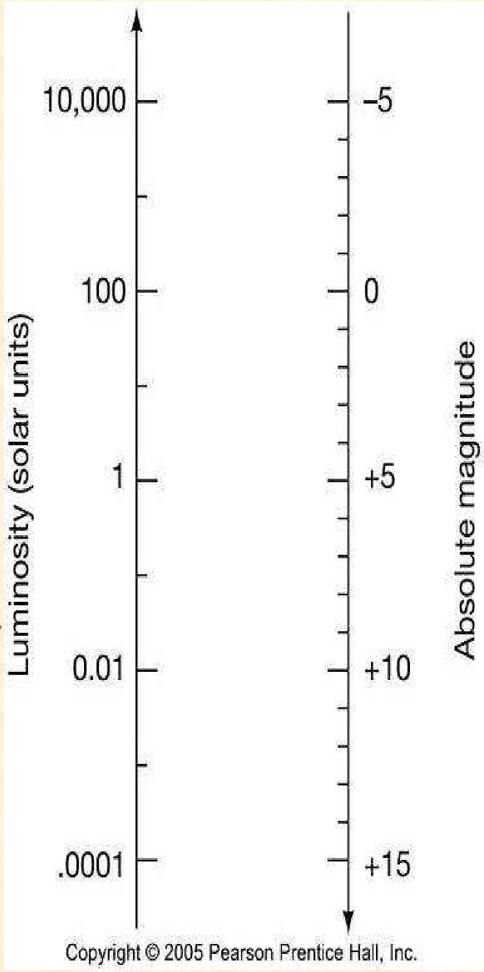
Example

Sun's absolute magnitude is 4.83

- L = 100 Solar luminosity →

  Absolute magnitude = 4.83 – 5 = – 0.17
- L = 0.01 Solar luminosity →

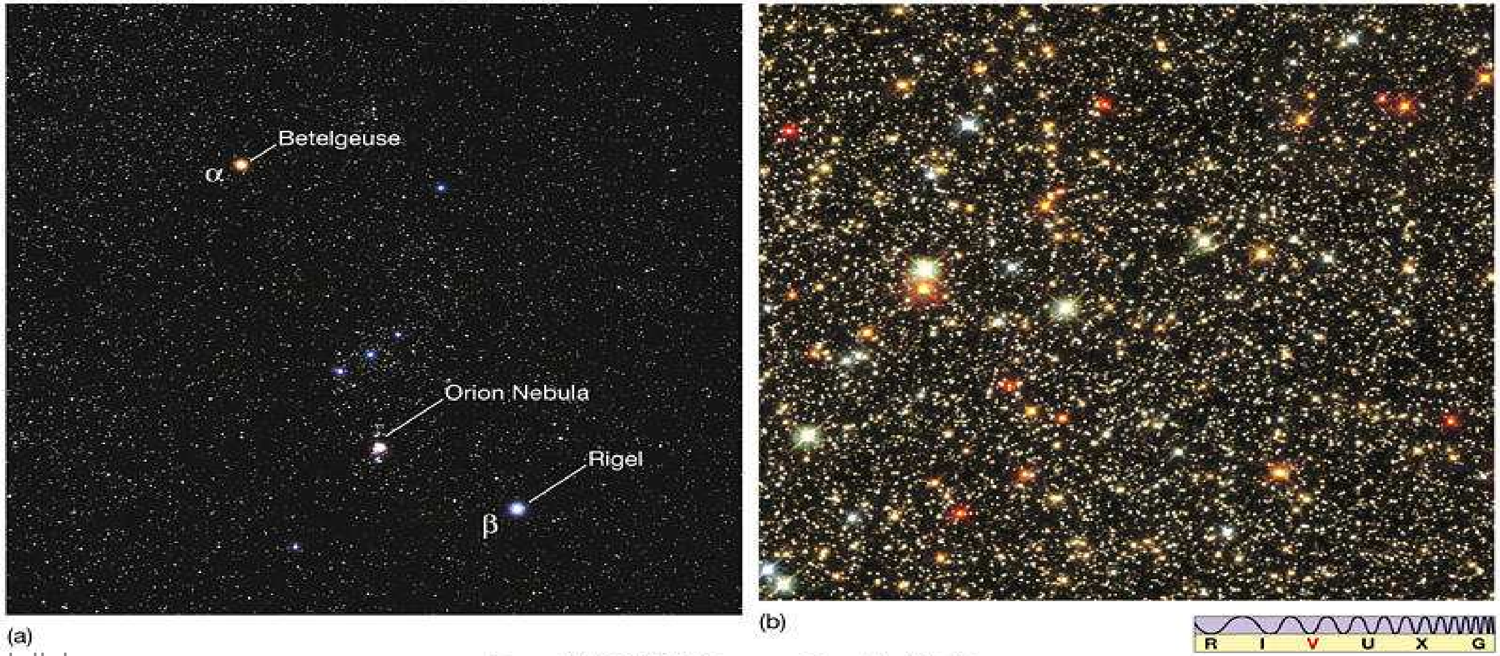
  Absolute magnitude = 4.83 + 5 = 9.83
- L (solar units) = $10^{-(M-4.83)/2.5}$
  - o Sirius M = 1.45 ➔ L = $10^{1.35}$ = 22 solar units
  - o Bernard M = 13.24 → L = $10^{-3.35}$ = 4.3 x 10^{-4} Solar unit



- **Difference between absolute magnitude (M) and apparent magnitude (m):**
  - o **M = m – 5 log(d/10 pc); d ➔ distance in pc.**
  - o **d = 10 pc * $10^{(m-M)/5}$**
  - o **Alpha Centauri has m = 0 and M = -4.4**
  - o **Its distance d = 1.3 pc.**

17.3 Stellar Temperature

- Looking at the stars will tell us about their temperatures.
- Cool red star Betelgeuse.
- Hot blue star Rigel
- Colors are intrinsic properties of the stars and have nothing to do with Doppler redshifts or blueshifts.



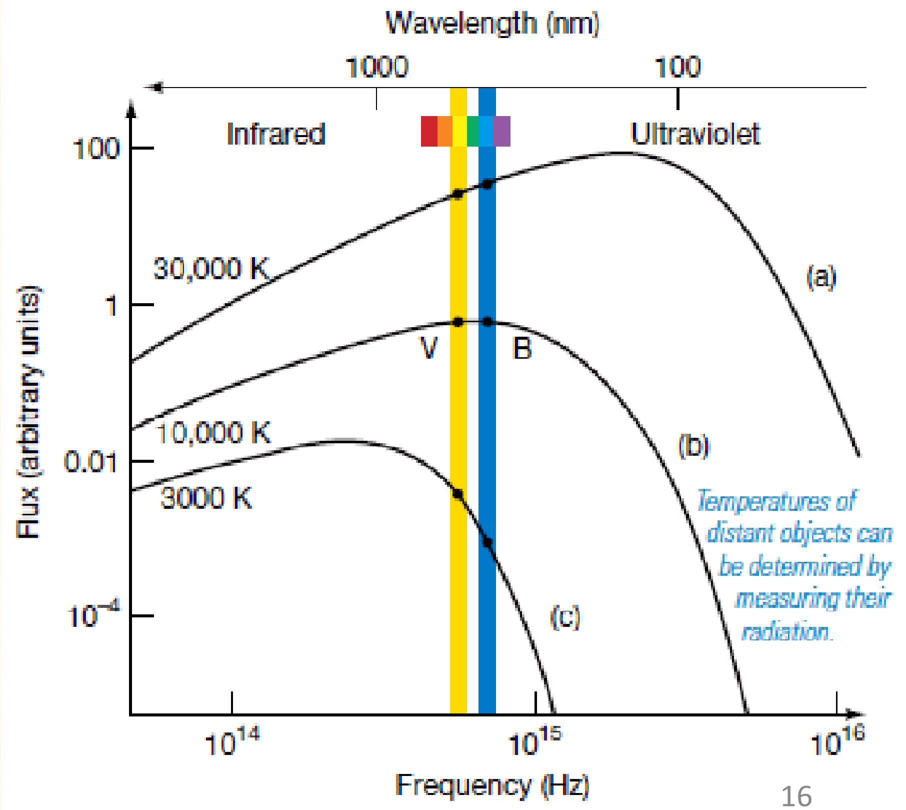
17.4 Stellar Temperature

- **Colors and the Blackbody curve.**
- **Measure only the star's surface temperature.**
- **Matching the apparent brightness at several frequencies to the appropriate blackbody curve.**

*** Only two measurements at selected wavelengths are required.**

- ❑ **B (blue) filter ➔ blue and violet, 380-480 nm.**
- ❑ **V (visual) filter ➔ green to yellow, 490-590 nm.**

- **Make a comparison between B&V intensities: 1- (B/V); 2- B-V**
- **Extrapolate blackbody curve ➔ Temp**



17.4 Stellar Temperature

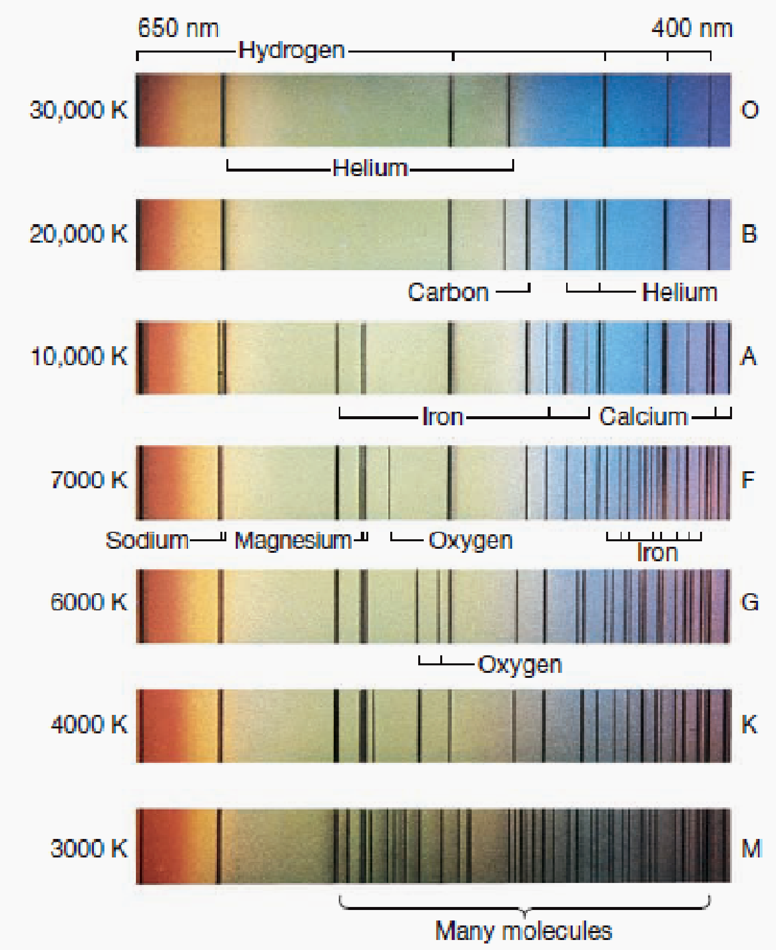
- **This type of <u>non-spectral-line</u> analysis, in which a star's intensity is measured through a set of standards filters, is known as Photometry.**

TABLE 17.1 Stellar Colors and Temperatures

B flux / V flux	Approximate Surface Temperature (K)	Color	Familiar Examples
1.3	30,000	blue-violet	Mintaka (δ Orionis)
1.2	20,000	blue	Rigel
1.00	10,000	white	Vega, Sirius
0.72	7000	yellow-white	Canopus
0.55	6000	yellow	Sun, Alpha Centauri
0.33	4000	orange	Arcturus, Aldebaran
0.21	3000	red	Betelgeuse, Barnard's Star

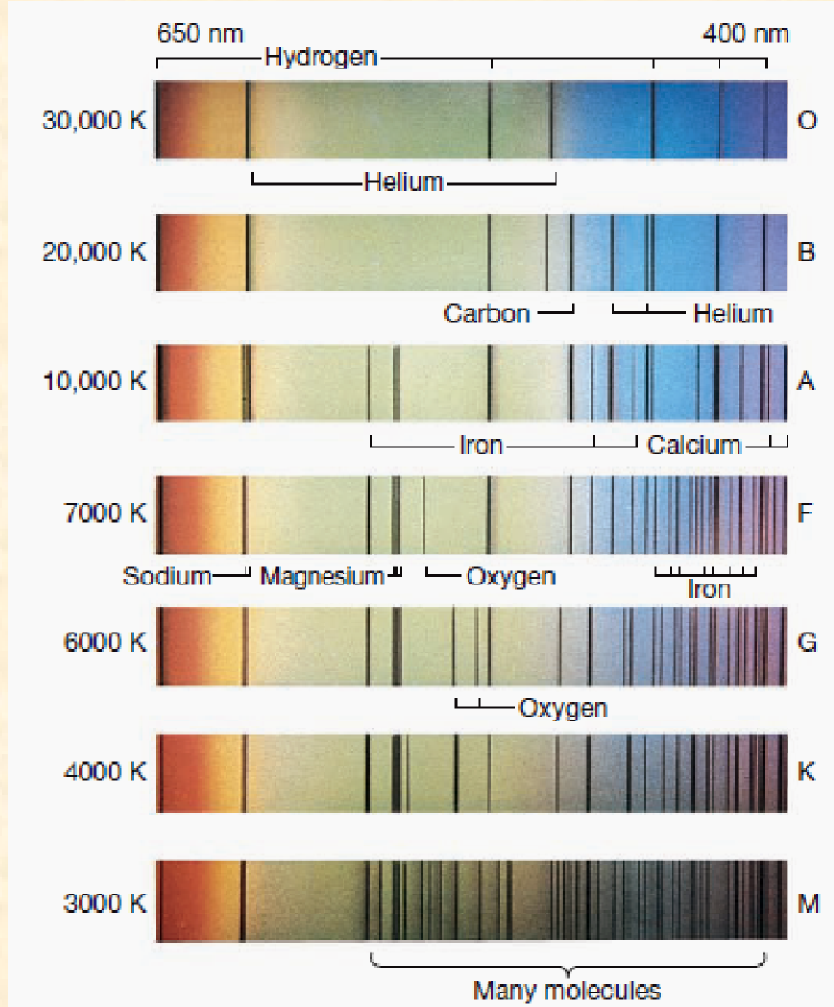
17.4 Stellar Temperature

- **Stellar Spectra: More detailed scheme to classify stellar properties.**
- **Spectra extended 400-650 nm.**
- **Dark absorption lines superimposed on a background of continuous color.**
- **Stars may display strong lines in the long wavelength of the spectrum.**
- **Others have strongest lines at short wavelength.**
- **What this difference imply? Not the chemical compositions!**
- **Ionization state of atoms depends on temperature.**
- **Energy of light (and therefore absorption) depends on temperature**



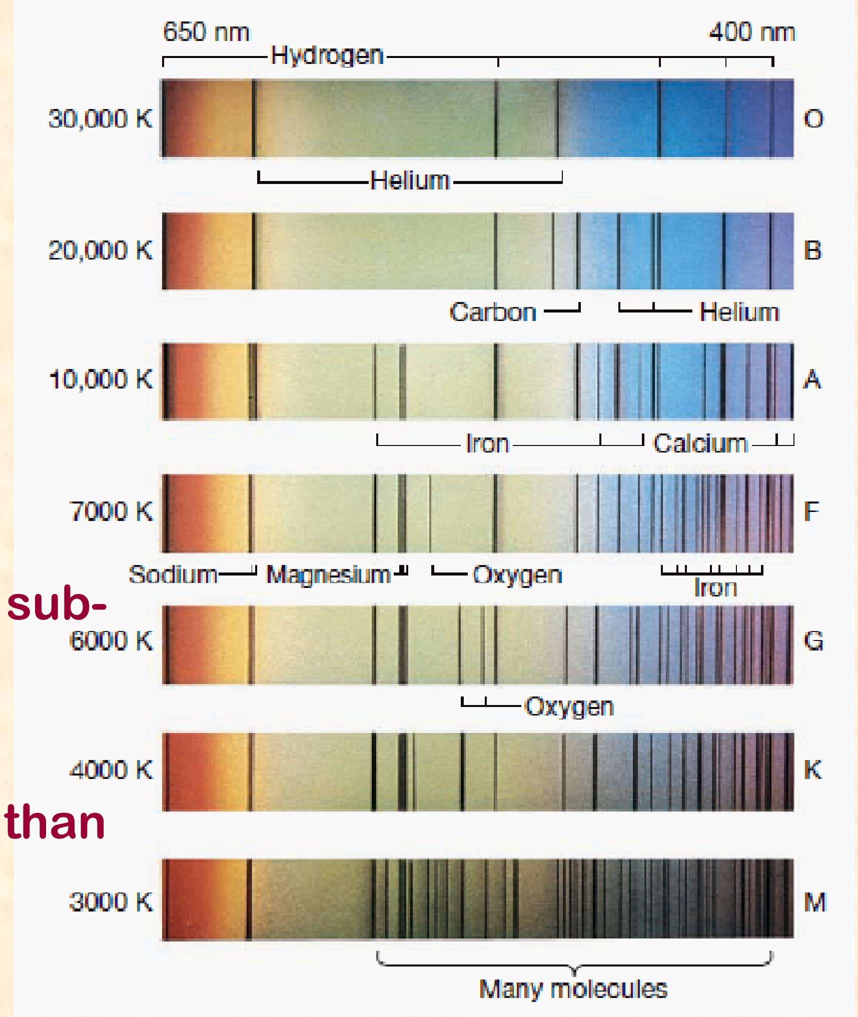
17.4 Stellar Temperature

- Seven stars of the same components.
- If T > 25,000 K strong absorption lines of ionized atoms: He, O, N, C, Si, no H.
- H-lines are strongest in stars T = 10,000 K.
- If T < 4,000 K weak H-lines; electrons in their ground states, produces lines are from molecules.
- *SPECTRAL CLASSIFICATION.*
- A, B, C, D, E, F, ...P, A stars have more hydrogen than B stars.
- Modern scheme: O, B, A, F, G, K, M, ..



17.4 Stellar Temperature

- **Spectral Classification.**
- Types of Spectra
  - o Hydrogen Lines Strongest in A spectra
  - o Molecular Lines Strongest in M spectra
  - o Neutral Metals Strongest in G,K, and M
  - o Neutral Helium Strongest in B
  - o Ionized Helium Strongest in O



- **Each lettered spectral class is further sub-divided in 10 subdivisions, denoted by 0-9**

  so, for example:
  - **o The Sun is G2, (cooler than G1, hotter than G3)**
  - **o Betelgeuse is M2,**
  - **o Barnard's star is M5**

17.4 Stellar Temperature

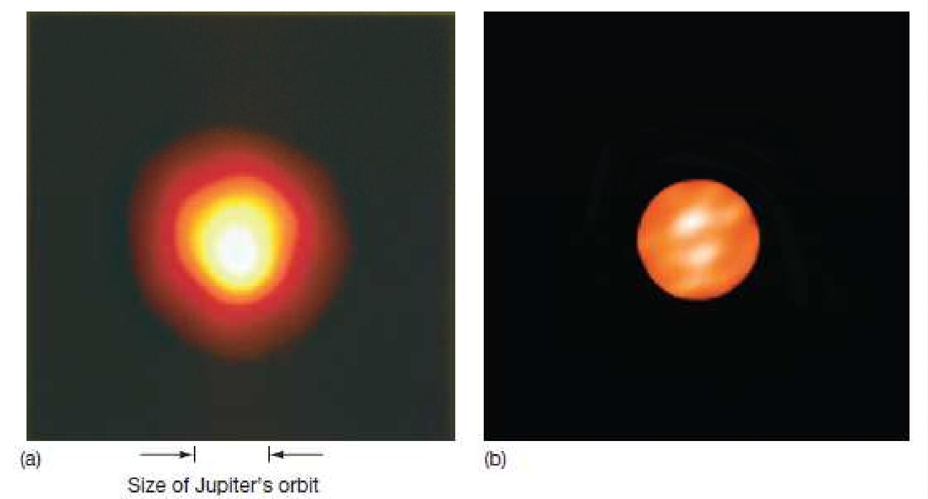
Spectral Class Characteristics

Spectral Class	Intrinsic Color	Surface Temperature (K)	Prominent Absorption Lines
O	Blue	41,000	He^+, O^{++}, N^{++}, Si^{++}, He, H
B	Blue	31,000	He, H, O^+, C^+, N^+, Si^+
A	Blue-white	9,500	H(strongest), Ca^+, Mg^+, Fe^+
F	White	7,240	H(weaker), Ca^+, ionized metals
G	Yellow-white	5,920	H(weaker), Ca+, ionized & neutral metal
K	Orange	5,300	Ca^+(strongest), neutral metals strong, H(weak)
M	Red	3,850	Strong neutral atoms, TiO

17.5 Stellar Sizes

- Most stars appear as points of light, so their sizes cannot be directly measured
- However, for a few we measure the size directly:

•Betelgeuse; D = 130 pc, 0.045” ➔ its radius is 630 times of the Sun.



- We must use indirect means (temperature and brightness, emitted radiation)

17.5 Stellar Sizes

Combining the Stefan-Boltzman law for the power per unit area emitted by a blackbody as a function of temperature with the formula for the area of a sphere gives the total luminosity

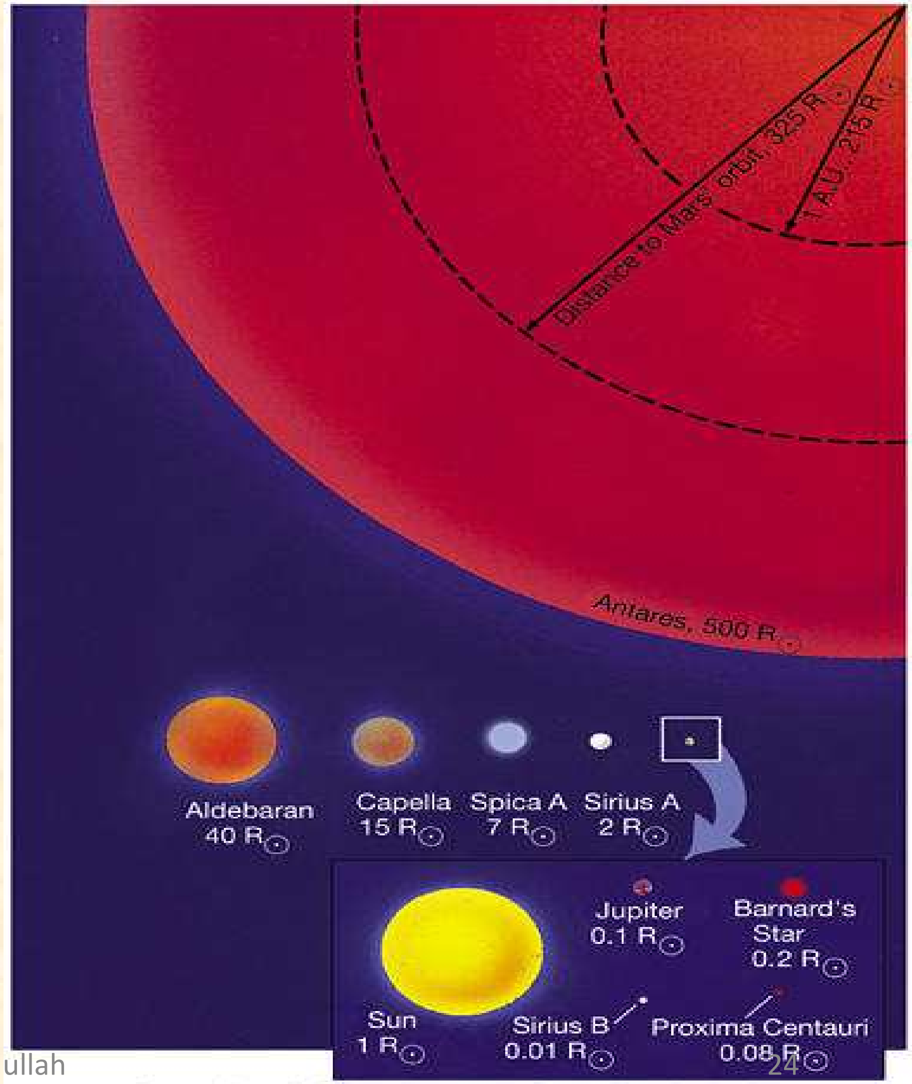
$$L = 4\pi\sigma R^2 T^4$$

If we measure luminosity, radius, and temperature in solar units, we can write

$$L = R^2 T^4$$

17.5 Stellar Sizes

- Stars can be classified by their size
  - o Giants (10-100 times the Sun's radius)
  - o Supergiants (100-1000 times the Sun's radius)
  - o Dwarf (comparable to or smaller than the Sun)



17.5 Stellar Sizes

- **Examples**
- **Aldebaran**; $L = 1.3 \times 10^{29}$ W / 3.9×10^{26} W = 330, T = 4000 K / 5800 K = 0.69

  ➔ its radius is $R = (330)^{0.5} / 0.69^2 = 39$ solar radii

  ➔ Giant Star

- **Procyon B**; $L = 2.3 \times 10^{23}$ W / 3.9×10^{26} W = 0.0006, T = 8500 K / 5800 K = 1.5

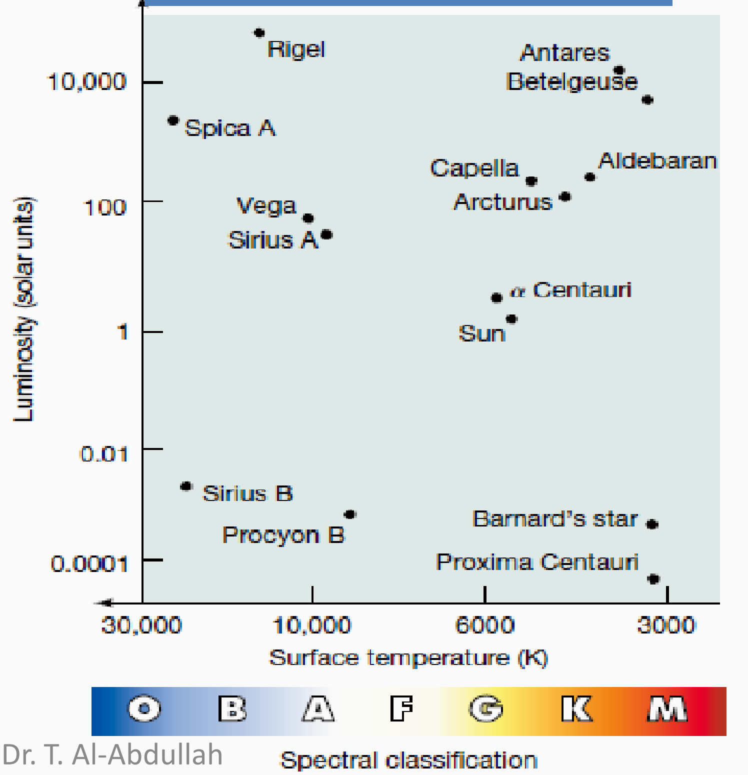
  ➔ its radius is $R = (0.0006)^{0.5} / 1.5^2 = 0.01$ solar radii

  ➔ dwarf Star

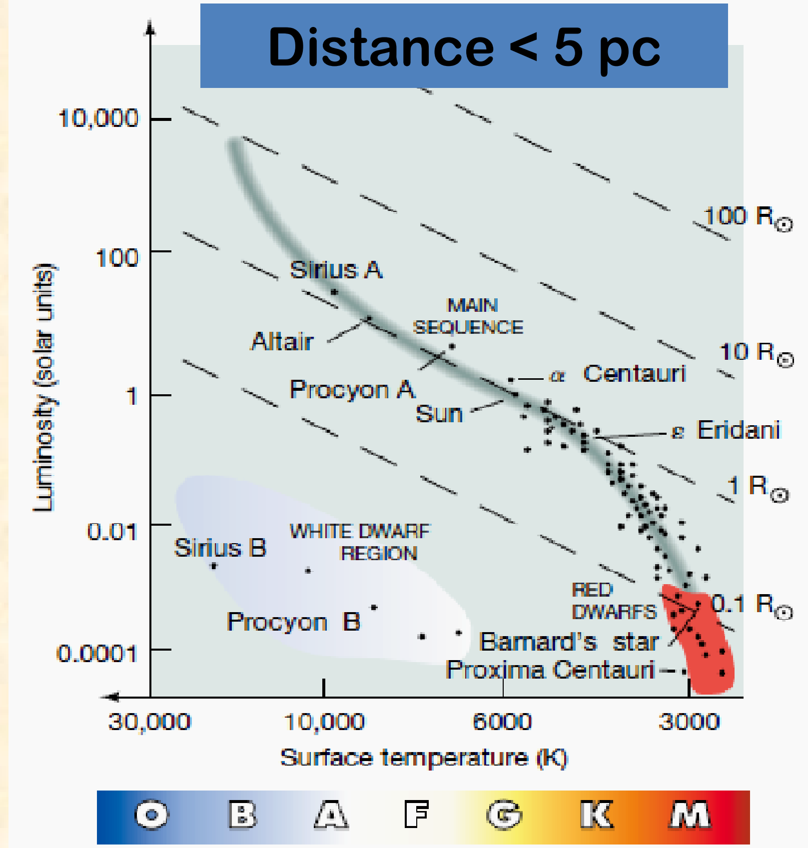
17.5 The Hertzsprung-Russell Diagram

- **Relating Luminosity ($10^{-4} – 10^{4}$) to surface temperature (3000 – 30000 K).**
- **Cool stars tend to be faint and hot stars tend to be bright, this spanning of H-R diagram is known as "Main Sequence".**

Well-known Stars



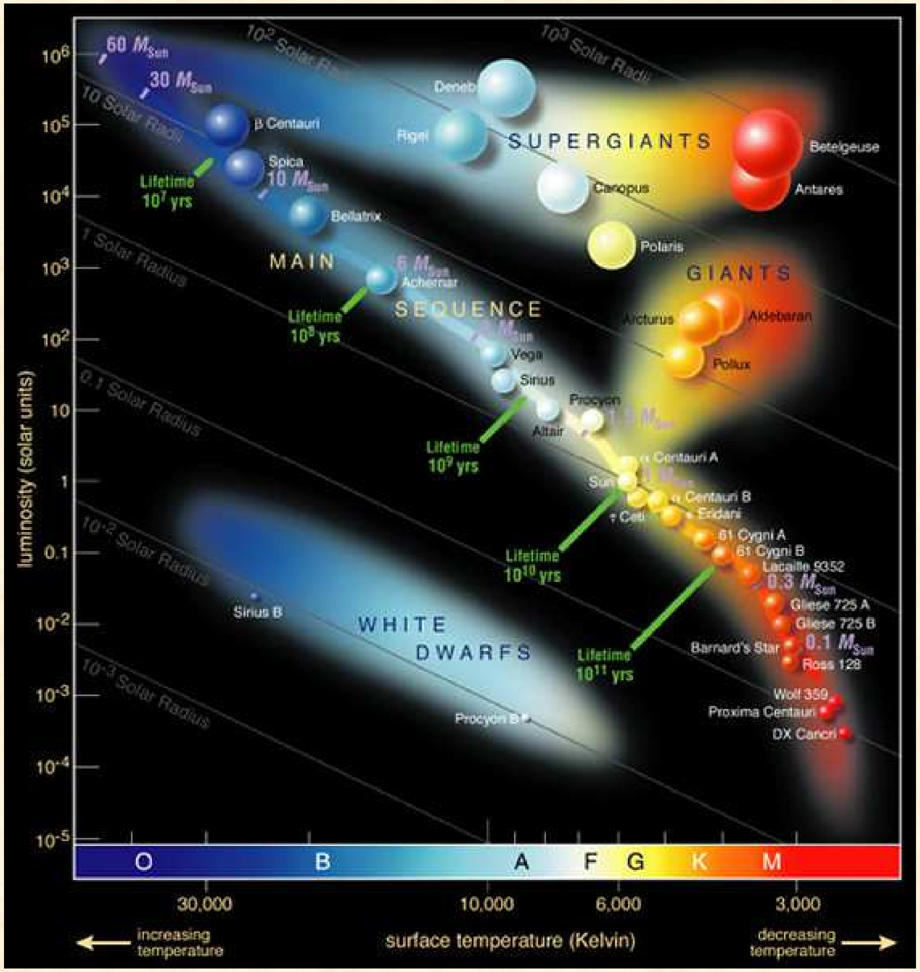
Distance < 5 pc



17.5 The Hertzsprung-Russell Diagram

Luminosity α Radius^2 X Temperature^4

- **On the main sequence (90%):**
  - **→Red dwarfs 80% of stars.**
  - **→ O- & B- types are rare: 1:10000**
- **Off the main sequence:**
  - **→white dwarfs: 9%**
  - **→red giants 1%.**



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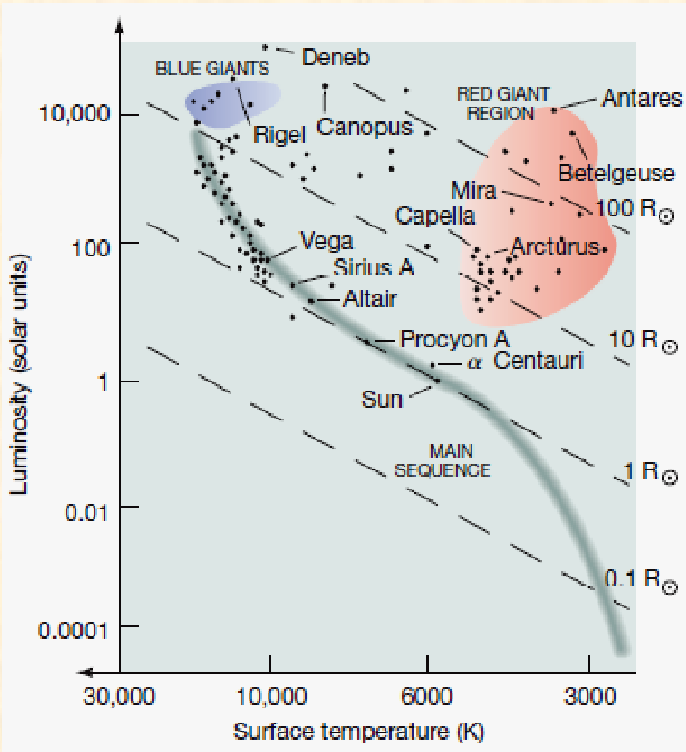
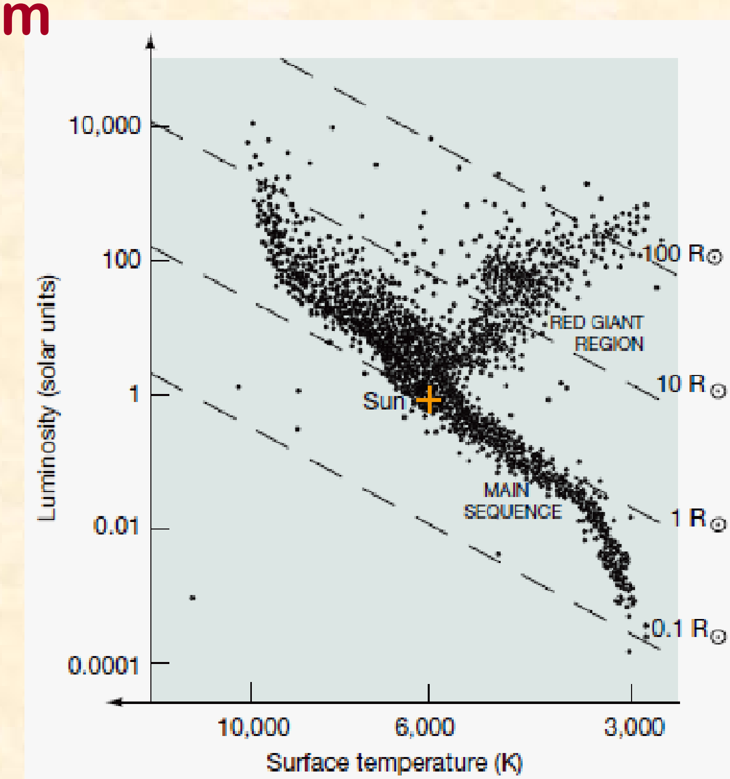
17.5 The Hertzsprung-Russell Diagram



100 brightest star > 10 pc



20,000 data points, as measured by the European Hipparcos spacecraft for stars within a few hundred parsecs of the Sun. Only stars with apparent magnitude > 12.

17.5 The Hertzsprung-Russell Diagram

17.6 Extending the Cosmic Distance

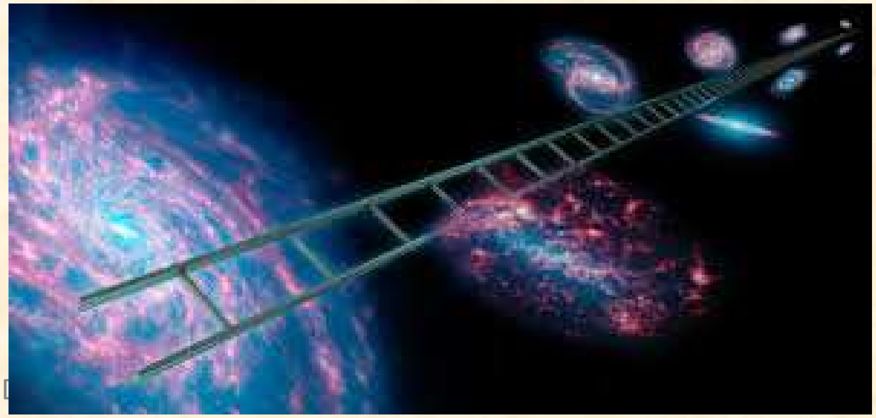
Spectroscopic Parallax

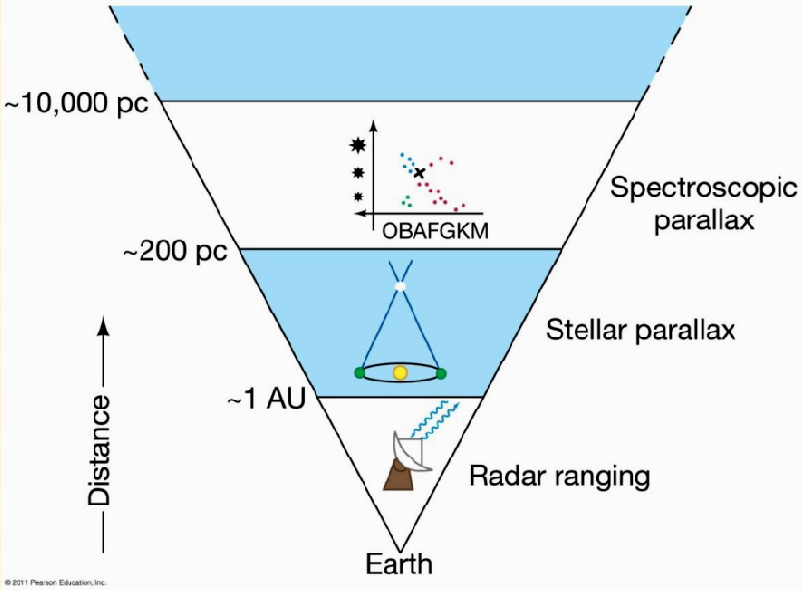
Measure the distance by a different method, differ than the stellar parallax:

1. Measure the star's apparent brightness and spectral type
2. Use (H-R) diagram to estimate the luminosity from temperature
3. Apply the inverse Square law to determine the distance.

$$\text{apparent brightness} \; \alpha \; \frac{\text{luminosity}}{\text{distance}^2}$$

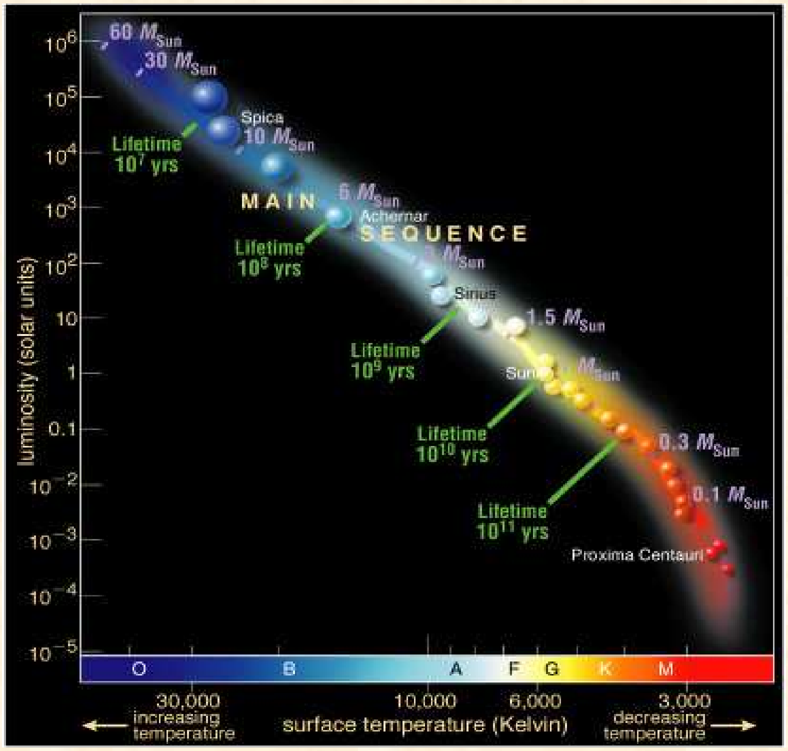
Extend the scale to several thousands pc





17.6 Extending the Cosmic Distance

- **Example:**
- **Alpha Centauri;**
- **Surface Temp: 5790 K → Spectral type: G2V**
  - → L= 1.519L_{sun}
  - ➔ Use: L(solar units)=$10^{-(M-4.83)/2.5}$
    - → Absolute Magnitude M = 4.34
  - ➔ Apparent magnitude m = -0.01
  - ➔ Use: m – M = 5 $\log_{10}$ (distance / 10 pc)
    - → d = 1.35 pc



- **Results obtained by parallax 0.77”➔1.35pc**

17.6 Extending the Cosmic Distance

Spectroscopic Parallax has limitations

H-R diagram is calibrated using nearby stars.

Far stars should be compared with a similar nearby stars.

They fall on the same main sequence. Its not a line, it has a thickness.

➔Large uncertainty in estimating the distance ±25%.

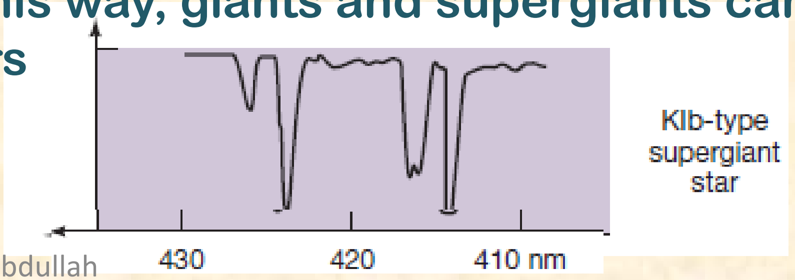
➔ Main sequence is not really a line, it has thickness in H-R diagram

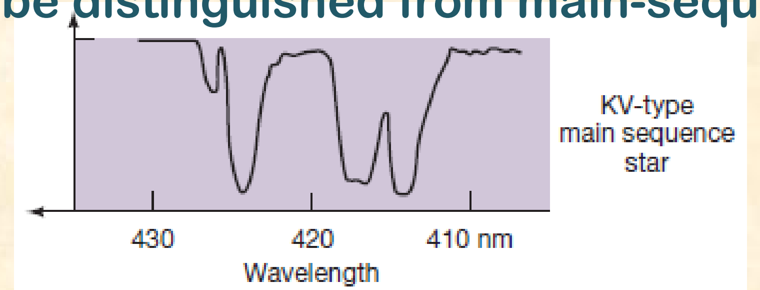
➔Example: A0 – star has L = 30 – 100 luminosity of the sun

Luminosity Class

Analysis of the spectral line widths depends on the density of the gas. (Ch4)

In this way, giants and supergiants can be distinguished from main-sequence stars





17.6 Extending the Cosmic Distance

Specifications according to the widths of their spectroscopic lines:

The Sun: G2 → G2V

Rigel (blue supergiant) B8 → B8Ia

Bernard (red dwarf) M5 → M5V

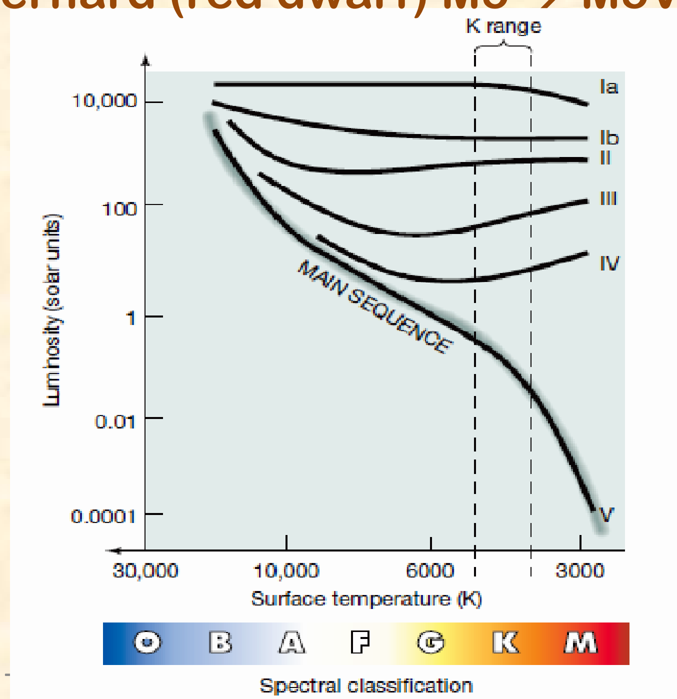


TABLE 17.3 Stellar Luminosity Classes

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

Example:

K2-type star, T=4500K, spectral line widths is on the main sequence➔ K2V ➔ L= 0.3

If the width is narrow ➔ K2III giant ➔ L=100

Very narrow ➔ K2Ib super giant ➔ L=4000

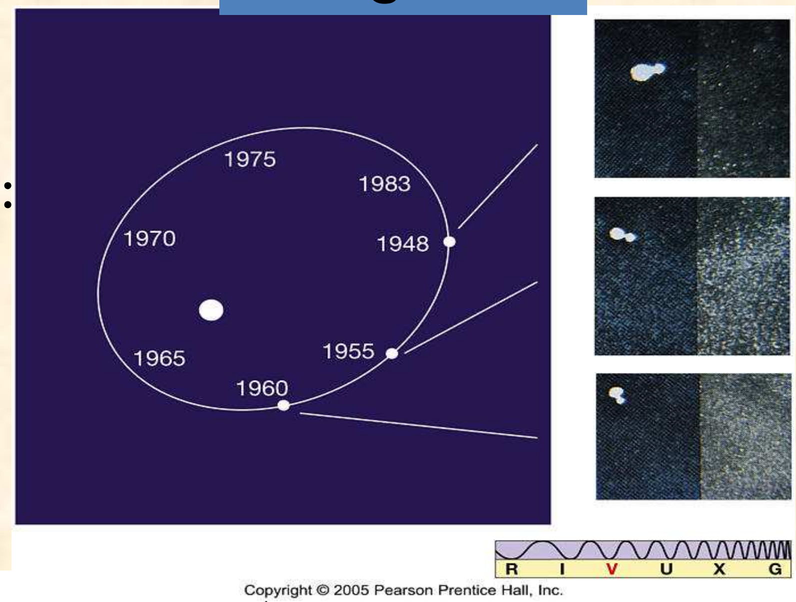
17.7 Stellar Masses

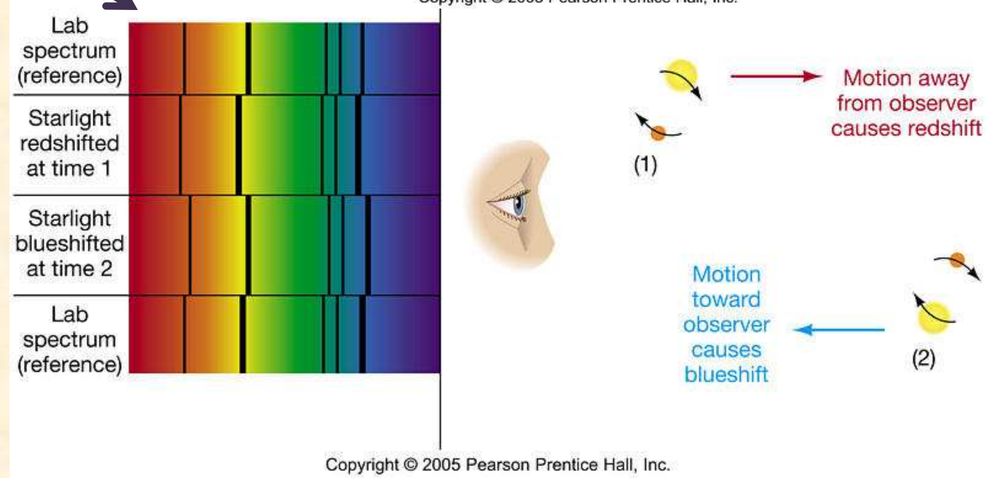
- The mass and the composition are fundamental properties of any star.
- They determine the star's internal structure, its external appearance, and its future evolution.
- PRINCIPLE: a star's mass is measured by it gravitational influence on some nearby objects.
- If the distance between two bodies are known ➔ Newton's law to calculate their masses.

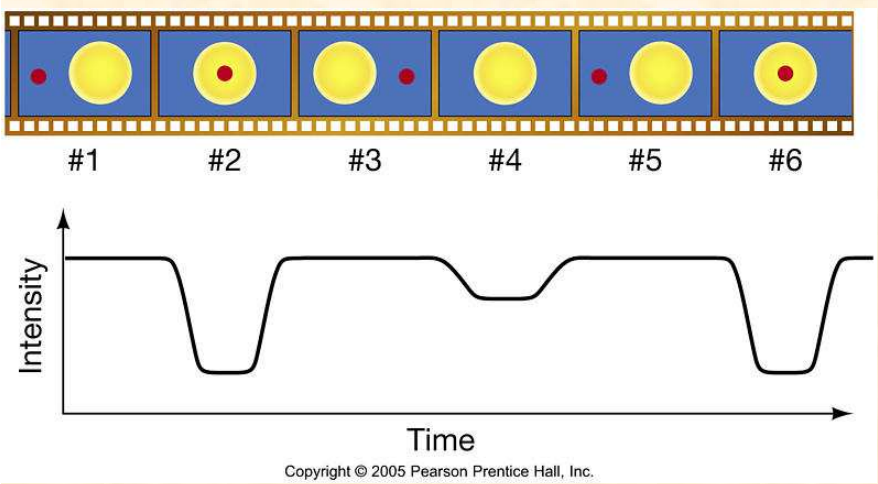
17.7 Stellar Masses

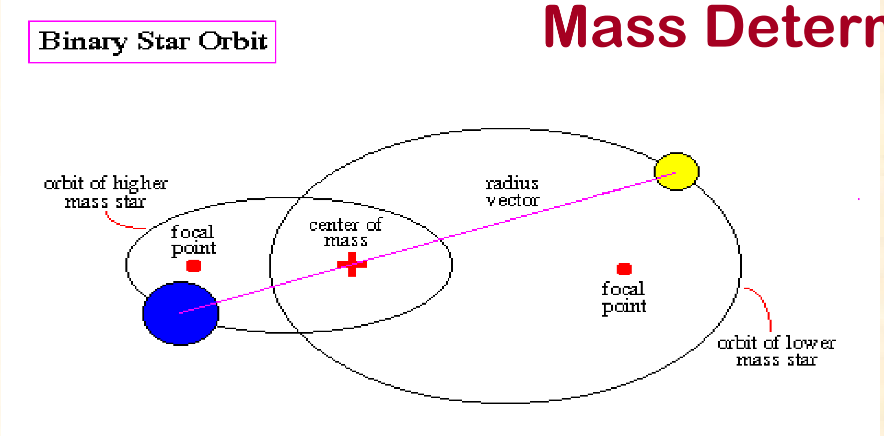
- Most stars are part of a multiple star system.
- The majority of stars are binary-star systems.
- Classifications according to their appearance:
  - o Visual binaries:
  - o Spectroscopic binaries.
  - o Eclipsing binaries

Kruger 60

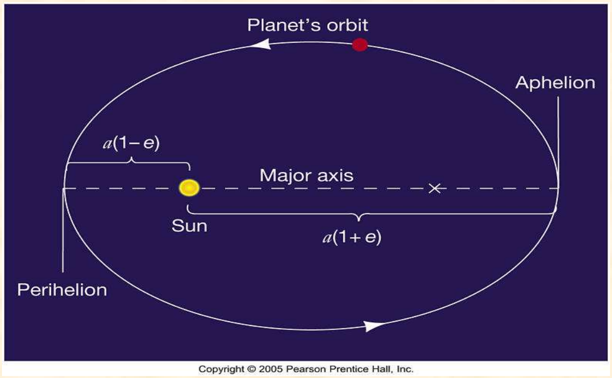








Mass Determination



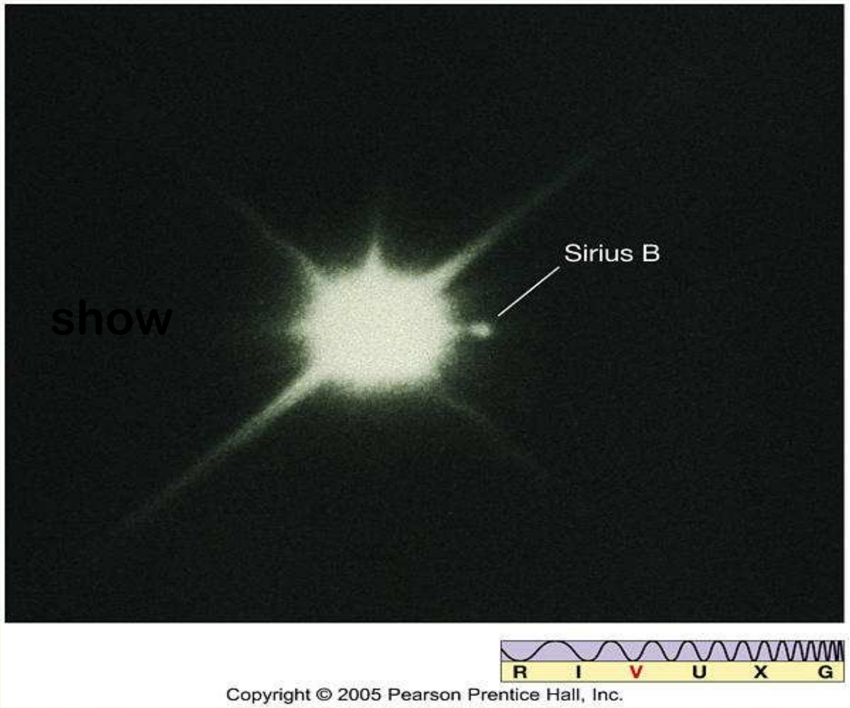
- Astronomers measure the binary's orbital period; hours-centuries.
- Extracted information depends on the type of the binary involved.
- If the distance to a visual binary is known → Its semimajor axis can be determined directly.
- For visual binary use the modified Kepler's third law to deduce the combined mass: $M_1 + M_2 \sim a^3/p^2$
- Measuring the distance from each star to the center of mass ➔ M_1/M_2.
- Knowing M_1+M_2 and M_1/M_2 ➔ we calculate M_1 and M_2.
- Our knowledge of the masses of stars is based on these binary measurements.

EXAMPLE

- A binary star: Sirius (the brightest star in the sky)

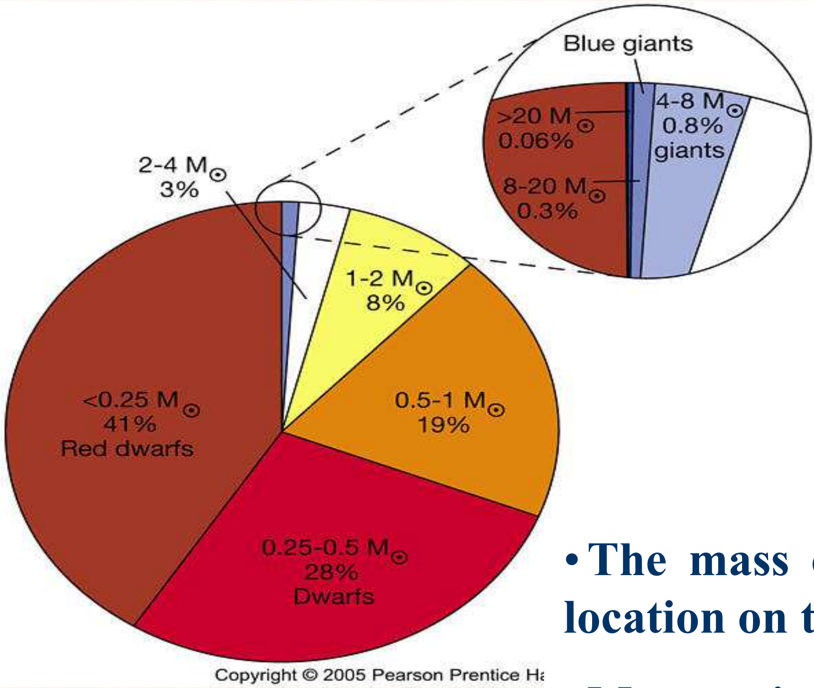
  bright Sirius A and faint companion Sirius B

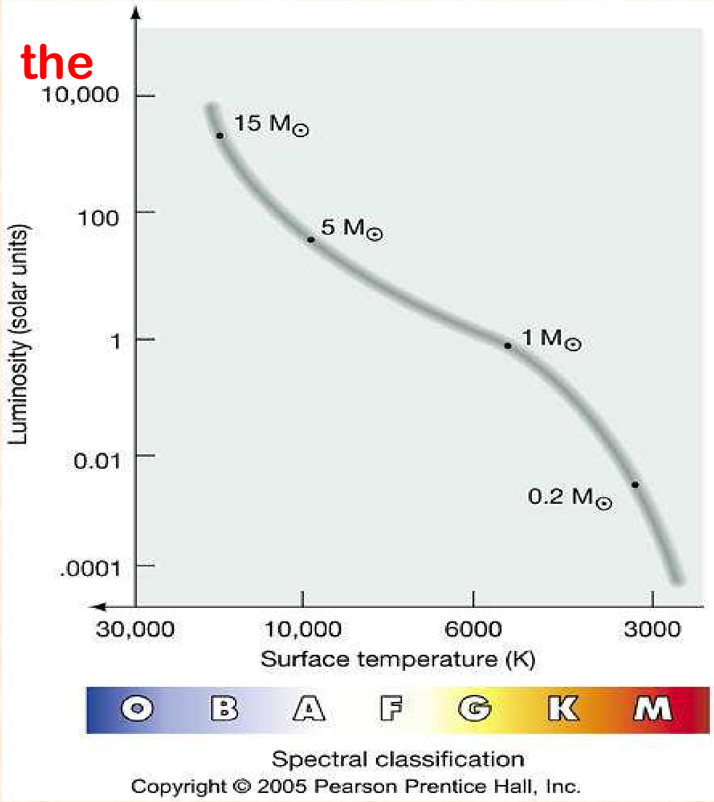
  - orbital period (*P*) = 50 years
  - semi-major axis (*a*) = 20 AU
  - $M_A + M_B = 3.2\ M_{sun}$
  - Doppler observations show Sirius A moves at 0.5 speed of Sirius B
  - ➔ $M_A = 2 \times M_B$
  - $M_A = 2.1\ M_{sun}$
  - $M_B = 1.1\ M_{sun}$



17.8 Mass and Other Stellar Properties

- H-R diagram shows stellar mass varies along the main sequence.
- Low-mass red dwarf → high-mass blue giants.
- Main sequence stars range 0.1 -- 20 $M_{\odot}$

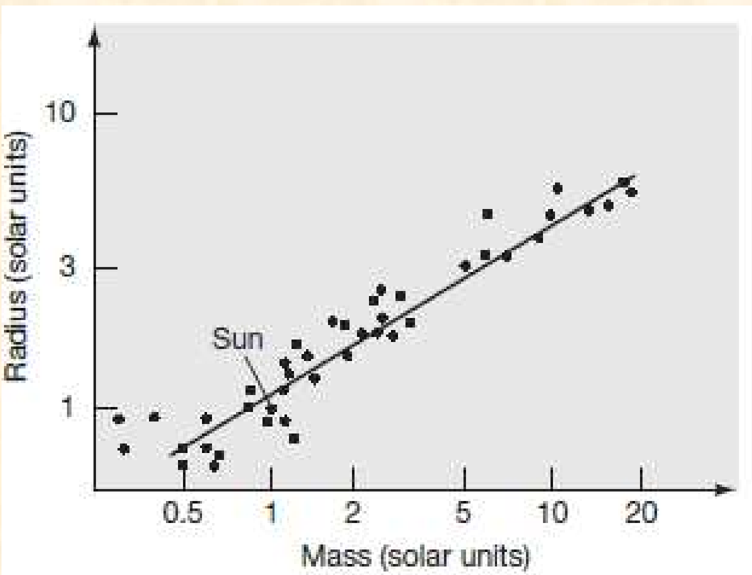


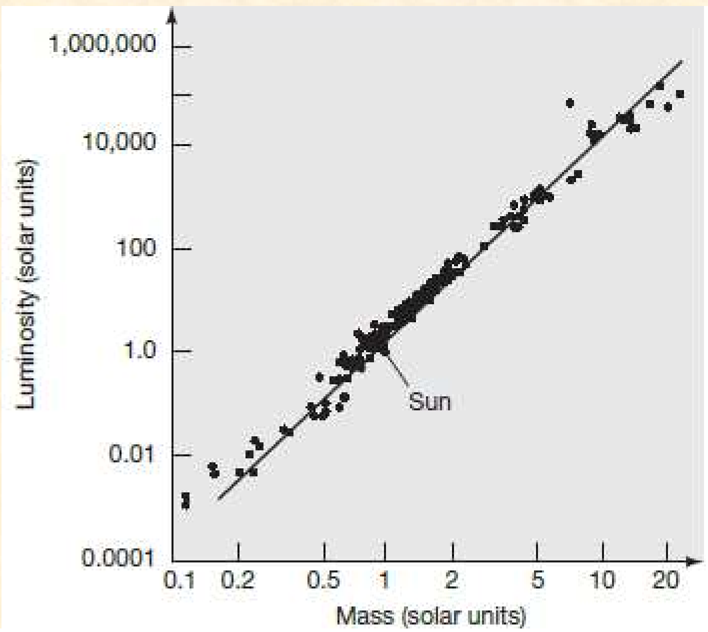


- The mass of the star at the time of formation determines its location on the main sequence
- Most main-sequence stars are low-mass stars, and only a small fraction are much more massive than the Sun

17.8 Mass and Other Stellar Properties

- **A main-sequence star's radius and luminosity depend on its mass.**
- **mass-radius and mass-luminosity relations are based on observations of binary-star systems.**
- **Luminosity ~ mass^3(massive) or mass^4 (common). (approximate)**
- **Radius increases proportionally to stellar mass.**
- **Example: a $2M_\odot$ main sequence star has a $2R_\odot$ and $16L_\odot$.**





17.8 Mass and Other Stellar Properties

- **Lifetime: How long can the fire continue to burn?.**
- **It depends on the fuel available (mass) and the rate of burning:**
- **lifetime is simply:** $\text{stellar lifetime} \propto \dfrac{\text{stellar mass}}{\text{stellar luminosity}}$
- **Using the mass-luminosity relation:** $\text{stellar lifetime} \propto \dfrac{1}{(\text{mass})^3}$
- **More massive stars burn up fastest and have shortest lives**

TABLE 17.6 Key Properties of Some Well-Known Main-Sequence Stars

Star	Spectral Type	Mass, *M* (Solar Masses)	Central Temperature (10^6 K)	Luminosity, *L* (Solar Luminosities)	Estimated Lifetime (*M/L*) (10^6 years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

**The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).*

Summary

Stellar Property	Measurement Technique	"Known" Quantity	Measured Quantity	Theory Applied	Section
Distance	stellar parallax spectroscopic parallax	astronomical unit main sequence	parallactic angle spectral type apparent magnitude	elementary geometry inverse-square law	17.1 17.6
Radial velocity		speed of light atomic spectra	spectral lines	Doppler effect	17.1
Transverse velocity	astrometry	distance	proper motion	elementary geometry	17.1
Luminosity		distance main sequence	apparent magnitude spectral type	inverse square law	17.2 17.6
Temperature	photometry spectroscopy		color spectral type	blackbody law atomic physics	17.3 17.3
Radius	direct indirect	distance	angular size luminosity temperature	elementary geometry radius–luminosity–temperature relationship	17.4 17.4
Composition	spectroscopy		spectrum	atomic physics	17.3
Mass	observations of binary stars	(distance)	binary period binary orbit orbital velocity	Newtonian gravity and dynamics	17.7


END OF CHAPTER 17
Dr.T.Al-Abdullah