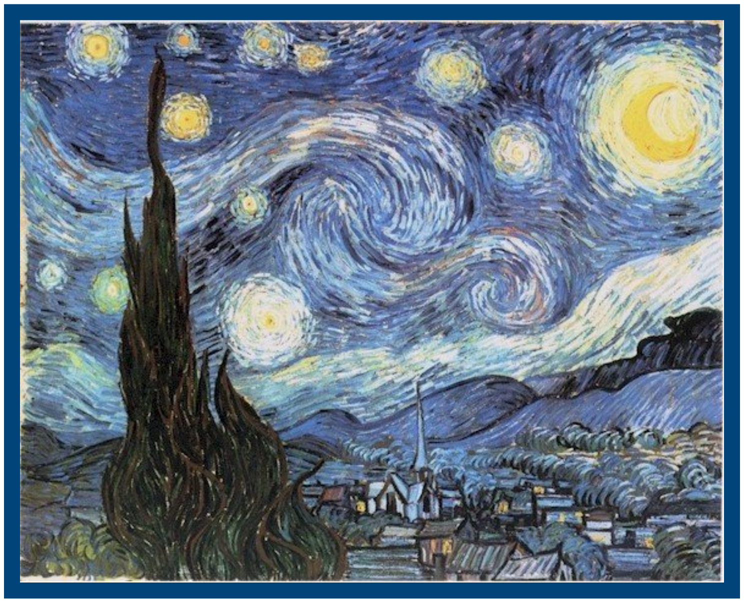
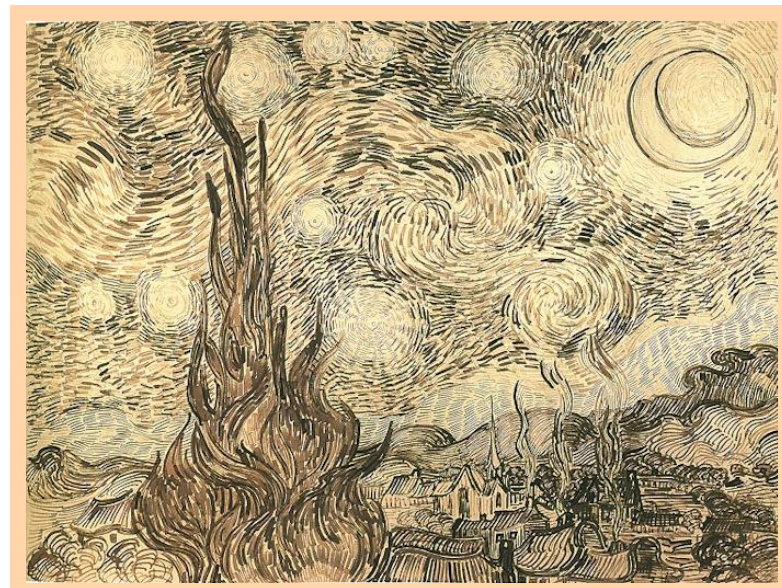
Astronomical Study: A Multi-Perspective Approach

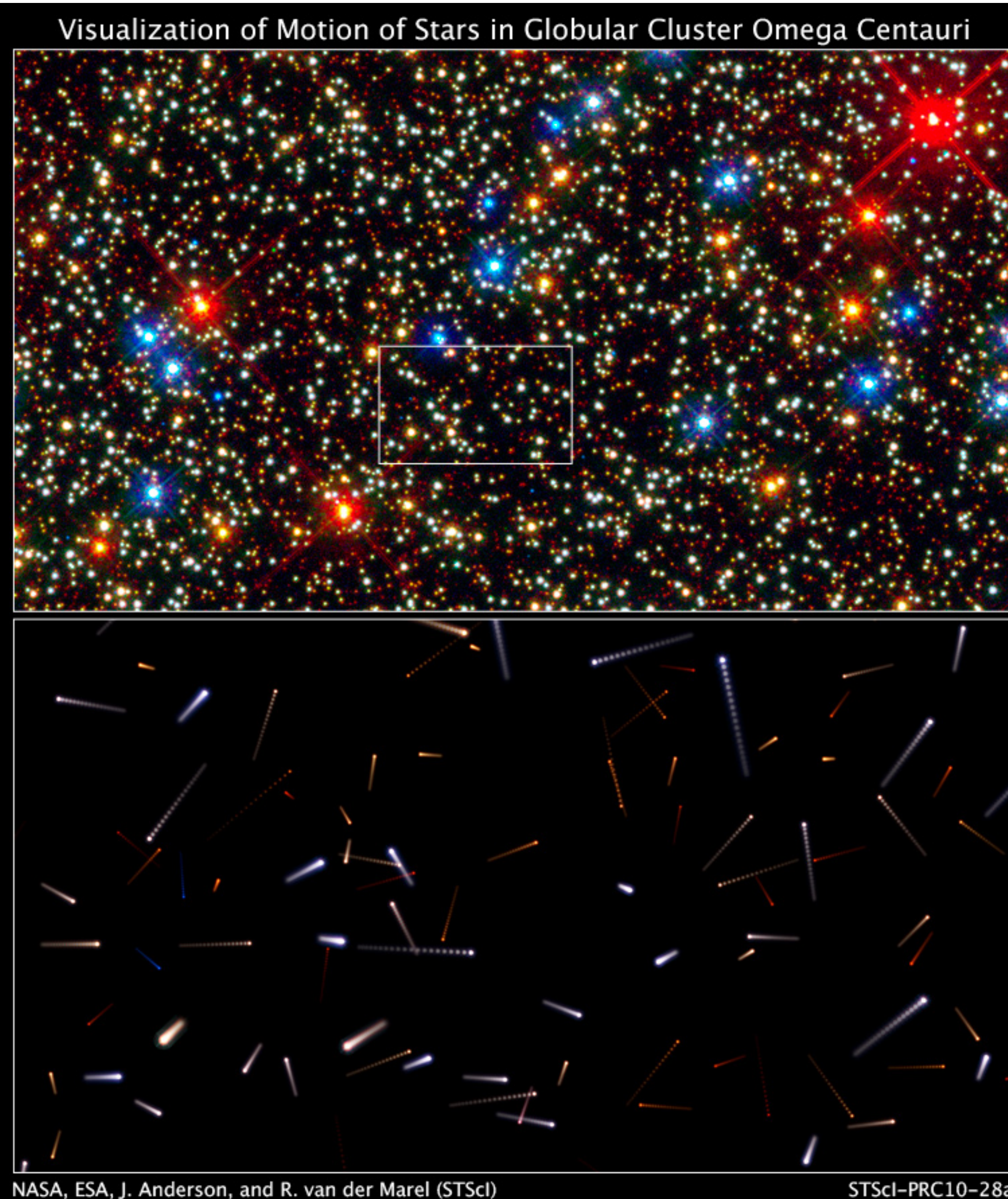




Overview of Stars

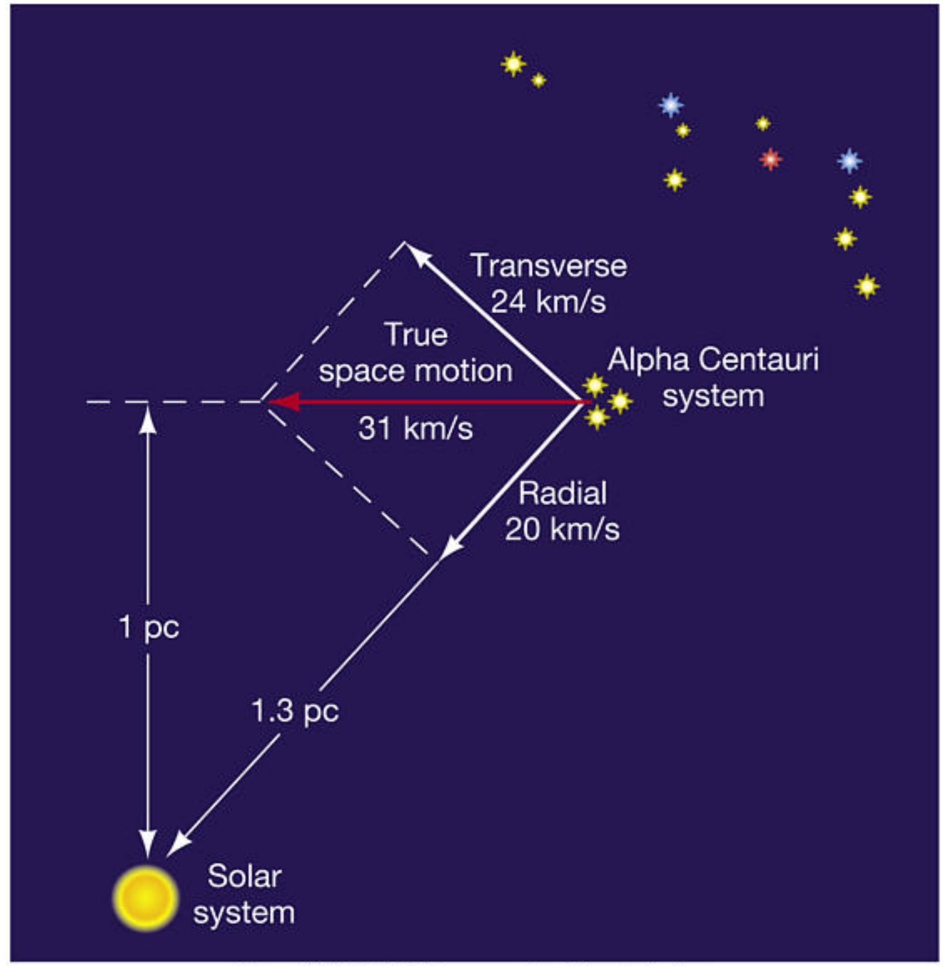
- Motion
- Distances
- Physical Properties
- Spectral Properties
  - Magnitudes
  - Luminosity class
  - Spectral trends
- Binary stars and getting masses
- Stellar census

Stars Move!

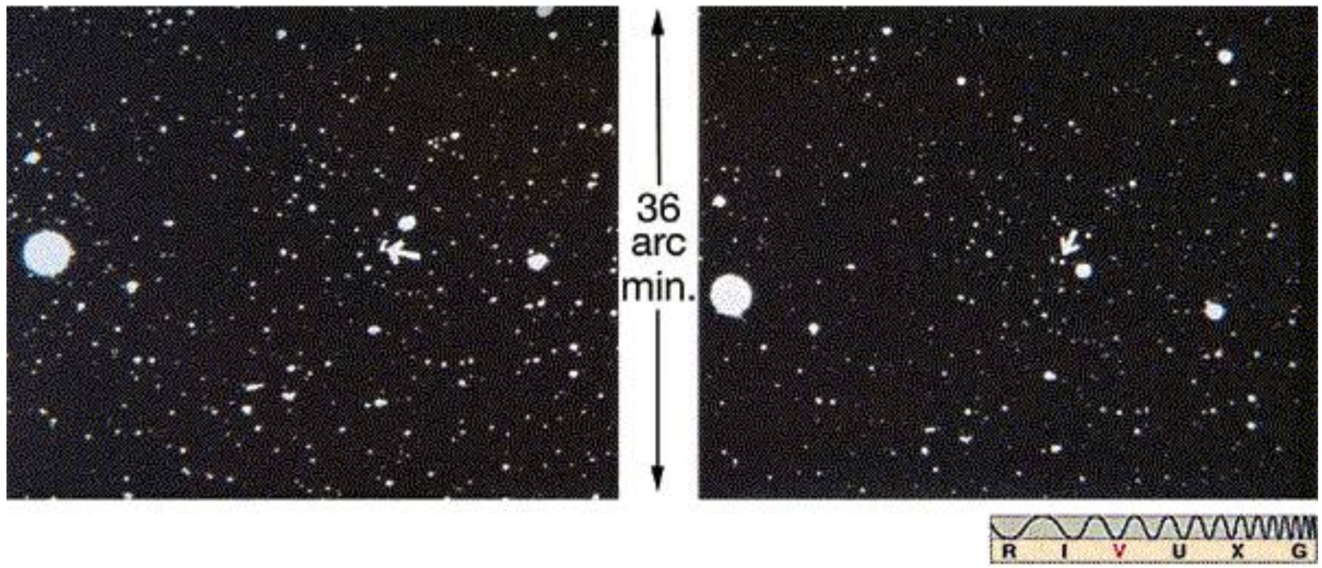

Visualization of Motion of Stars in Globular Cluster Omega Centauri
NASA, ESA, J. Anderson, and R. van der Marel (STScI)
STScI-PRC10-28a

Motion through Space

- Everything moves!
- From an Earth perspective, velocity has a component toward and transverse
- Radial velocity is toward or away – measure this with the Doppler effect
- Tangential velocity is transverse in the sky

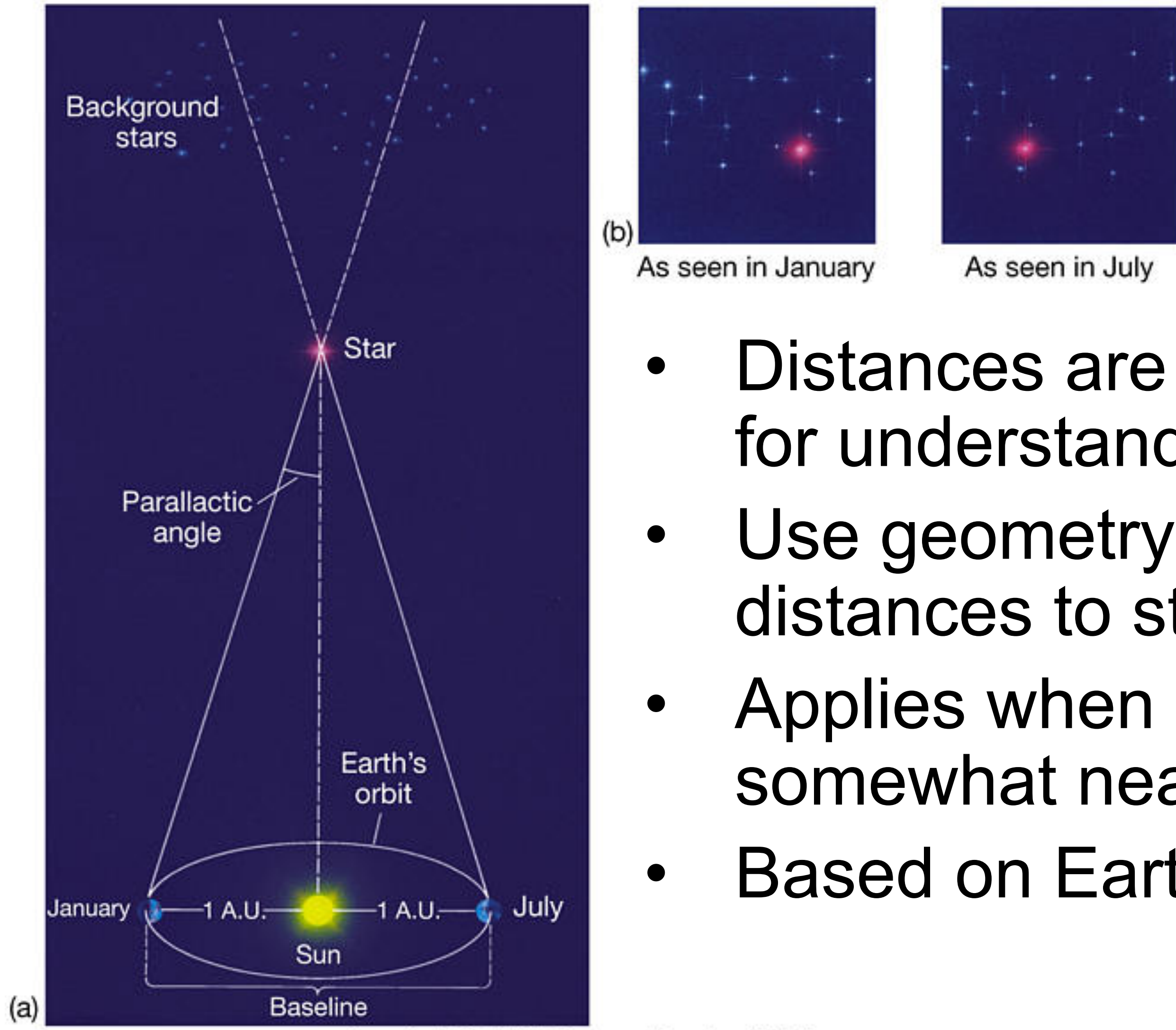


Proper Motion



Proper motion refers to the apparent change of position of an object in the sky. This is a result of the trangential (transverse) space motion of stars. This example is for Barnard's star.

Distances: Stellar Parallax



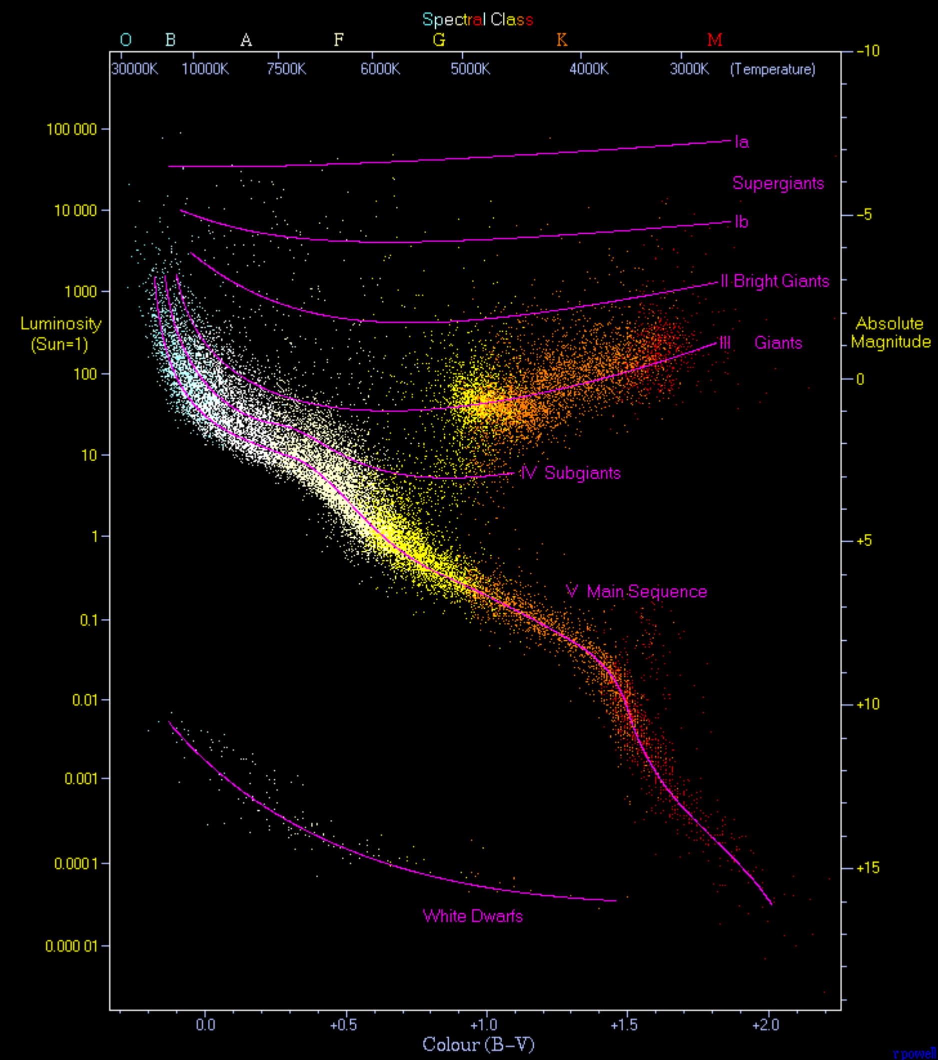
- Distances are important for understanding stars
- Use geometry to infer distances to stars
- Applies when star is somewhat nearby
- Based on Earth's orbit

Stars Come in Colors

(Canary Islands)

Hertzsprung-Russell Diagrams

- The "HRD" represents one way of grouping stars
- Three versions:
  - Theoretical - temperature plotted against luminosity
  - Observational - "color" plotted against apparent brightness
  - A 3rd version plots spectral class for color or for temperature



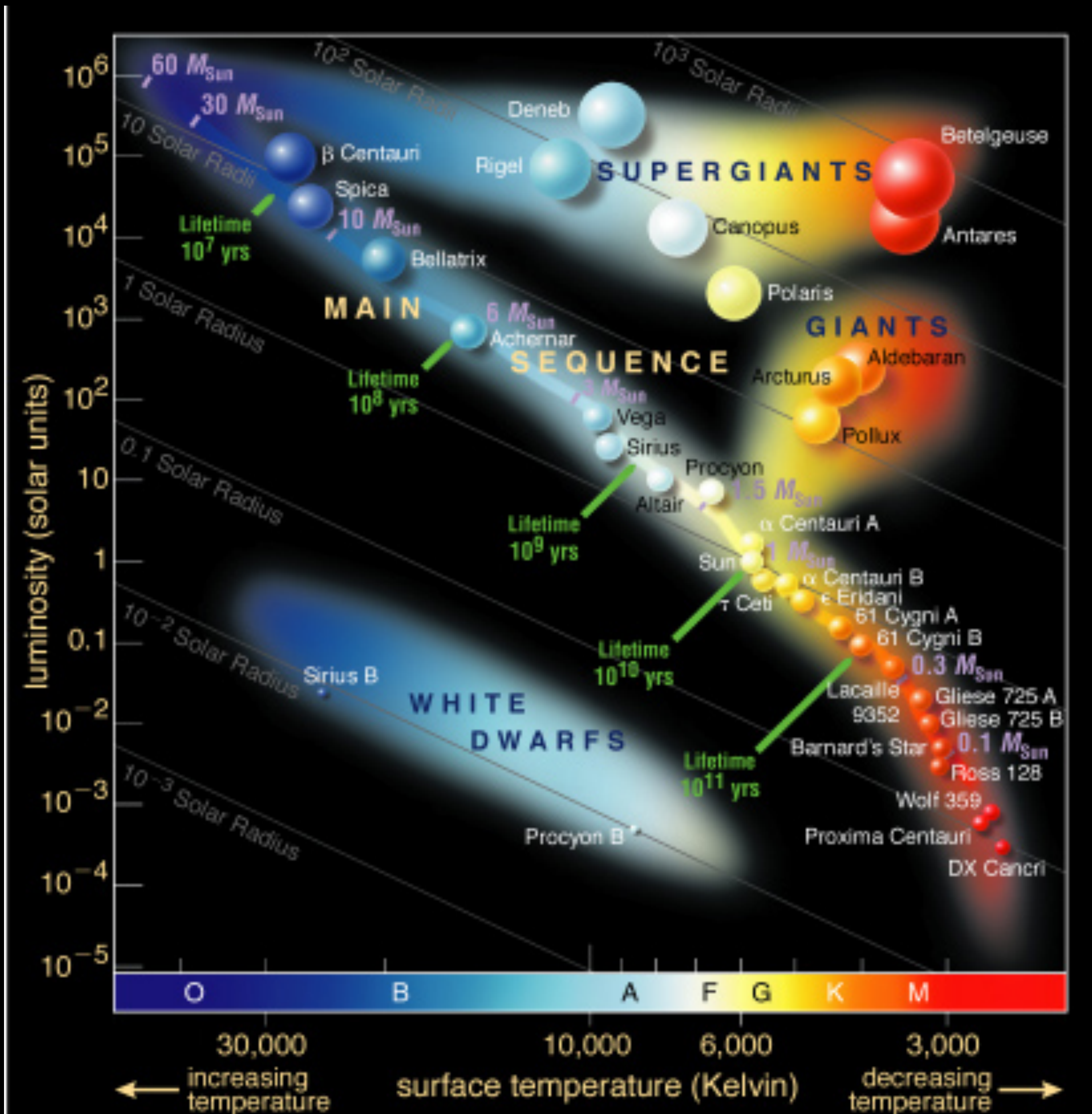
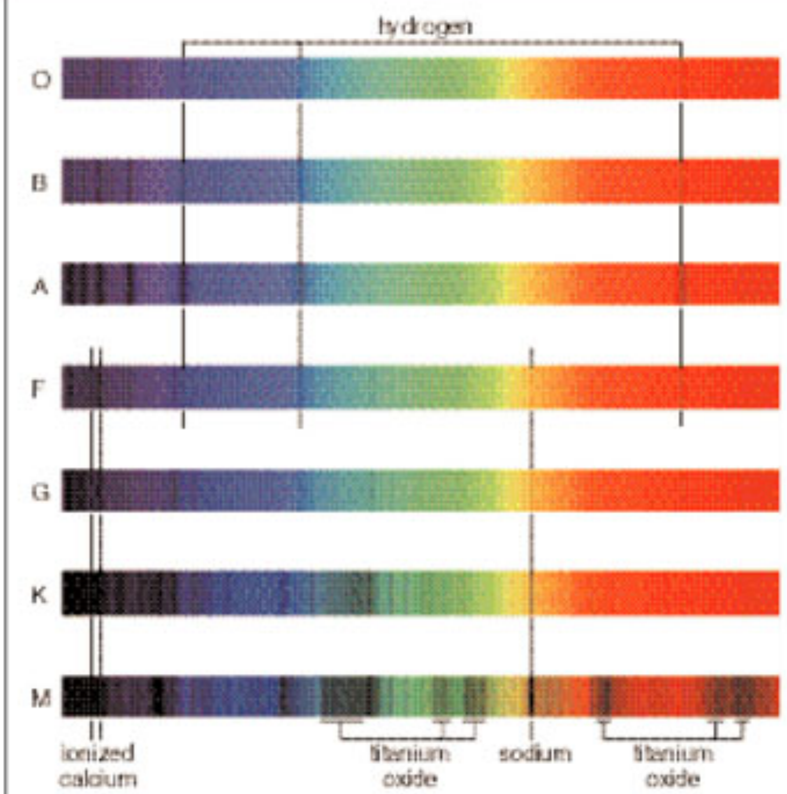

luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
3 M_Sun
1.5 M_Sun
1 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
Deneb
Betelgeuse
β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

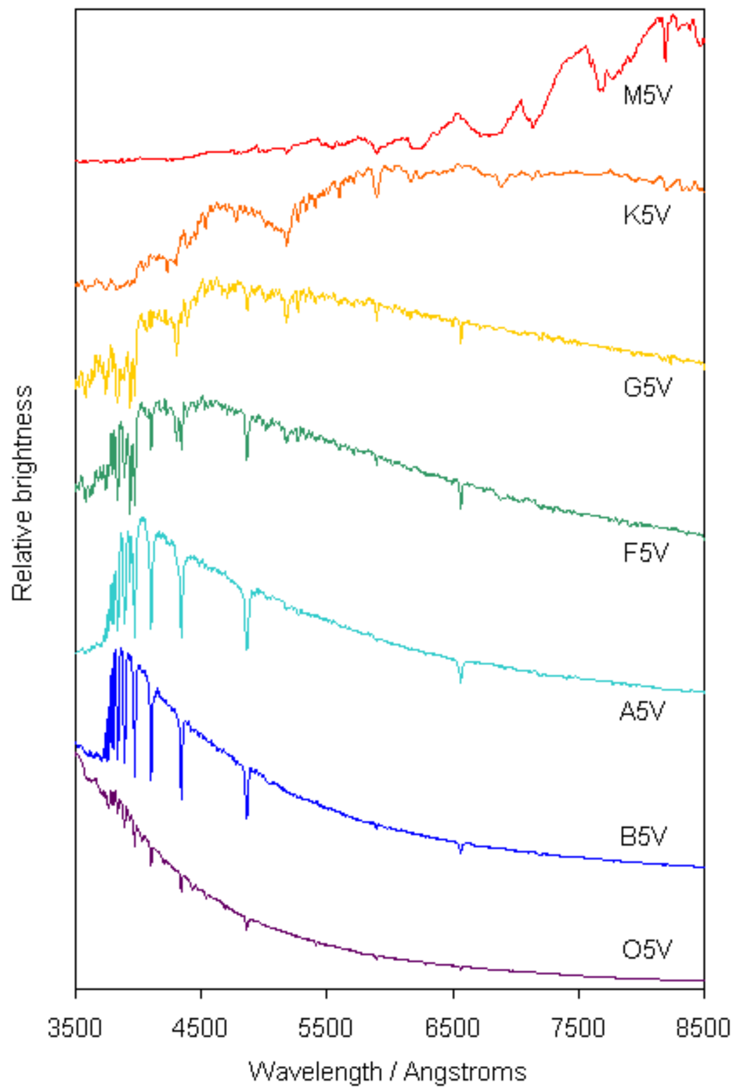
Table 16.1 The Spectral Sequence

Spectral Type	*Example(s)*	*Temperature Range*	*Key Absorption Line Features*	*Brightest Wavelength (color)*	*Typical Spectrum*
O	Stars of Orion's Belt	>30,000 K	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*	
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*	
A	Sirius	10,000 K–7,500 K	Very strong hydrogen lines	290–390 nm (violet)*	
F	Polaris	7,500 K–6,000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*	
G	Sun, Alpha Centauri A	6,000 K–5,000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)	
K	Arcturus	5,000 K–3,500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)	
M	Betelgeuse, Proxima Centauri	<3,500 K	Molecular lines strong	>830 nm (infrared)	



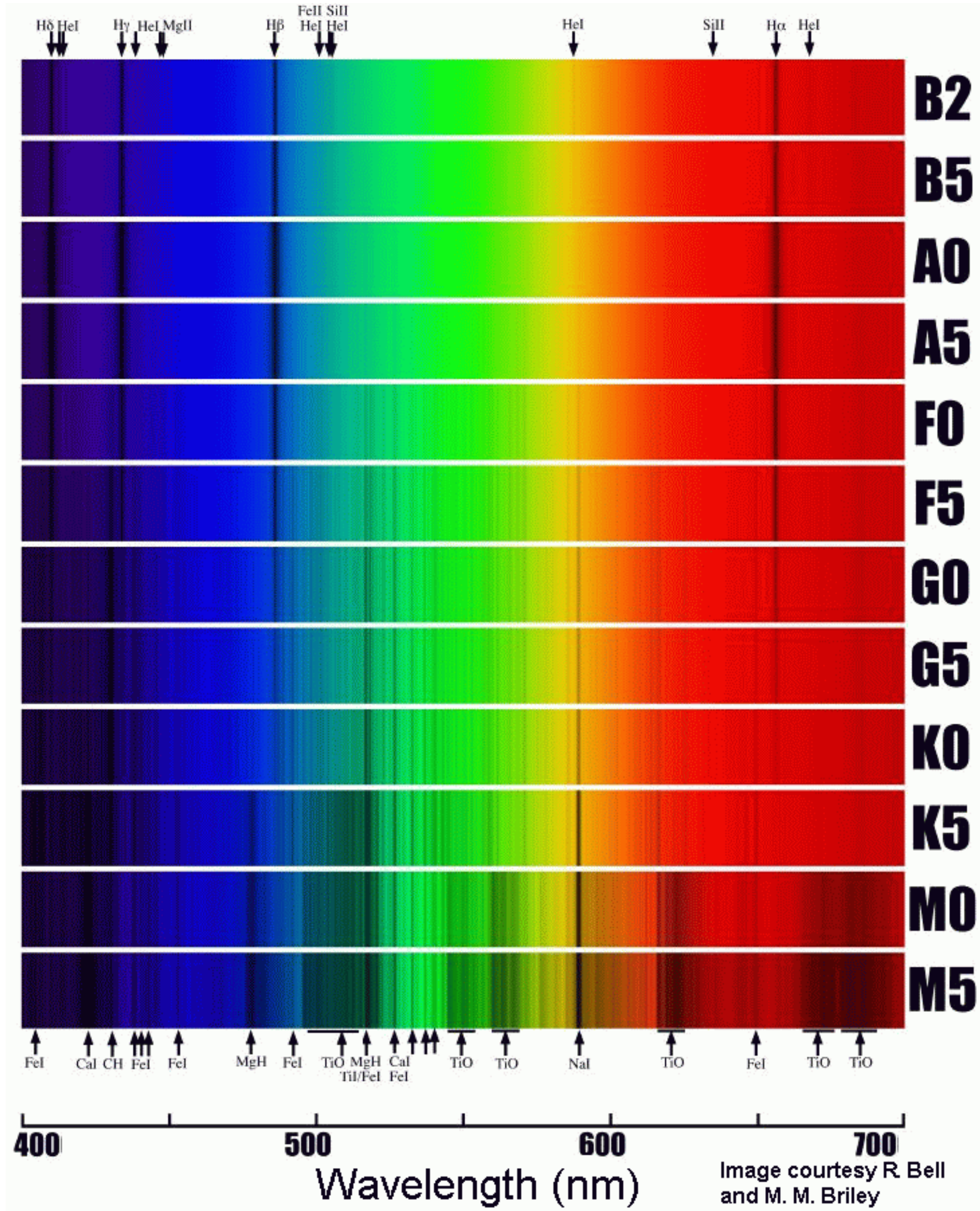
*All stars above 6,000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

Spectral Sequence in Visible Light

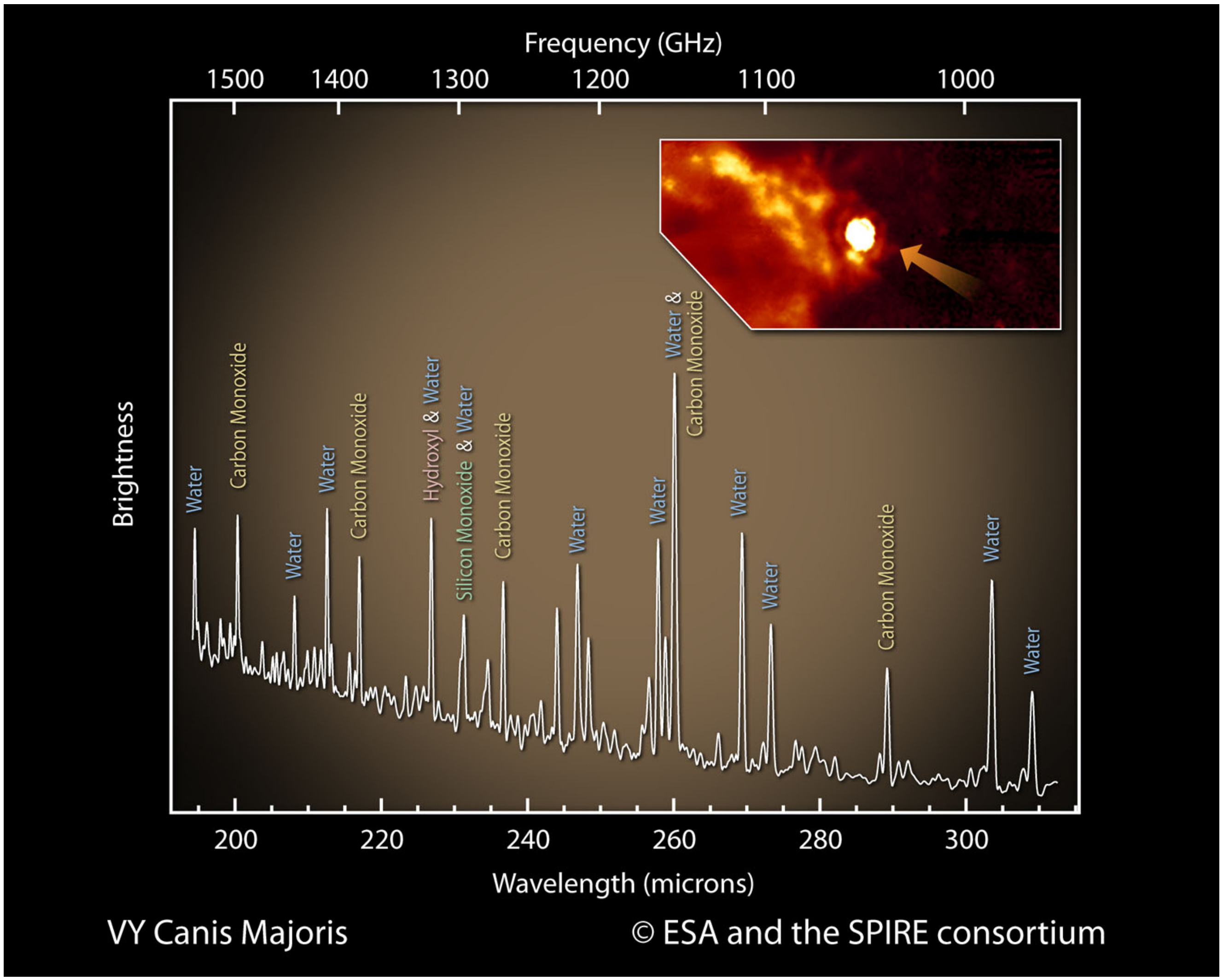


Detailed Line IDs

Just for show …

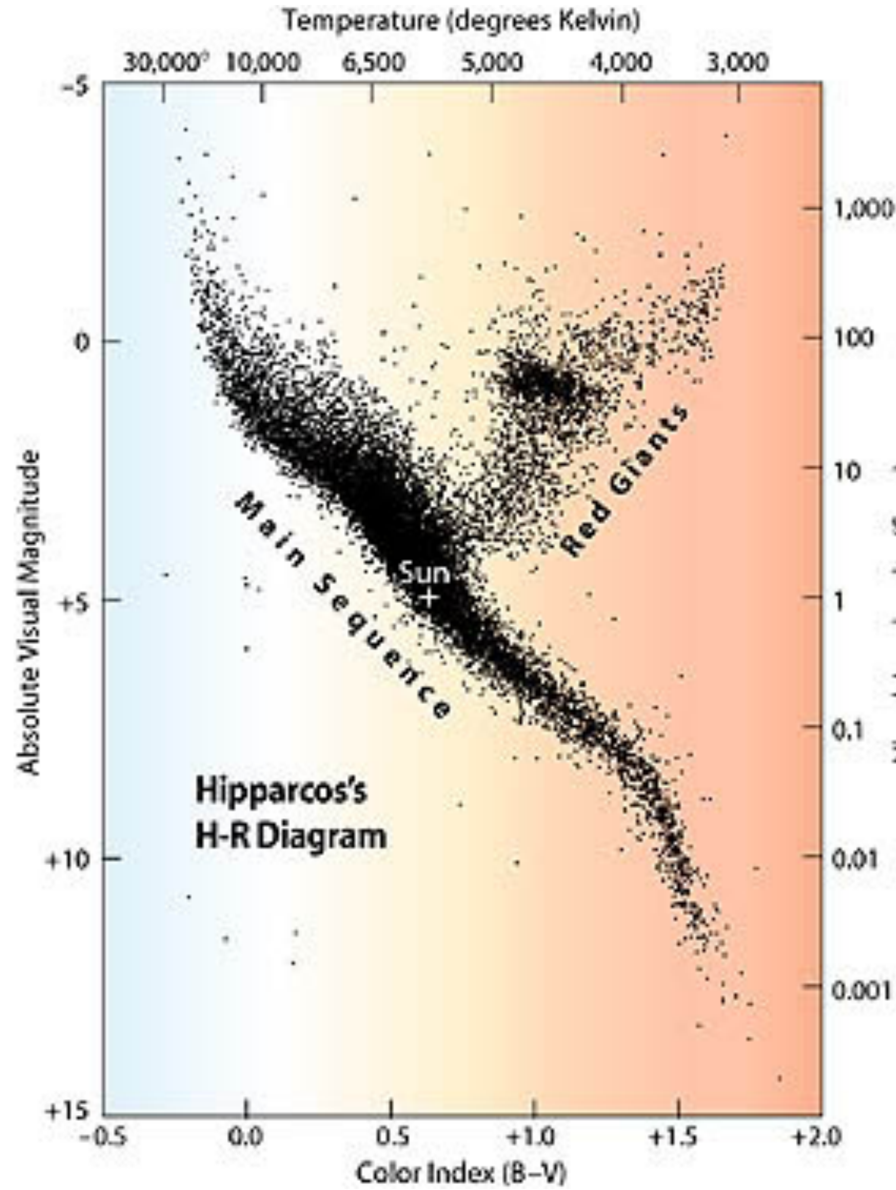


The Largest Known Star: This red hypergiant with about 35 times the Sun's mass is about 2600x bigger than the Sun (like Jupiter's orbit)



Observational HRD

Astronomers can easily construct color-magnitude diagrams which are just like a HRD, because color relates to temperature and magnitude to luminosity. For a bunch of stars at the same distance, brighter ones are more luminous (and vice versa).



Magnitudes

Magnitudes are a logarithm (I.e., powers of ten) approach to specifying brightnesses

- Apparent magnitude

  $$m = -2.5 \log(\text{flux}) + \text{constant}$$

  so m relates to apparent brightness

- Absolute magnitude M is m at a particular distance, namely 10 parsecs, so

  $$M = -2.5 \log[\, L / 4\pi\, (10\ \text{pcs})^2 \,] + \text{constant}$$

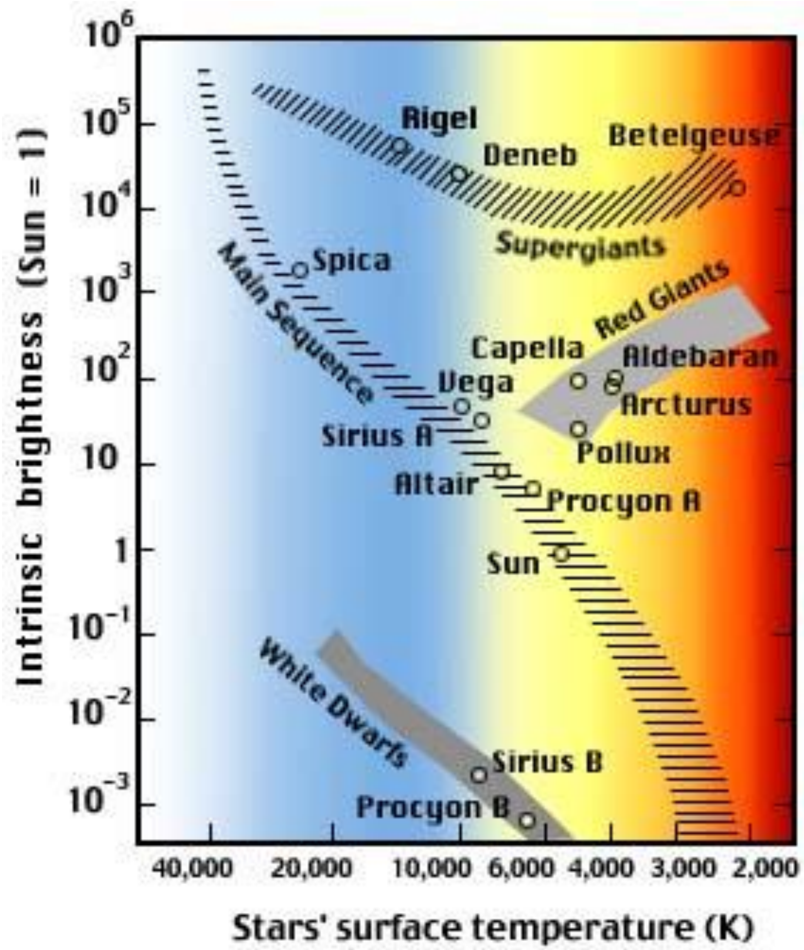
  so M relates to intrinsic brightness, in terms of luminosity

- Distance modulus is a way of relating an object's distance to its magnitude

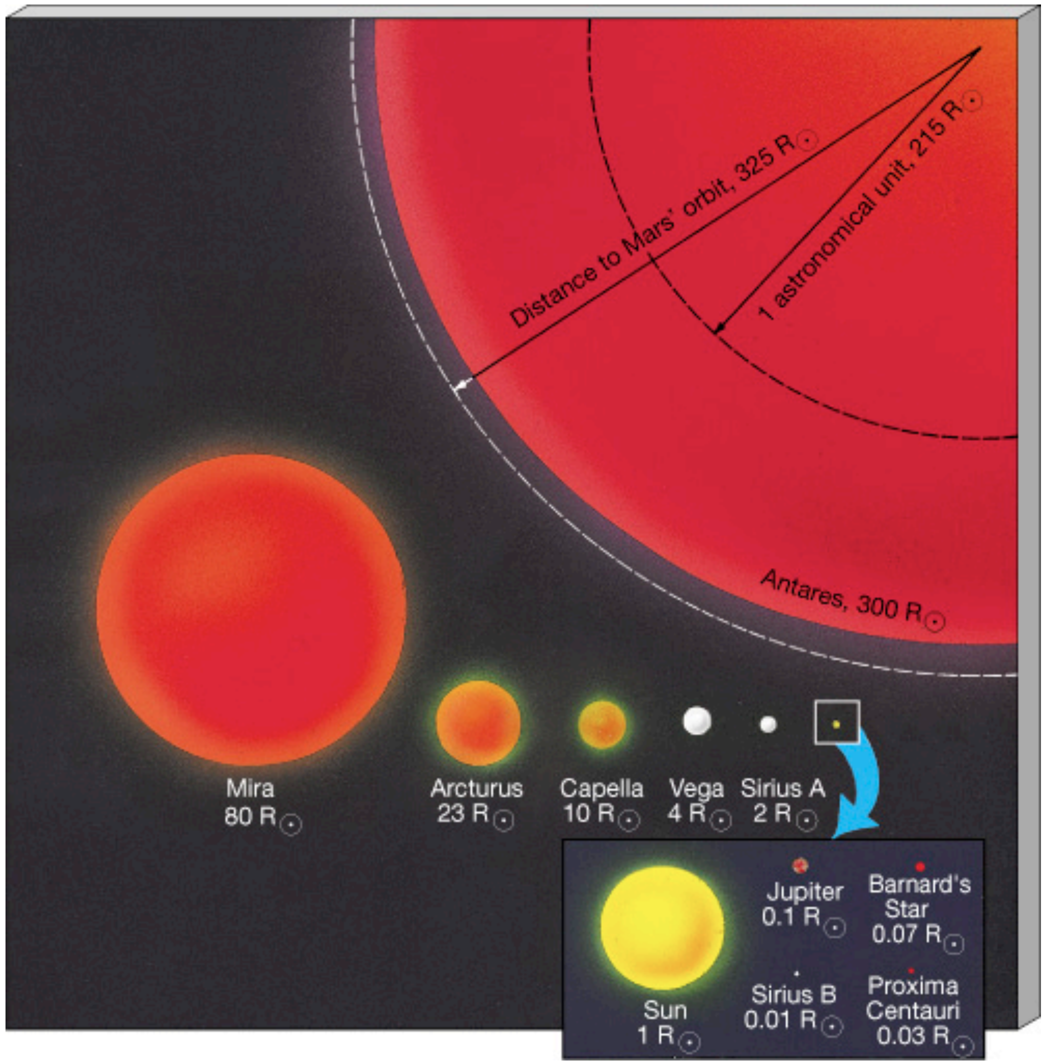
  $$m - M = -5 \log(\, d / 10\ \text{pcs}\,)$$

HRD Zones

- Main Sequence - where stars spend most of their lives; stars on the Main Seq. are undergoing core hydrogen fusion
- Giants – beginning of the end for a star
- Supergiants – as above, but for massive stars
- White Dwarf Branch - “dead” low-mass stars



Range of Stellar Sizes



How are spectral types useful?

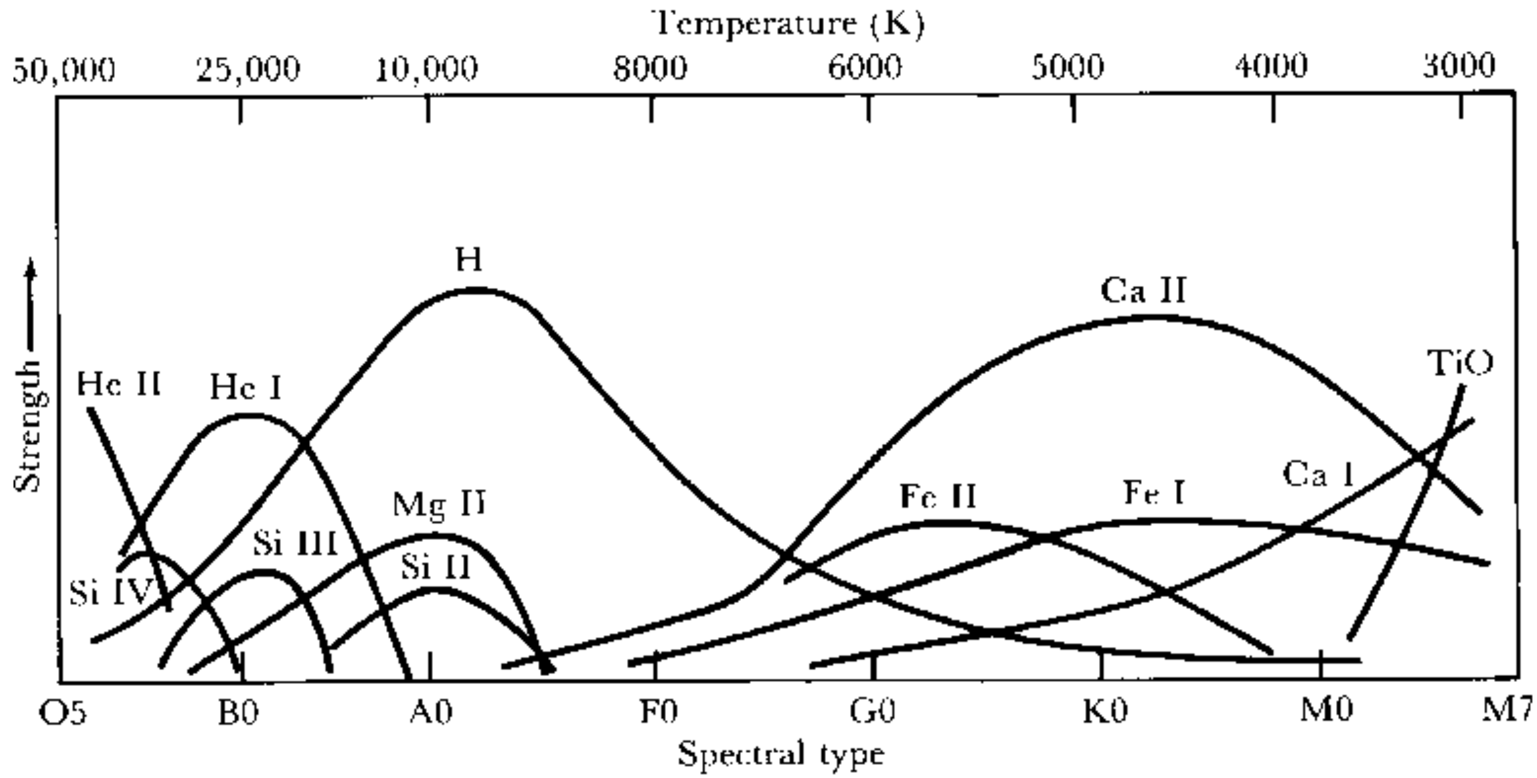


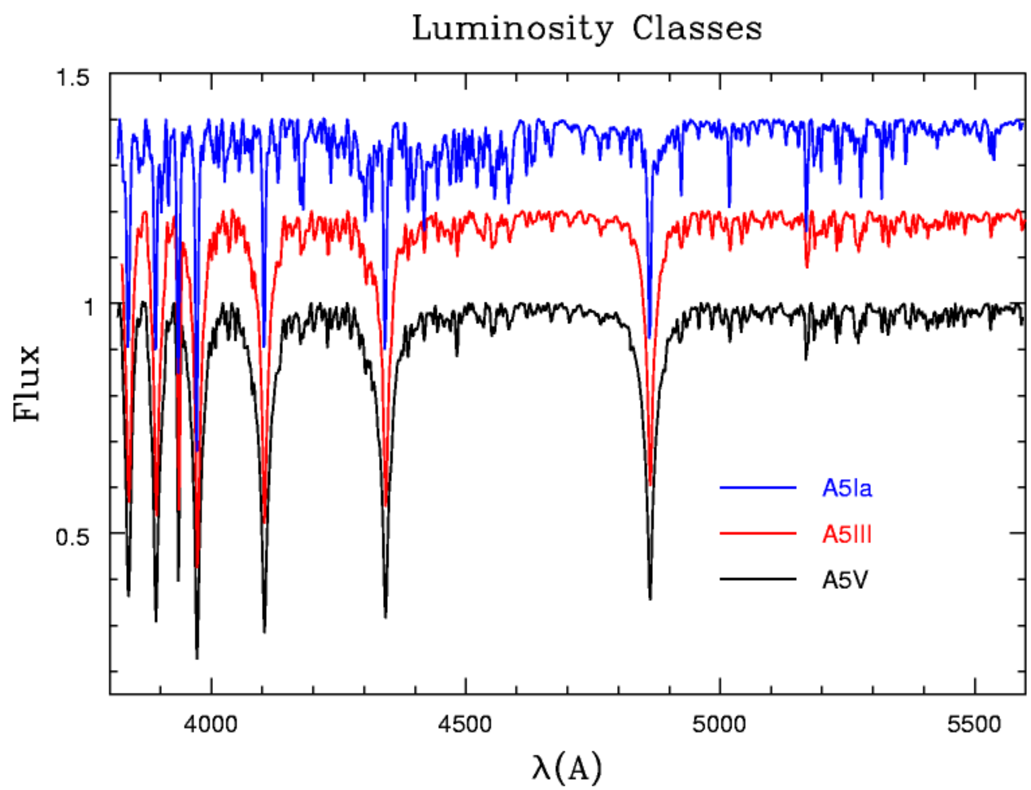
Figure 12-9
Kaufmann
DISCOVERING THE UNIVERSE
Second Edition

T-36

Luminosity Classes

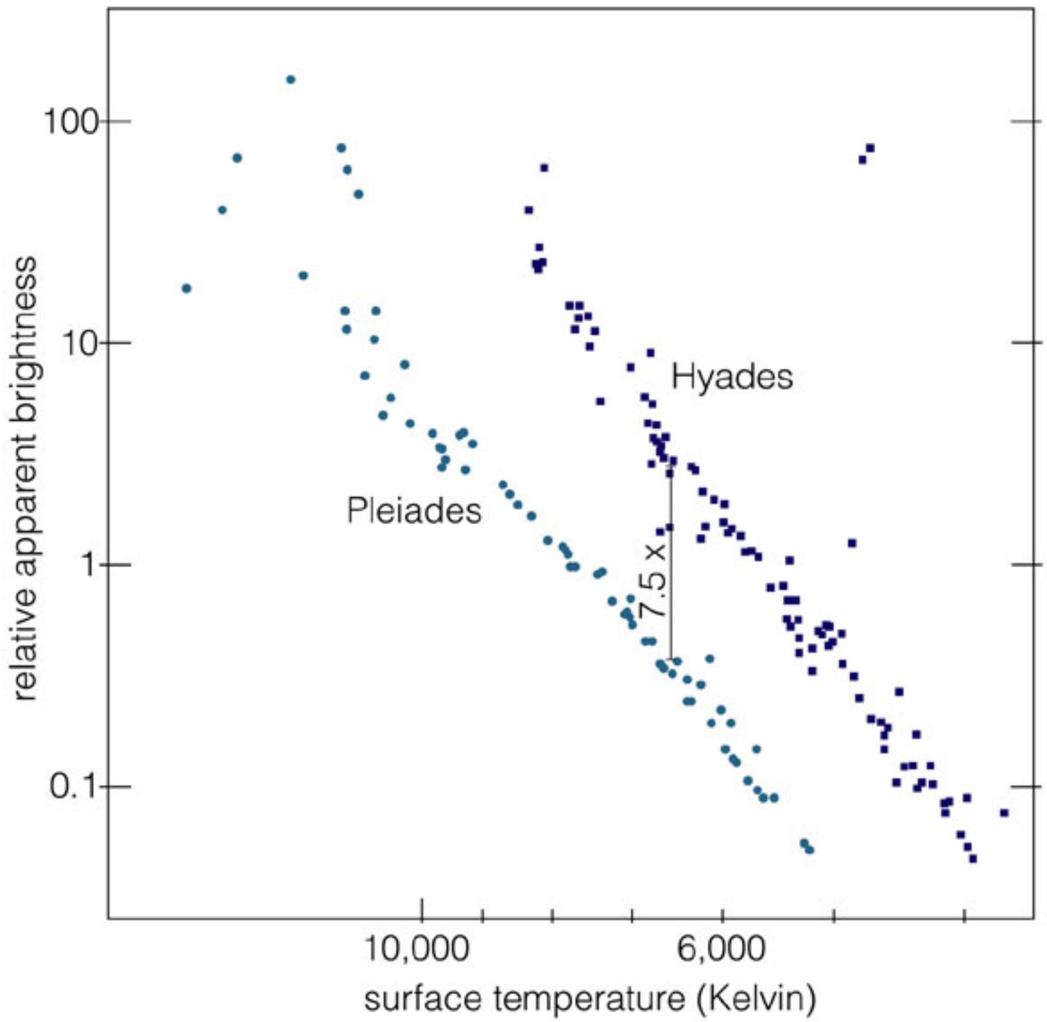
Luminosity classes are distinguished from using measures of spectral line widths

- I = supergiant
- III = giant
- V = main sequence



Spectroscopic Parallax

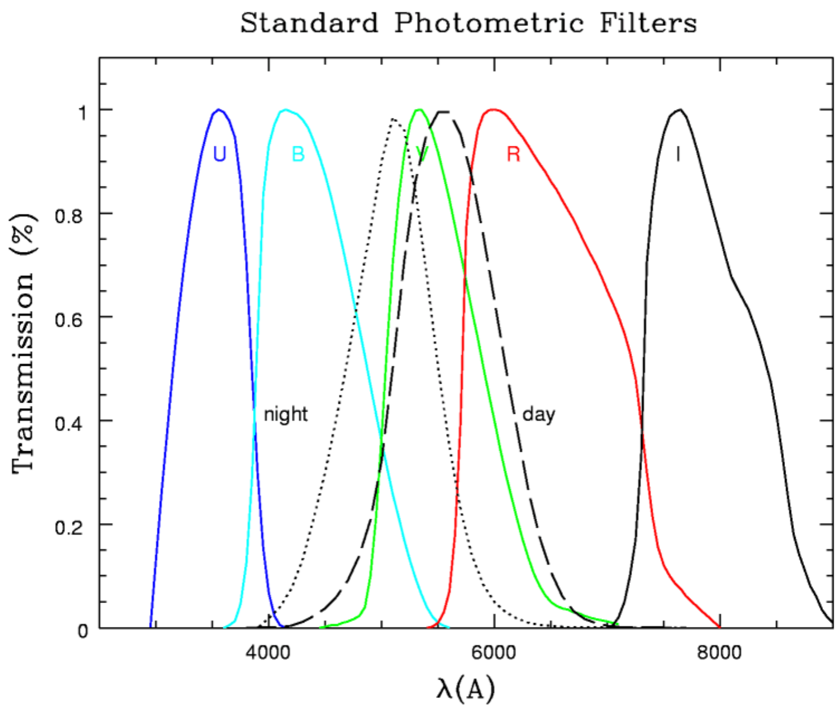
- Examples of two clusters of stars
- The points lying along straight lines make up the main seq.
- The vertical gap results from the clusters being at different **distances**.

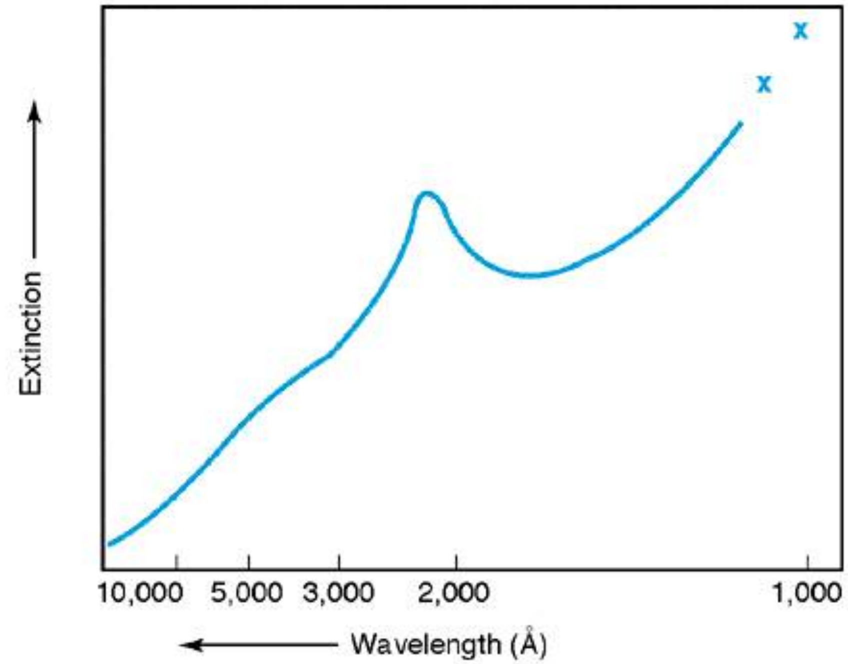


A Challenge for Magnitudes: Extinction

- The space between stars (the Interstellar Medium, or ISM) is not a vacuum, but filled with gas and dust.
- Extinction is "space haze" that makes objects appear dimmer than they really are
  - observed flux < true flux
  - so, inferred distance > true distance

Getting Star Colors





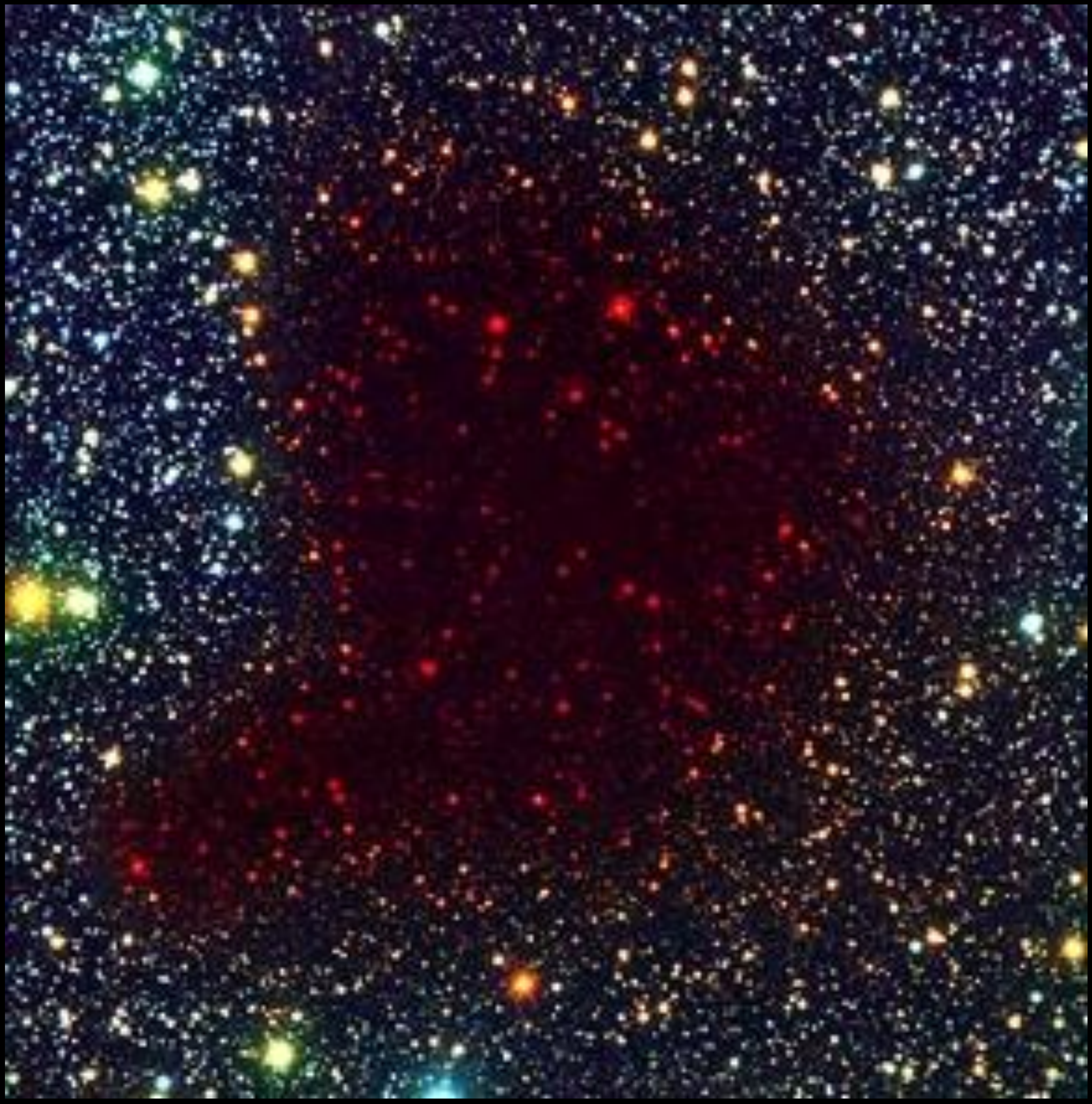
- Left are how color bands are defined
- Right shows how extinction becomes worse toward bluer light

Reddening

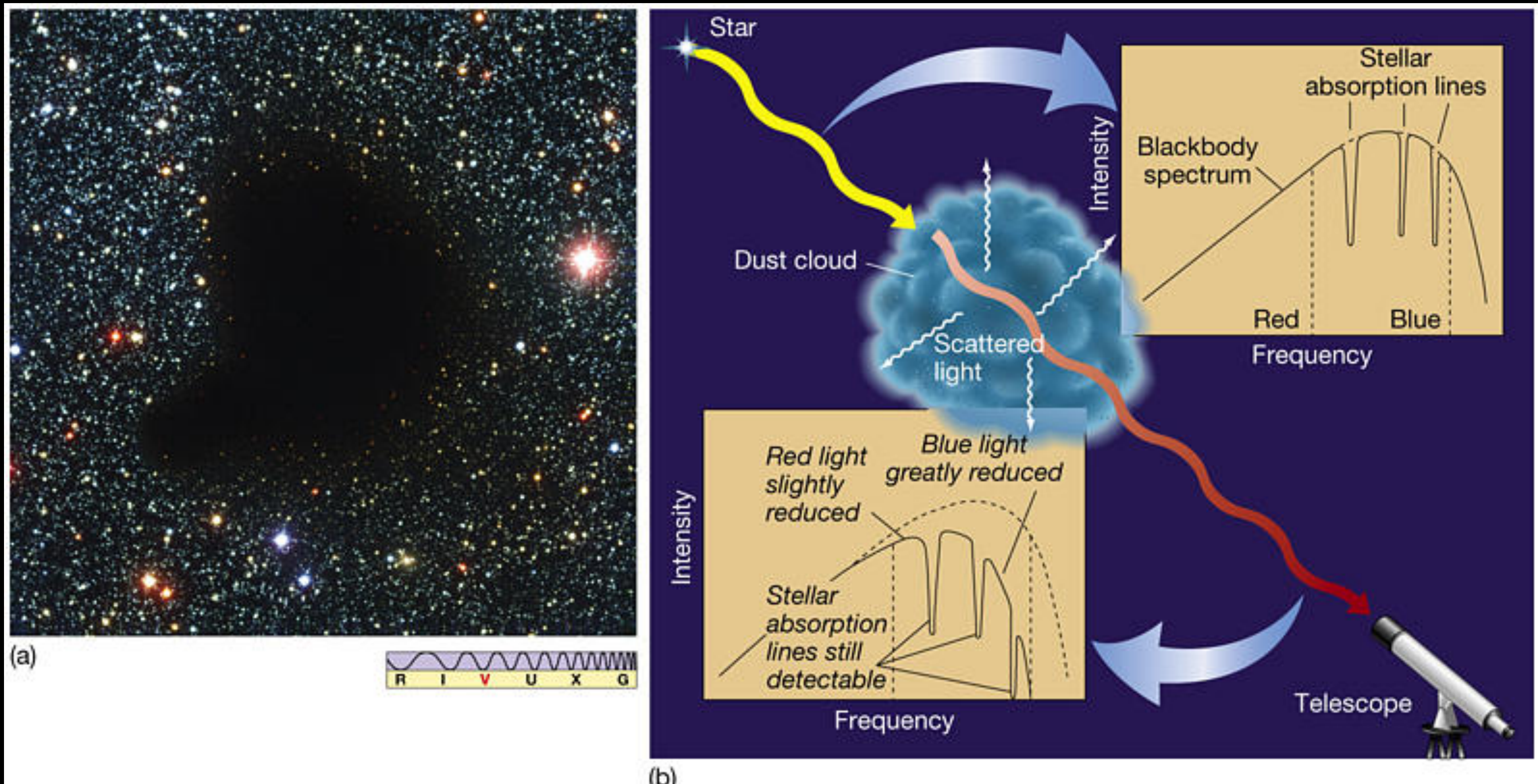
- Extinction dims starlight, but dimming by dust and gas is more severe for blue light than red
- *Reddening is color-dependent extinction*, resulting in an object appearing more red than it should
  - mMesses up spectral typing!
  - observed L_B/L_V < true L_B/L_V

Extinction/reddening are difficult to correct; they reduce confidence in distances derived from spectroscopic parallax

Severe Reddening



Influence of Reddening on Spectra



Stellar Census

- Most stars are on the Main Seq. Of these, most are low mass, low luminosity, red stars.
- Hot, massive stars are rare.
- HOWEVER, massive stars and giant stars are so much more luminous than red dwarfs, that they *dominate* the light output from galaxies

Binary Star Systems

EXTREMELY IMPORTANT

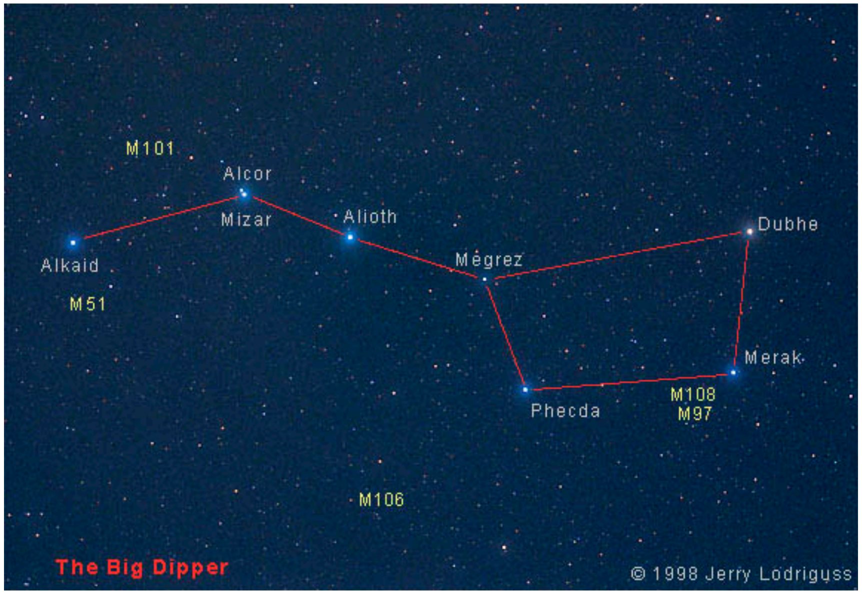
- Binaries consist of two stars orbiting one another because of gravity
- Can use Kepler's Laws to derive masses directly!

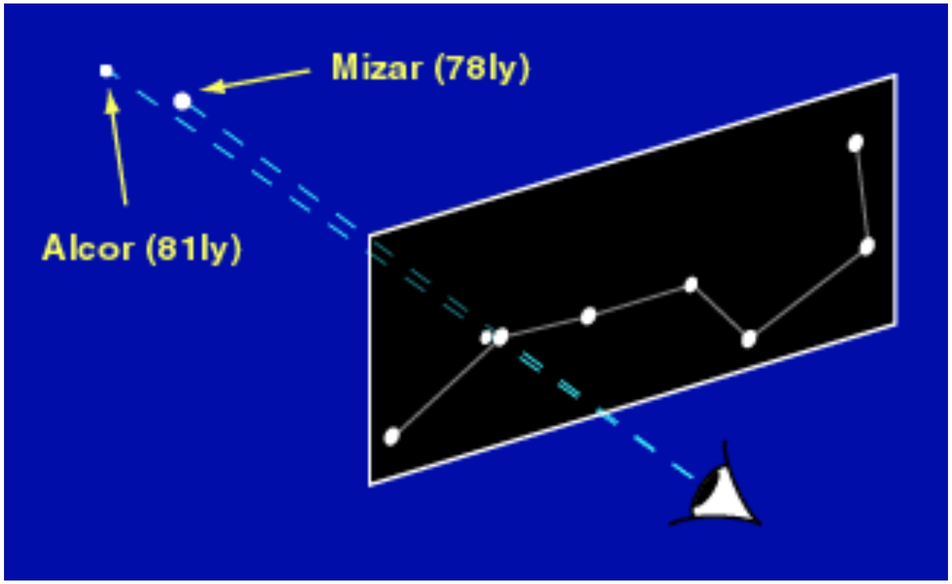
$$\frac{a^3}{P^2} = \frac{G(M_1 + M_2)}{4\pi^2}$$

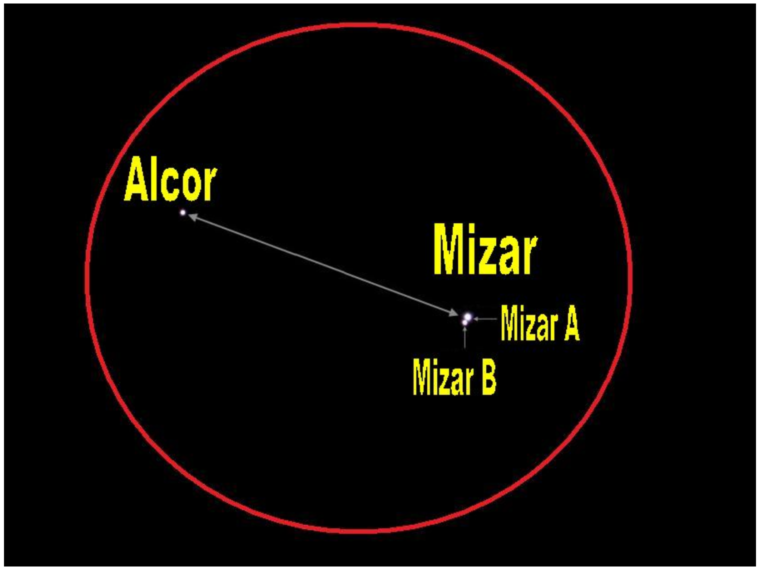
Wide and Close Binaries

- *Wide*: two stars are so far apart that they hardly interact, as if each were in isolation
- *Close*: two stars are near enough to interact; for example, mass exchange (possibly even engulfment)

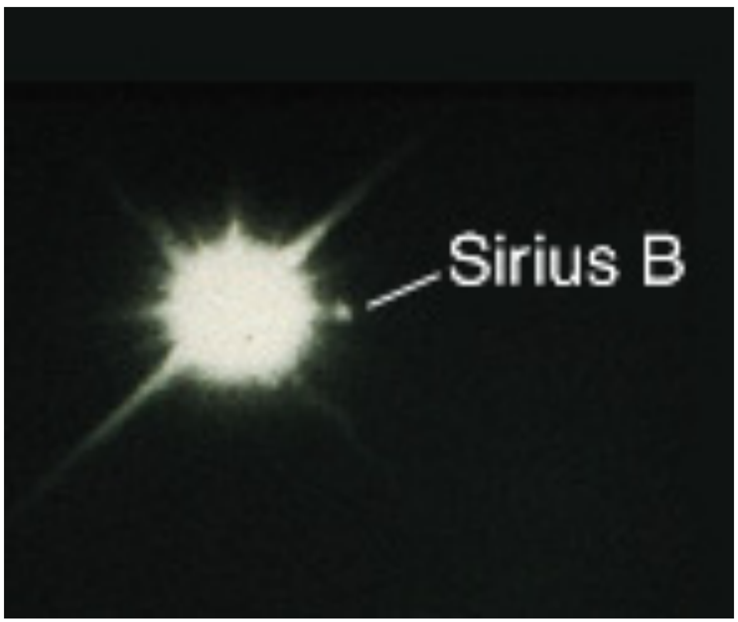
Alcor and Mizar

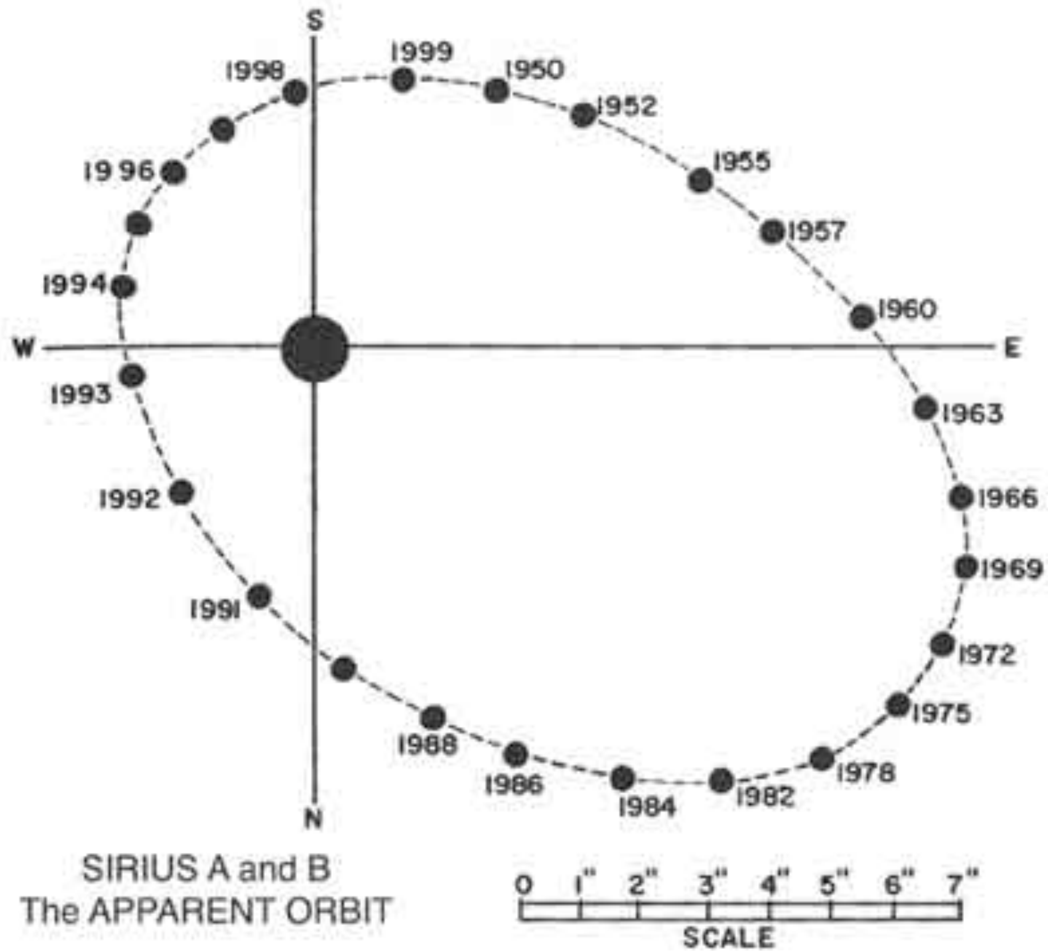






The Binary Sirius





Binary Types

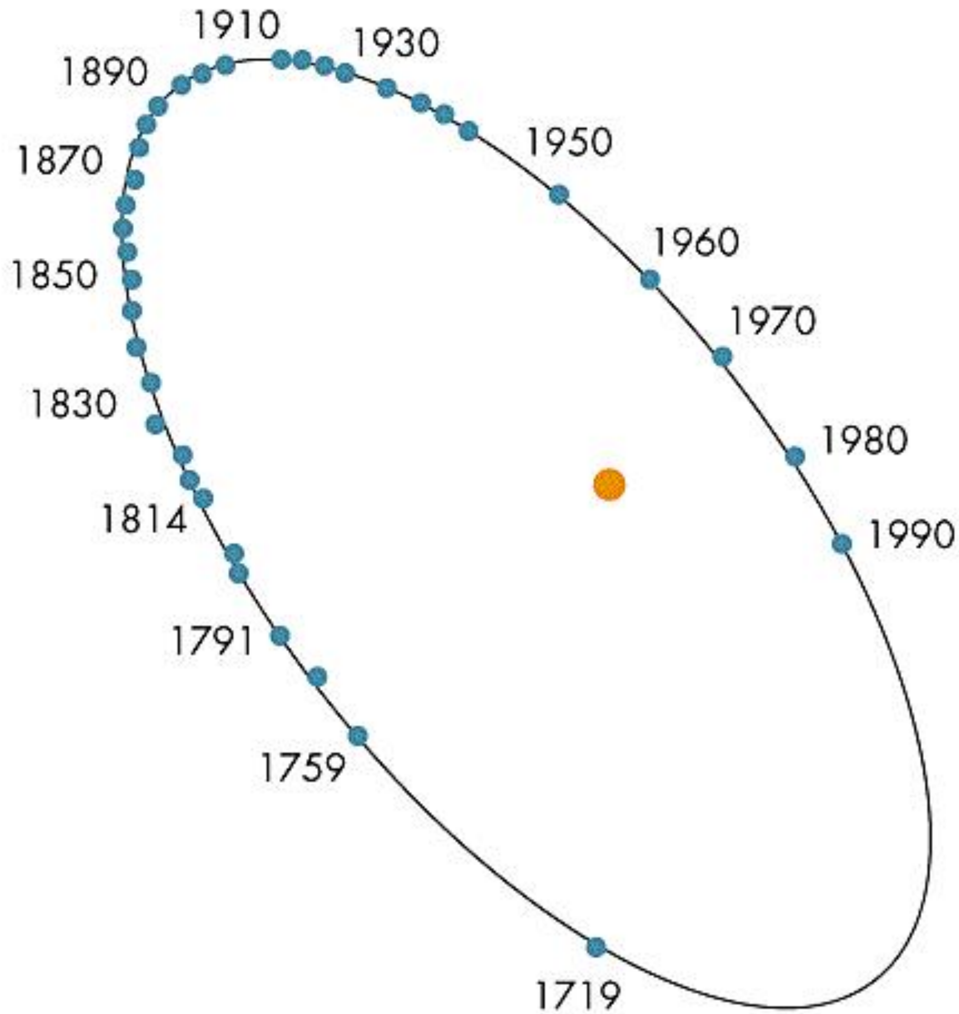
i. Visual double – not a true binary

ii. Visual binary – true binary in which each star can be seen

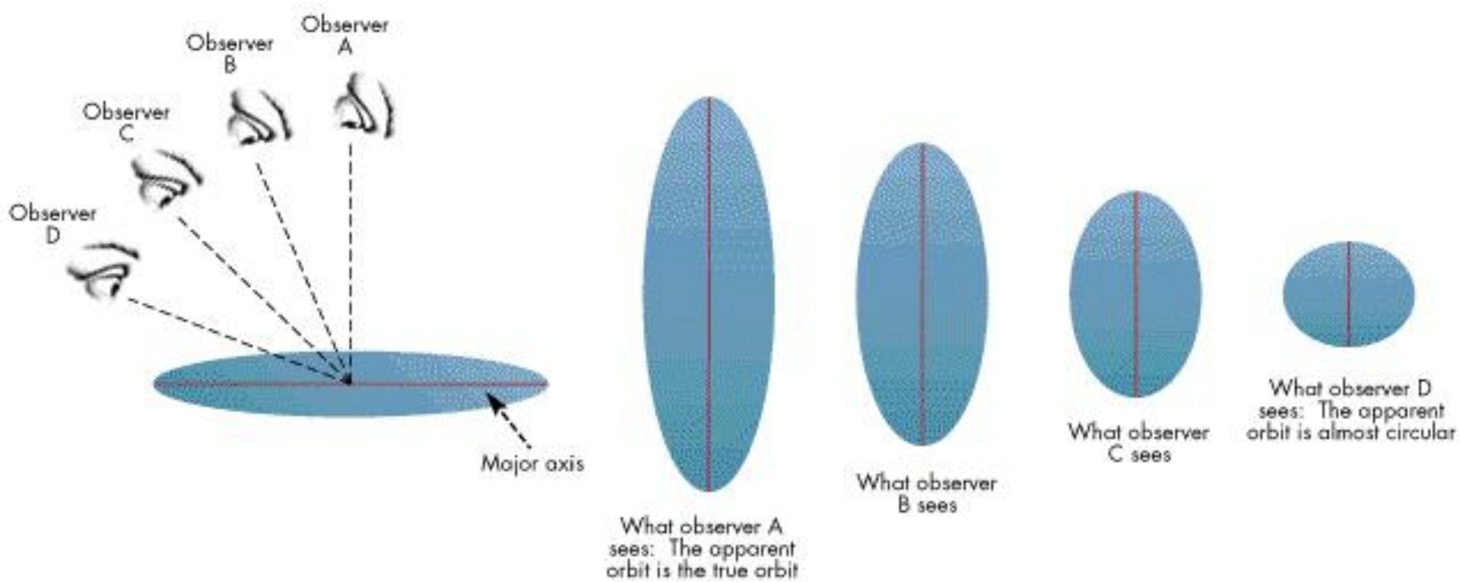
iii. Spectroscopic binary – binarity as evidenced by periodic movement of spectral lines owing to the Doppler effect as stars execute their orbital motion

iv. Eclipsing binary – orientation is such that the two stars alternately pass in front of each other over one full orbit

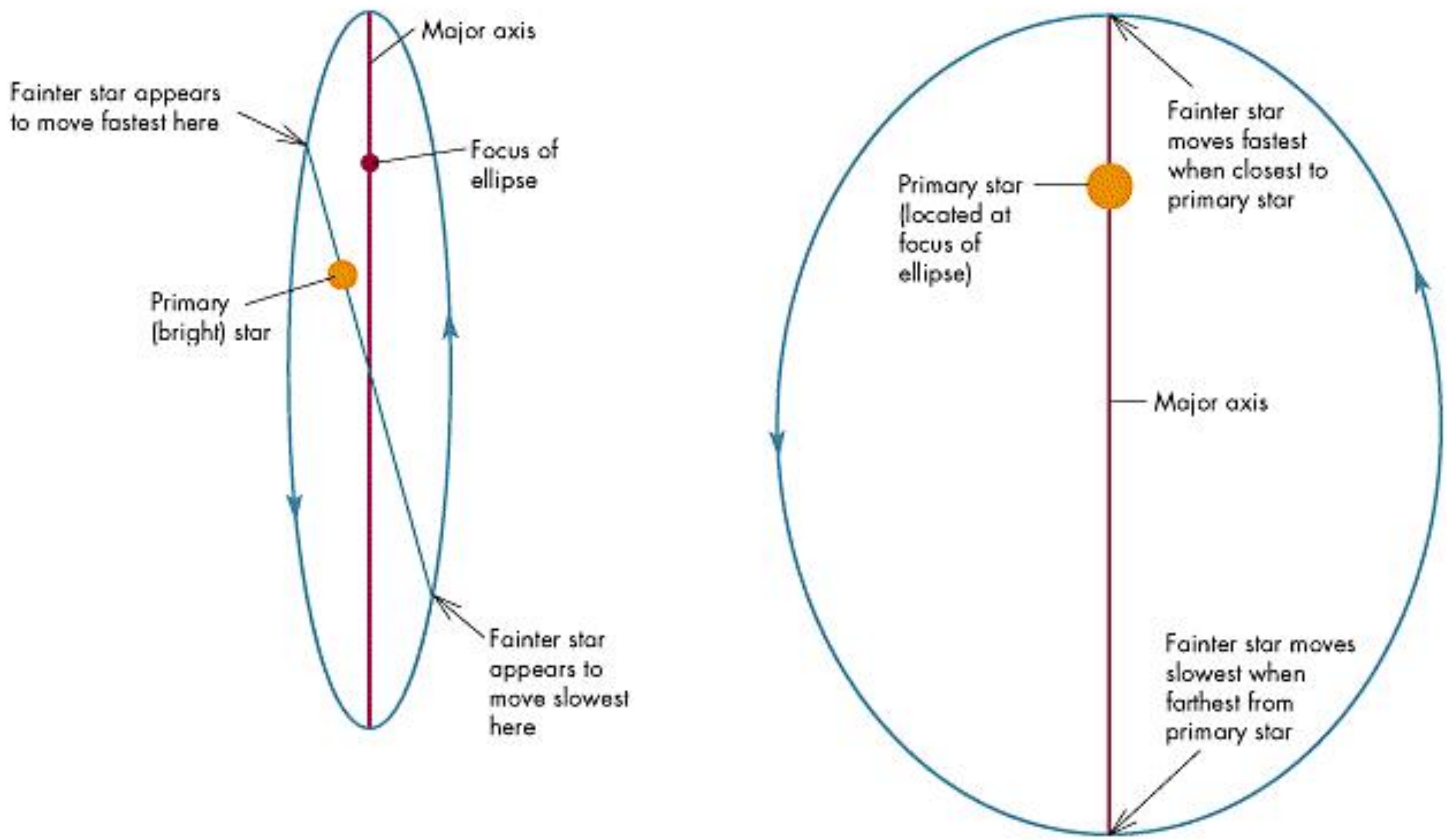
The Binary of Castor (Gemini)



Orbit Projections



The alpha Cen Example



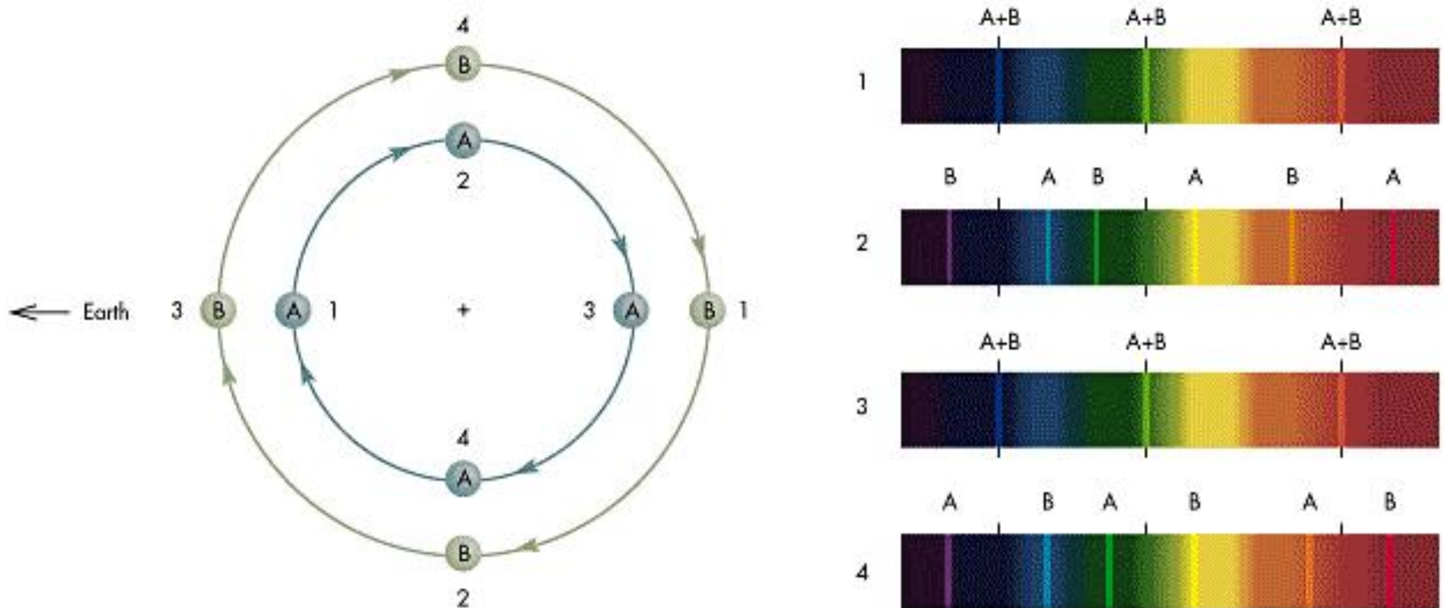
A Apparent orbit: Kepler's laws appear to be violated

B True orbit: Kepler's laws are obeyed

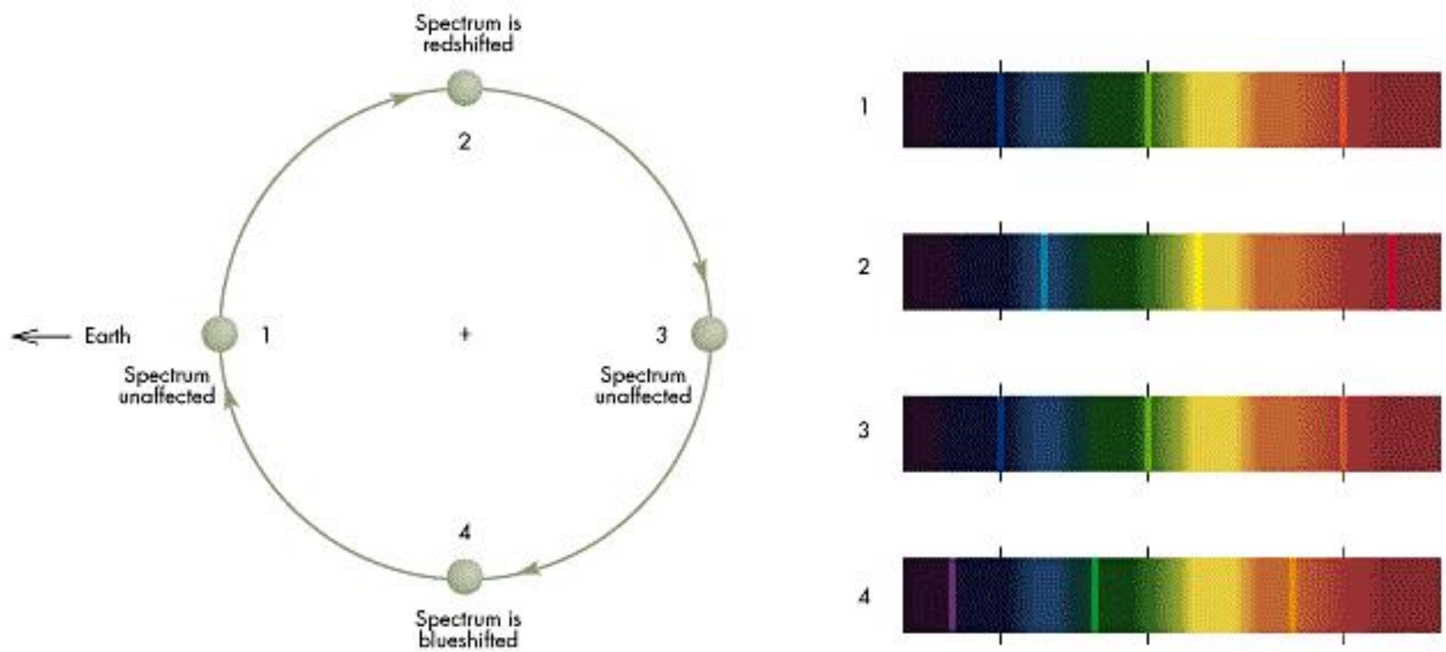
Binary Types

i. Visual double – not a true binary
ii. Visual binary – true binary in which each star can be seen
iii. **Spectroscopic binary – binarity as evidenced by periodic movement of spectral lines owing to the Doppler effect as stars execute their orbital motion**
iv. Eclipsing binary – orientation is such that the two stars alternately pass in front of each other over one full orbit

Double-Lined Spectroscopic Binaries



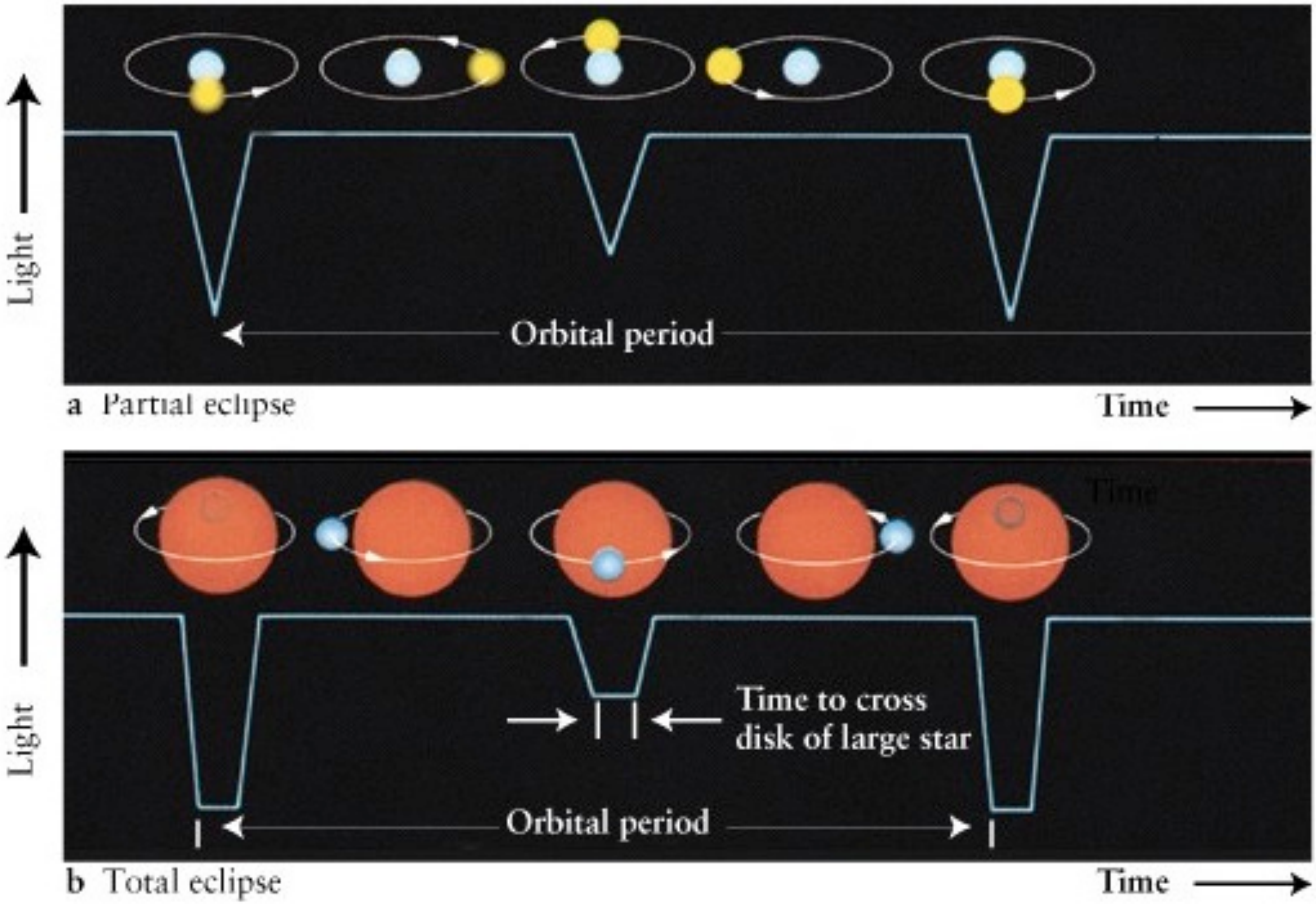
Single-Lined Spectroscopic Binaries



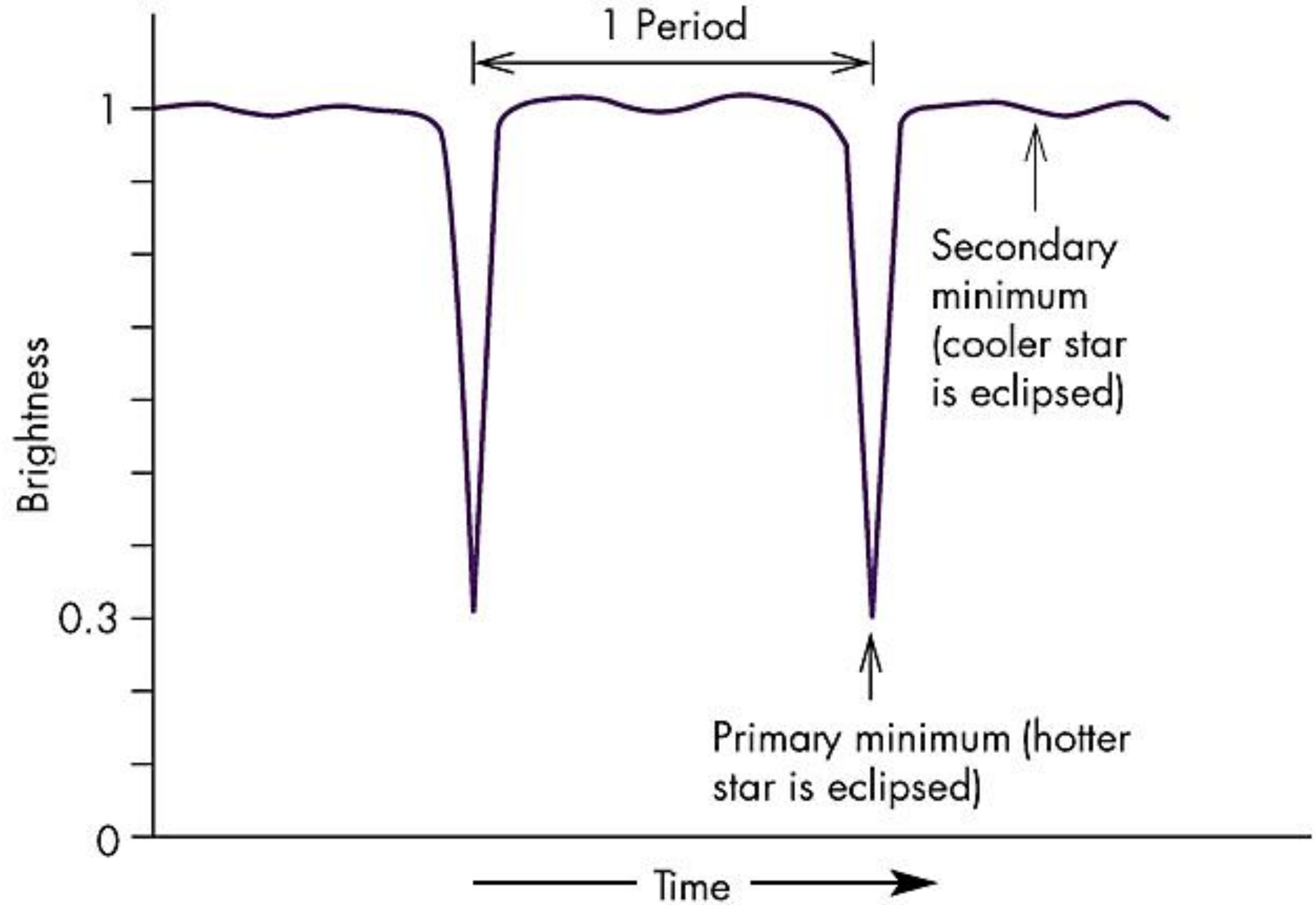
Binary Types

i. Visual double – not a true binary
ii. Visual binary – true binary in which each star can be seen
iii. Spectroscopic binary – binarity as evidenced by periodic movement of spectral lines owing to the Doppler effect as stars execute their orbital motion
iv. **Eclipsing binary – orientation is such that the two stars alternately pass in front of each other over one full orbit**

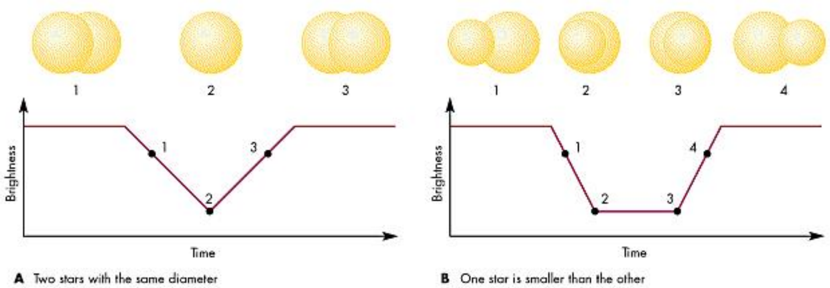
Eclipse Effects

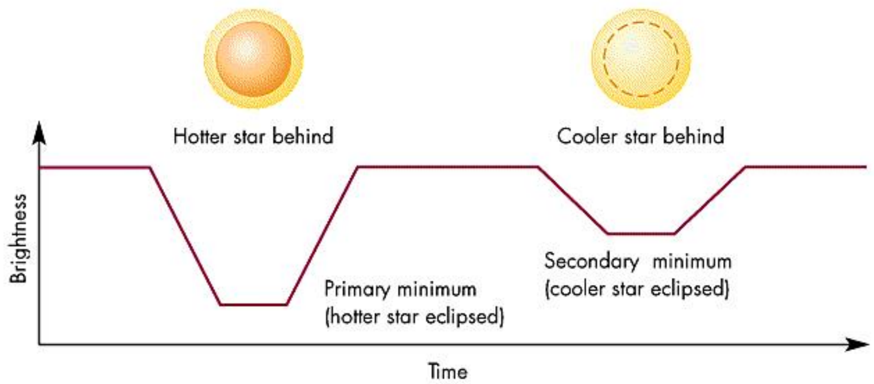


The Eclipsing Binary Algol



The Edge-On Case





Stellar Structure

- Stars change rather slowly with time, maintaining overall nearly constant *L, M, R, T* over millions or even billions of years
- Can we develop models to accurately represent the interior portions of stars?

YES!

Relevant Rules of Physics

- Assume spherical symmetry and that nothing changes with time, then
  - Conserve mass
  - Conserve energy
  - Conserve momentum (F=ma): balance forces, hydrostatic equilibrium
  - Energy transport (e.g., convection)
  - Energy generation (e.g., fusion)
  - Opacity (absorption of light)
  - Composition (amount of H, He, …)

Hey, just turn the crank!

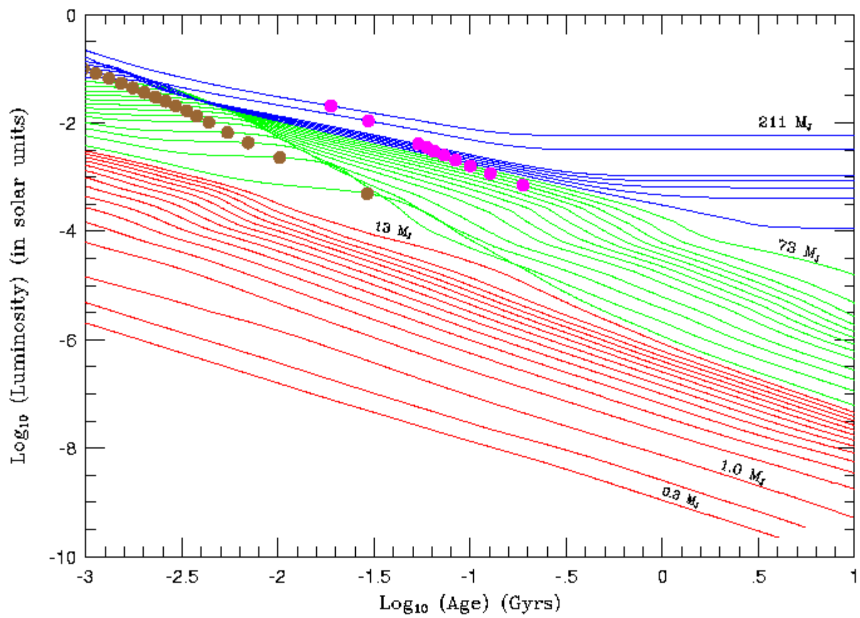
HSEQ

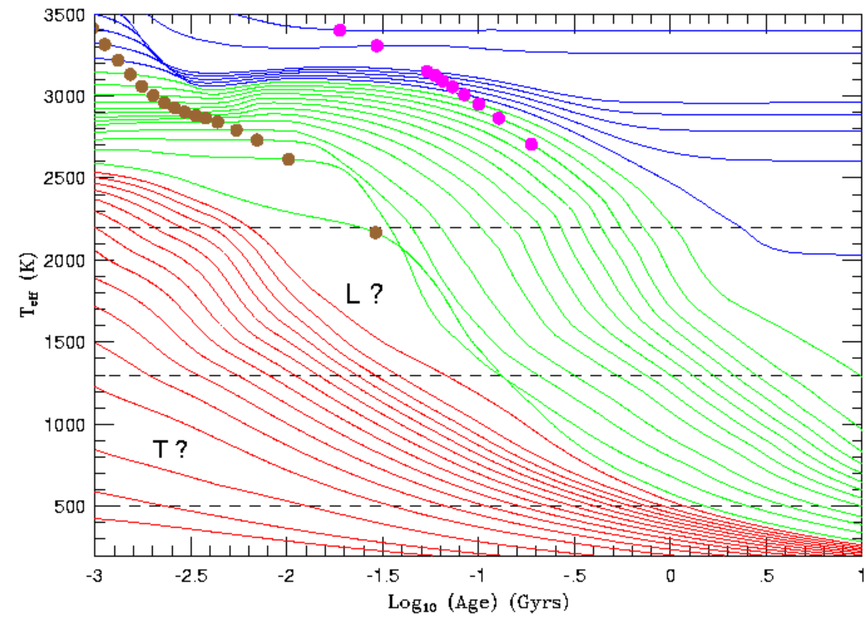
- OK, gravity generally seeks to pull matter together, so what prevents the Earth, Moon, and Sun from collapsing under their own weight?!
- For Earth and Moon, the structure of rock can uphold itself against gravity.
- For Sun (a big ball of gas), gas pressure does the trick.

Brown Dwarfs

- Stars are by definition large gaseous bodies that undergo core H-fusion
- Only bodies with $M>0.08\ M_o$ do so
- Less massive bodies are "failed stars", or Brown Dwarfs (BDs)
- If mass low enough, it is a planet (e.g., Jupiter is *not* a BD)

Brown Dwarf Properties





Red: stars with hydrogen burning; Green: brown dwarfs with lithium and deuterium burning; Blue: planets can have some deuterium burning

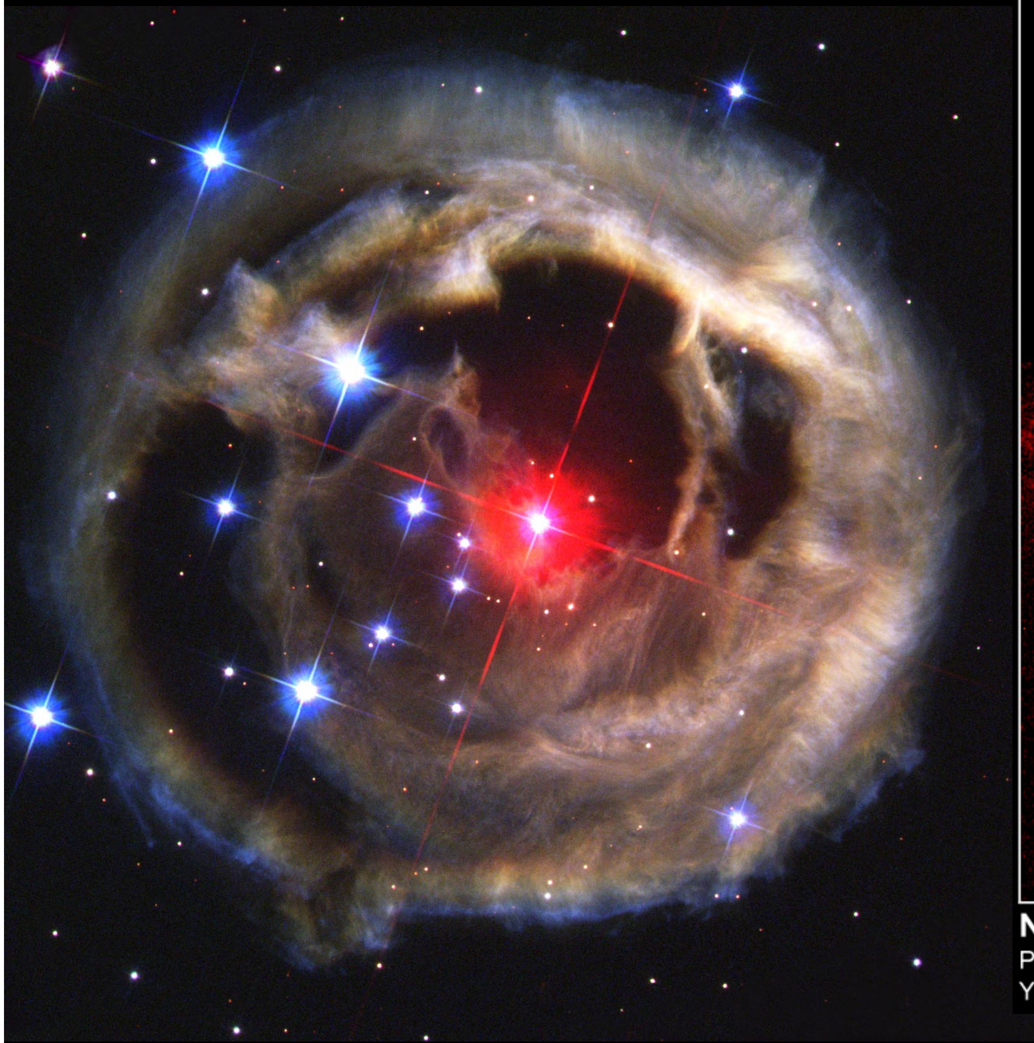
Eddington Limit

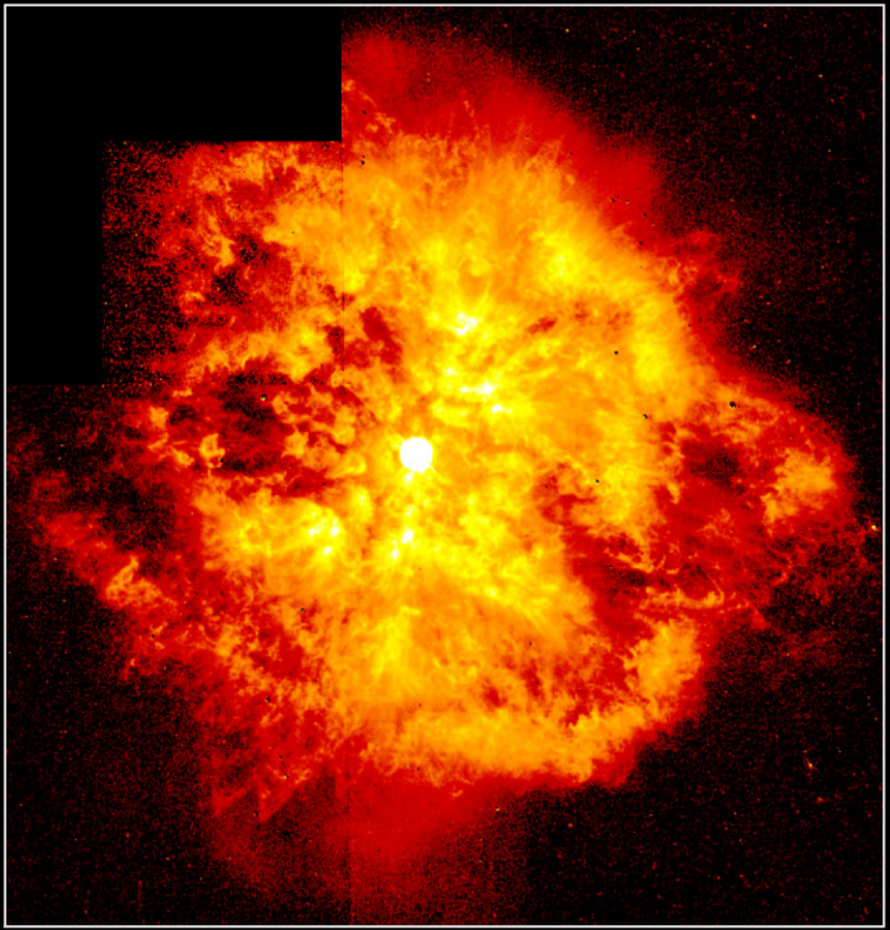
- Photons “random walk” or diffuse from core to photosphere. This occurs as atoms and electrons absorb and scatter (bounce) the photons.
- Aside from energy, photons also possess momentum, and so they give an outward “kick” against gravity as they work out.
- If strong enough, sum of kicks can exceed gravity, and star cannot hold together (unstable)

$$L/L_{\odot} > 30{,}000\, M/M_{\odot}$$

- “Super-Eddington” if limit is exceeded

Examples of Mass Loss





Nebula M1-67 around Star WR124 **HST • WFPC2**
PRC98-38 • STScI OPO • November 5, 1998
Y. Grosdidier and A. Moffat (University of Montreal) and NASA