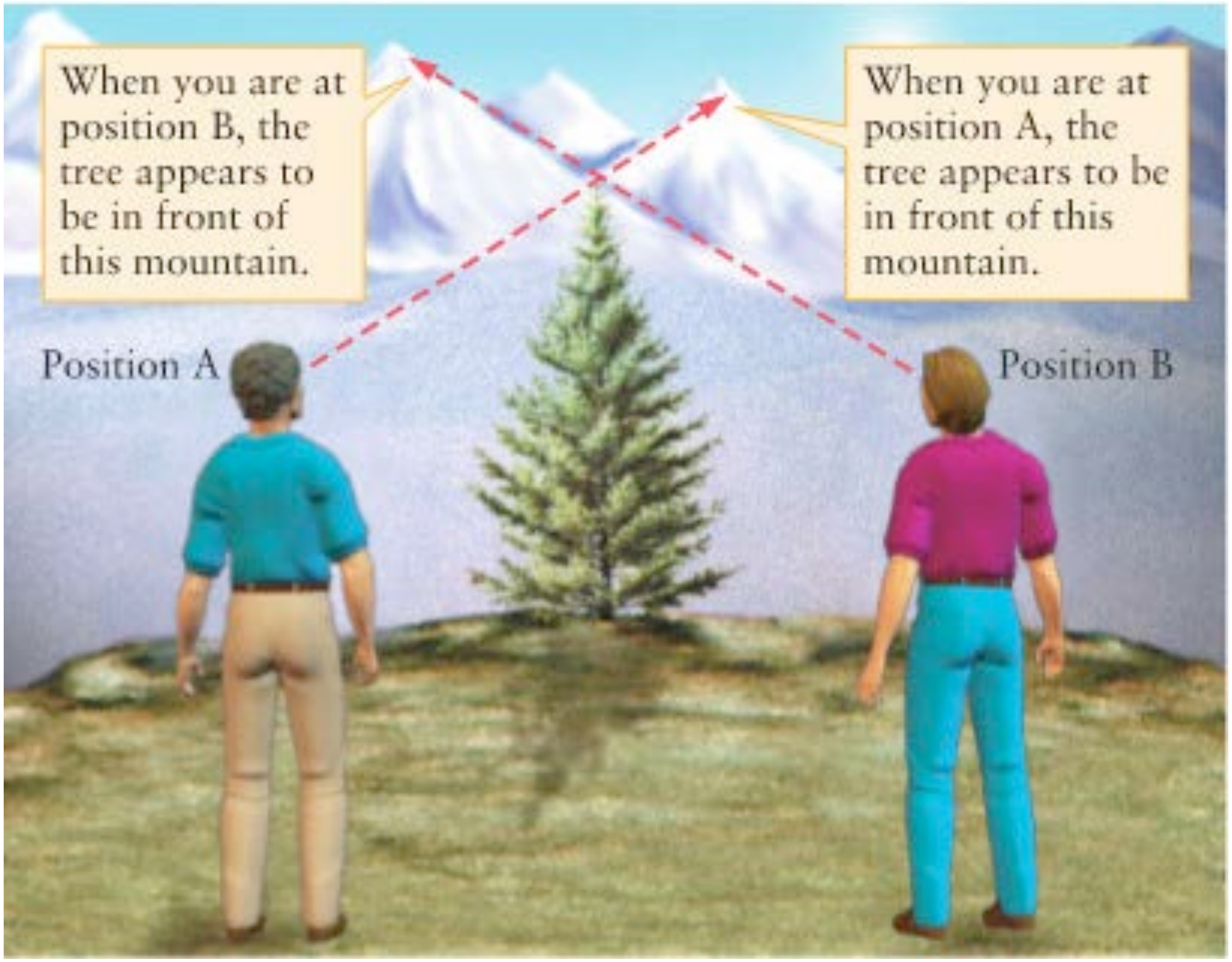
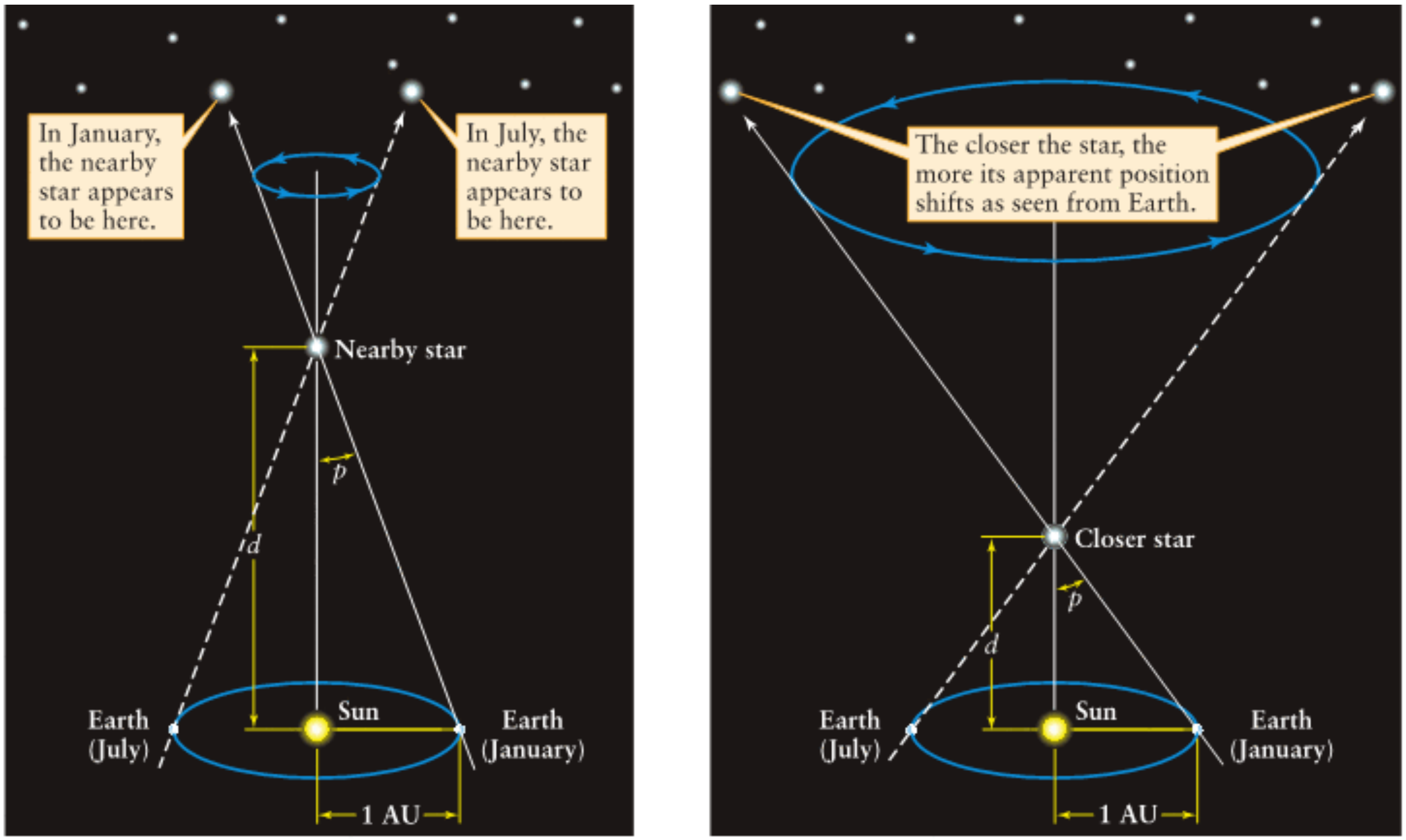
The Nature of Stars

Measuring Distances



Parallax



(a) Parallax of a nearby star

(b) Parallax of an even closer star

The distance d to the star (in parsecs) is just 1 over the parallax angle p (in arcseconds): **d = 1/p**.

HIPPARCOS

The smallest parallax angle that can be measured from the ground is about 0.01 arcsec so the furthest stars that can have distances measured from the ground are at d = 1/0.01 = 100 pc.

Observations made in space permit measurements of even smaller parallax angles down to 0.001 arcsec corresponding to distances of 1000 pc.

The satellite **Hipparcos** has measured about 118,000 stars using the parallax method.

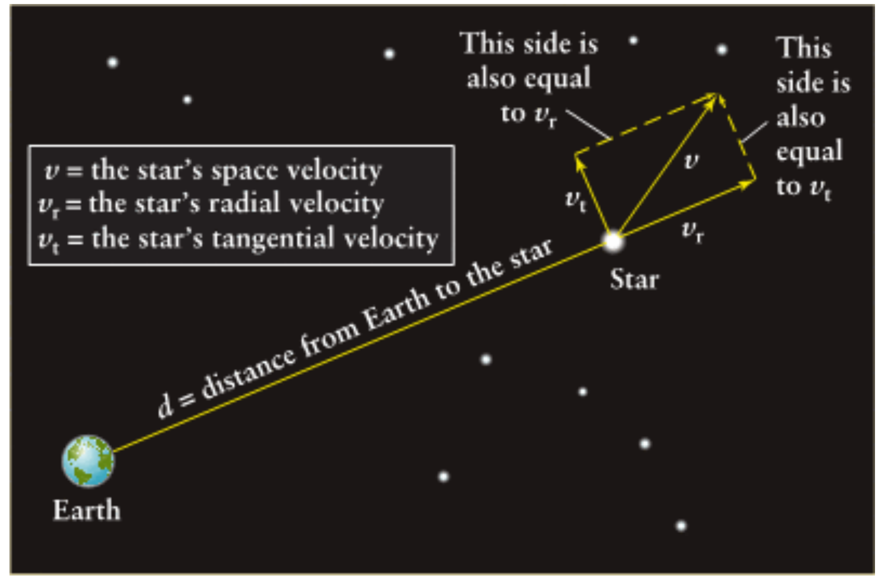
Hipparcos

Stellar Motions

$$v = \sqrt{v_t^2 + v_r^2}$$

v_r = radial velocity

v_t = tangential velocity



v_r is determined from Doppler shifts:

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v_r}{c}$$

v_t is determined from measurements of the proper motion μ :

$$v_t = 4.74 \mu d$$

v_t = the tangential velocity in km/s

proper motion μ = the angular distance in arcsec that the star moves in the sky per year

d = distance to the star in parsec

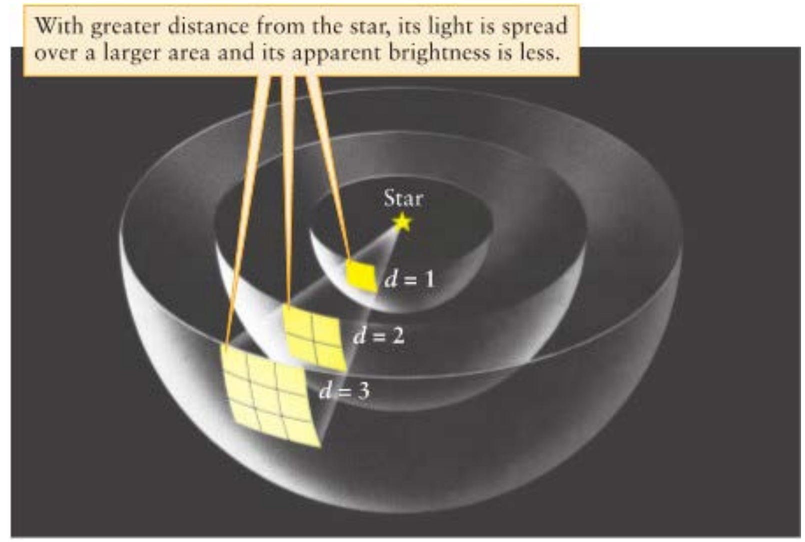
Stellar Motions: Example

Barnard's star has a proper motion of 10.358 arcseconds per year and a distance of 1.83 pc.

A particular spectral line of iron in the spectrum of Barnard's star has a wavelength (λ) of 516.445 nm. As measured in a laboratory on the Earth, the same spectral line has a wavelength (λ_0) of 516.629 nm.

What is the stars space velocity?

Apparent Brightness and Luminosity



Inverse Square Law

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

b = apparant brightness (or flux) in J s^{-1} m^{-2} (W m^{-2})

L = sources luminosity in J s^{-1}(W)

d = distance between observer and source in meters

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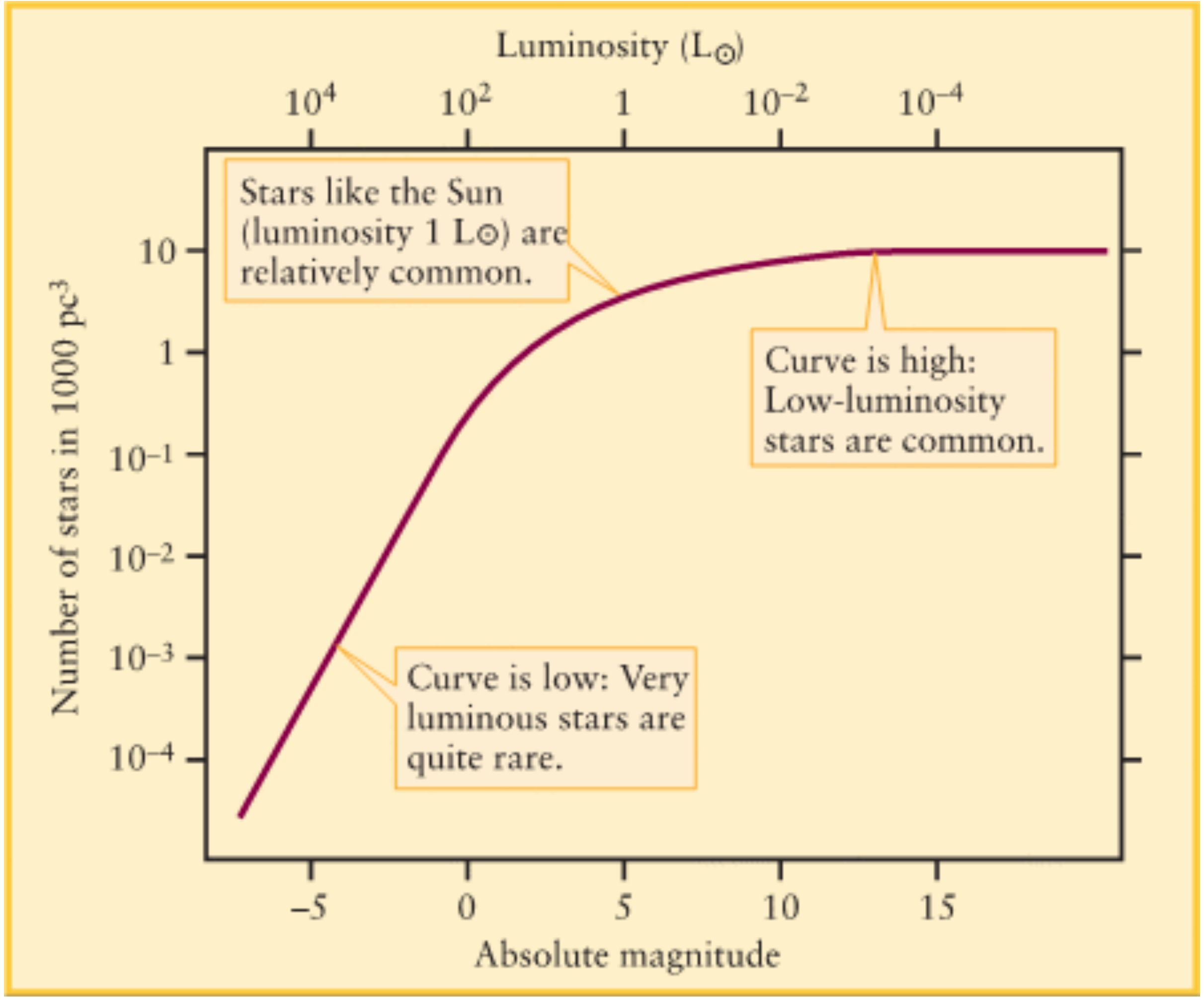
Example: The star ε (epsilon) Eridani is 3.23 pc from Earth. As seen from Earth, this star appears only 6.73×10^{-13} as bright as the Sun. (1 AU ≈ 150×10^{6} km ≈ 4.85×10^{-6} pc)

What is the luminosity of ε Eridani compared with that of the Sun?

Luminosity Function



This graph shows how many stars of a given luminosity lie within a representative 1000 cubic-parsec volume.

Magnitude Scale: Apparent Magnitude

The **magnitude scale** is a system used to denote the brightness of an astronomical object.

Keep in mind that **the greater the apparent magnitude, the dimmer the star.**

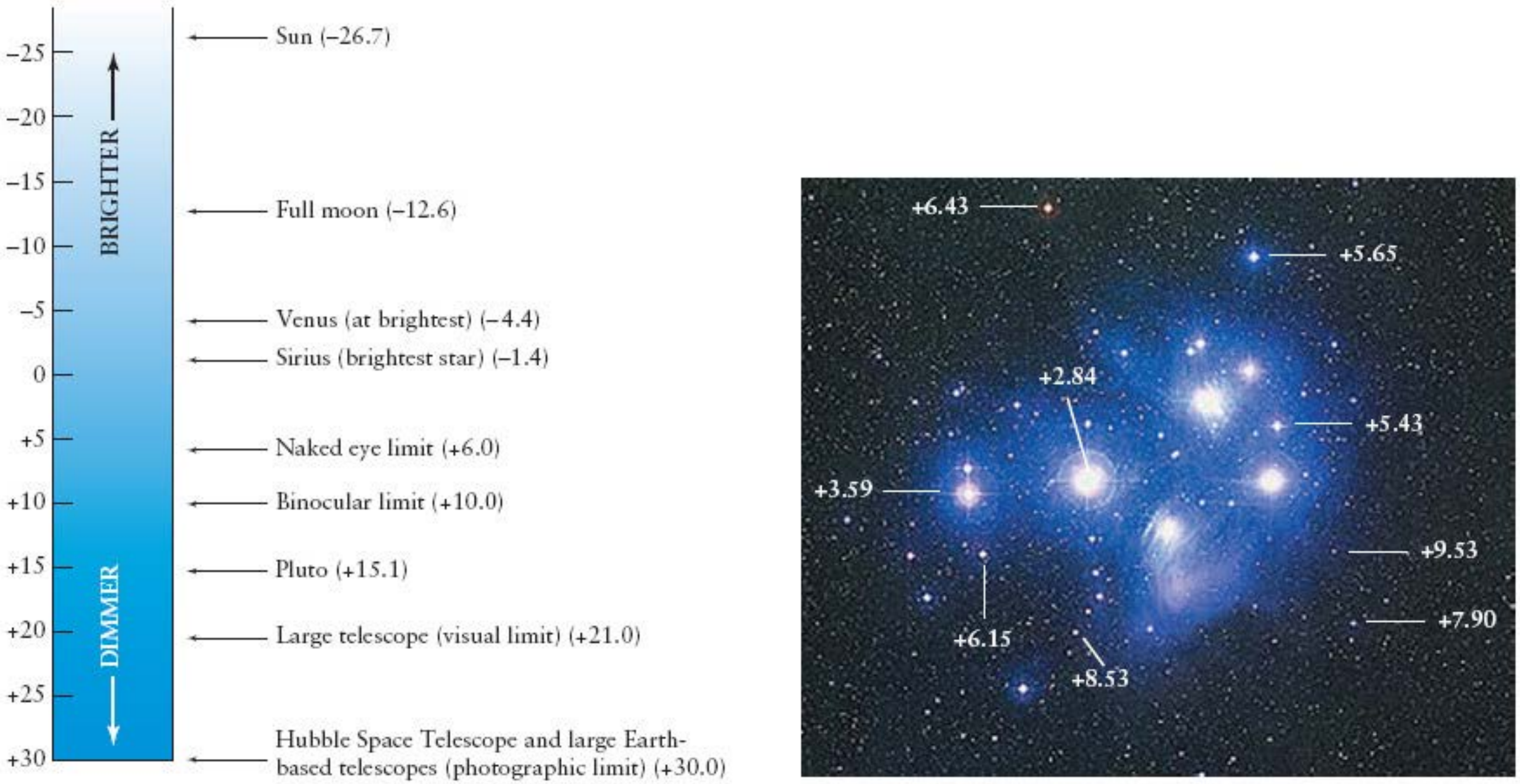
A second magnitude star is a factor of 2.512 fainter in brightness than a 1 magnitude star, a third magnitude star is fainter by a factor of 2.512 from a second magnitude star …

$$m_1 - m_2 = 2.5\log_{10}\left(\frac{b_2}{b_1}\right)$$

m_1, m_2 = apparent magnitudes of sources 1 and 2, respectively

b_1, b_2 = apparant brightnesses of sources 1 and 2, respectively

Magnitude Scale: Apparent Magnitude



(a) Some apparent magnitudes

(b) Apparent magnitudes of stars in the Pleiades

R I V U X G

Example: The variable star RR Lyrae in the constellation Lyra (the Harp) periodically doubles its light output. By how much does its apparent magnitude change?

Magnitude Scale: Absolute Magnitude

Absolute magnitude: The apparent magnitude that a star would have if it were at a distance of 10 parsecs from Earth.

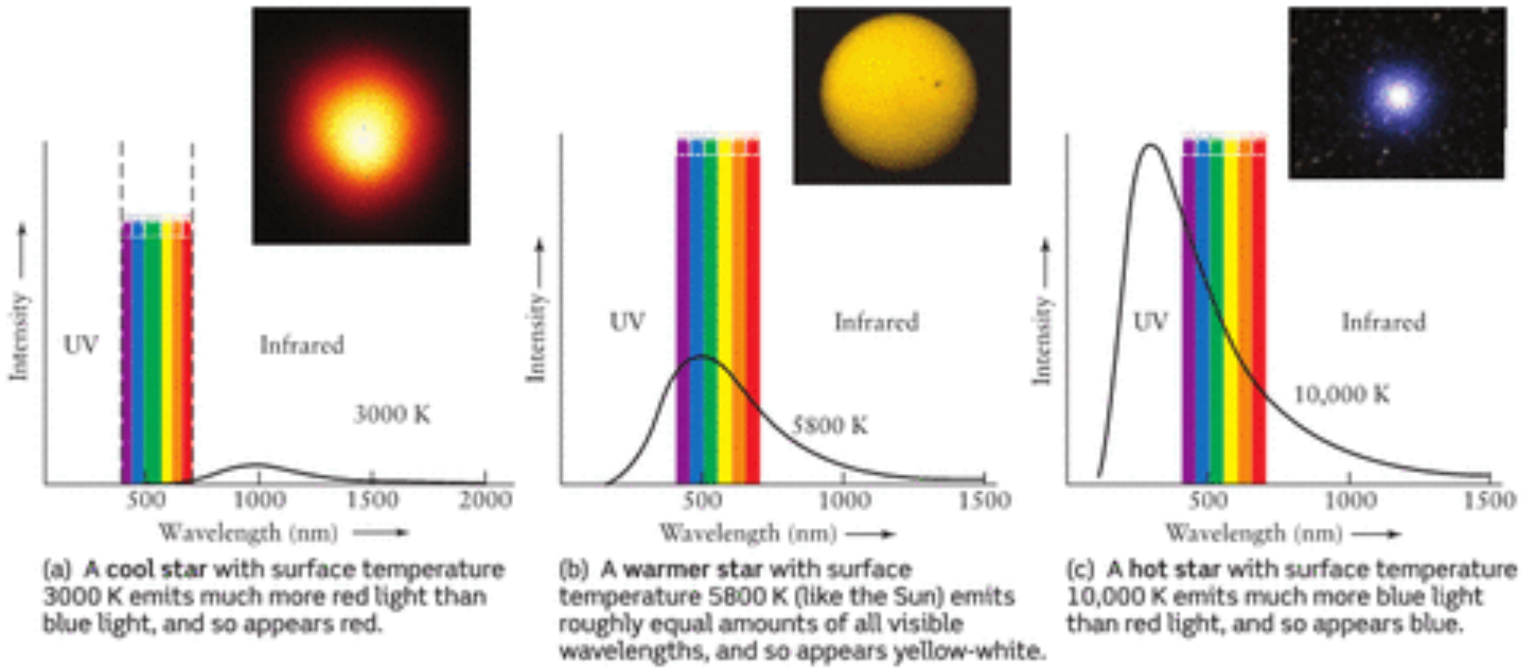
The apparent magnitude of the Sun is -26.7. If the Sun were moved to a distance of 10 parsecs from the Earth, it would look fainter and have a magnitude of +4.8.
(remember larger magnitudes means fainter)

The relation between the apparent and absolute magnitudes of an object is:

$$m - M = 5\log d - 5$$

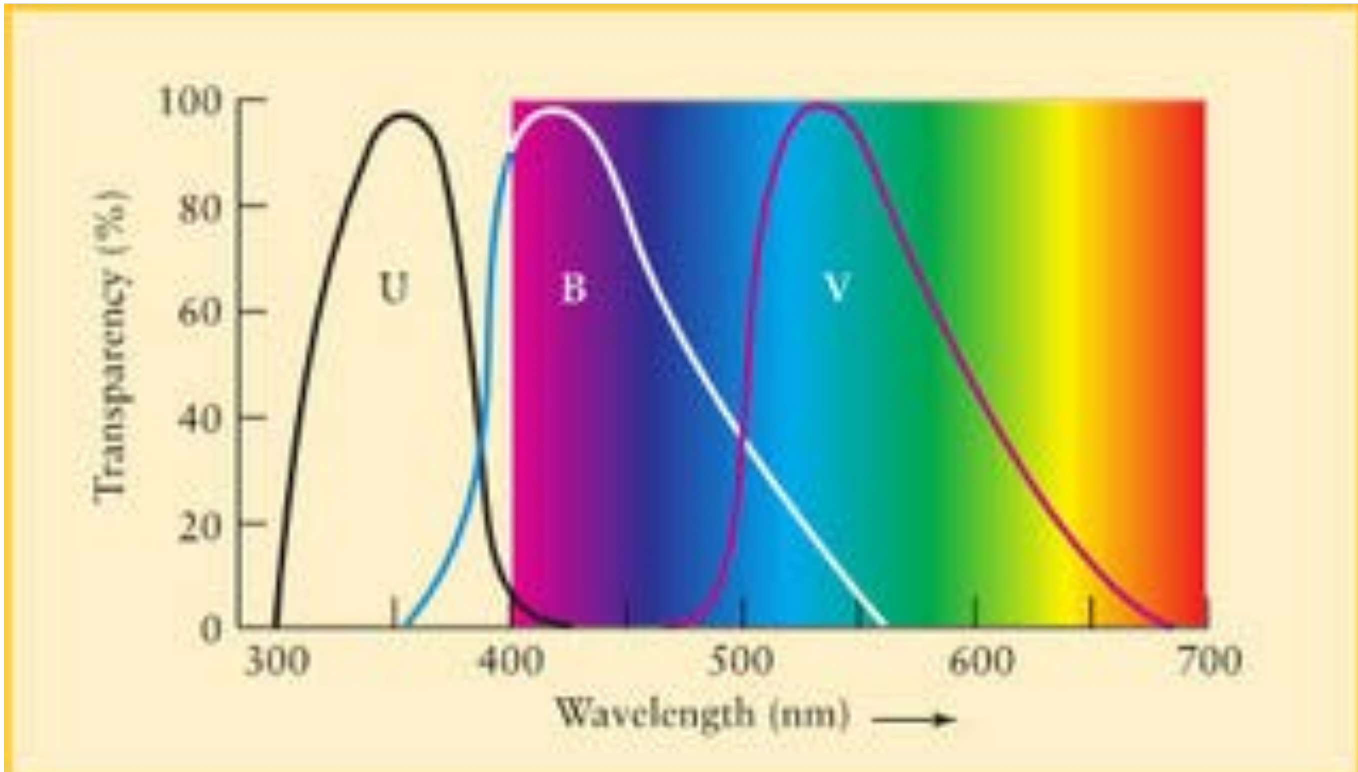
$d =$ distance between the Earth and the object in parsec

Colors and Temperature



A stars temperature is related its color. Red stars a relatively cold and blue stars are relatively hot.

Measuring Temperatures with Filters



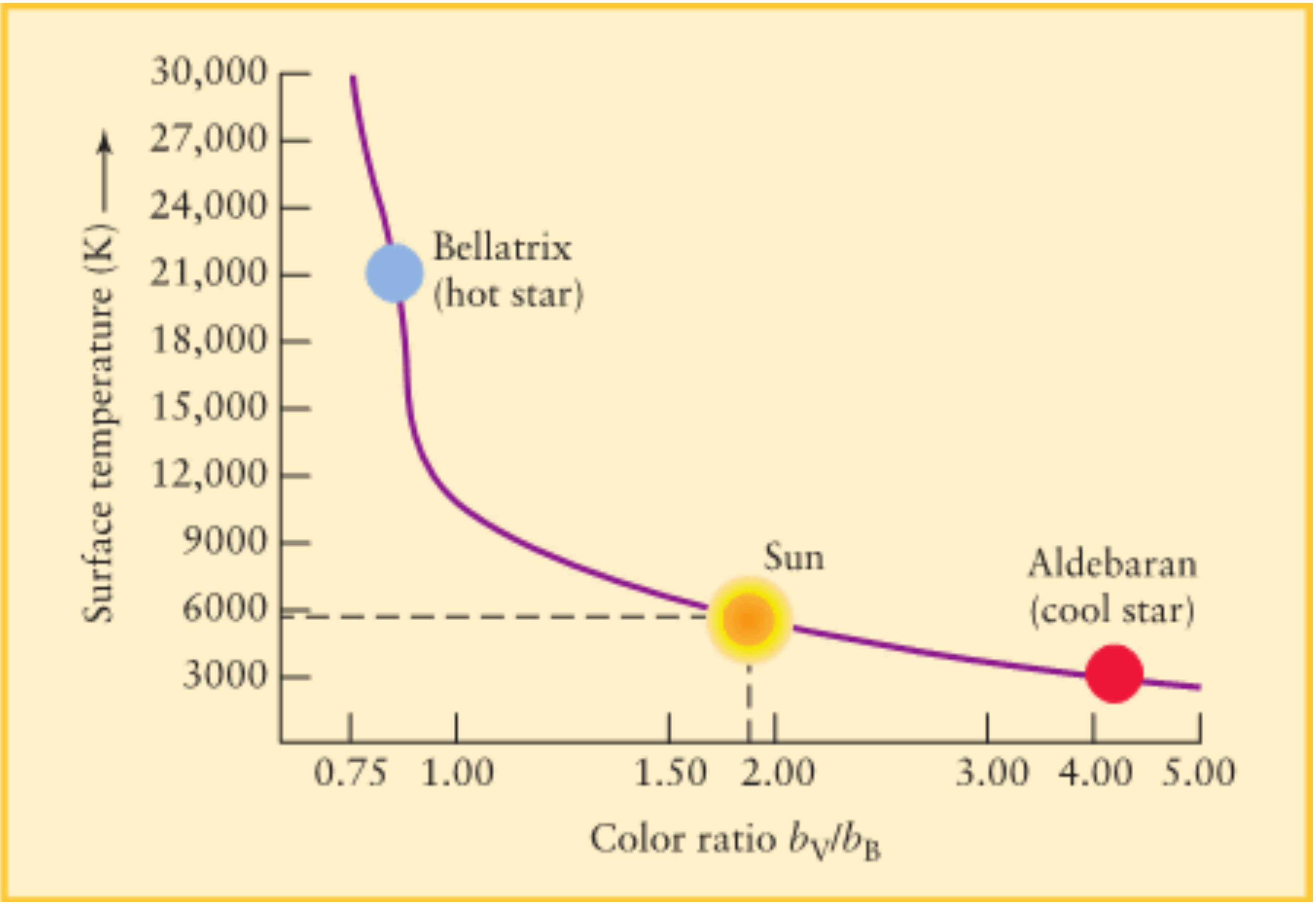
A filter is transparent to a certain wavelength band.
A **U filter** is more transparent in the ultraviolet band a **B filter** if more transparent in the blue and a **V filter** is more transparent in the yellow-green.

Measuring Temperatures with Filters

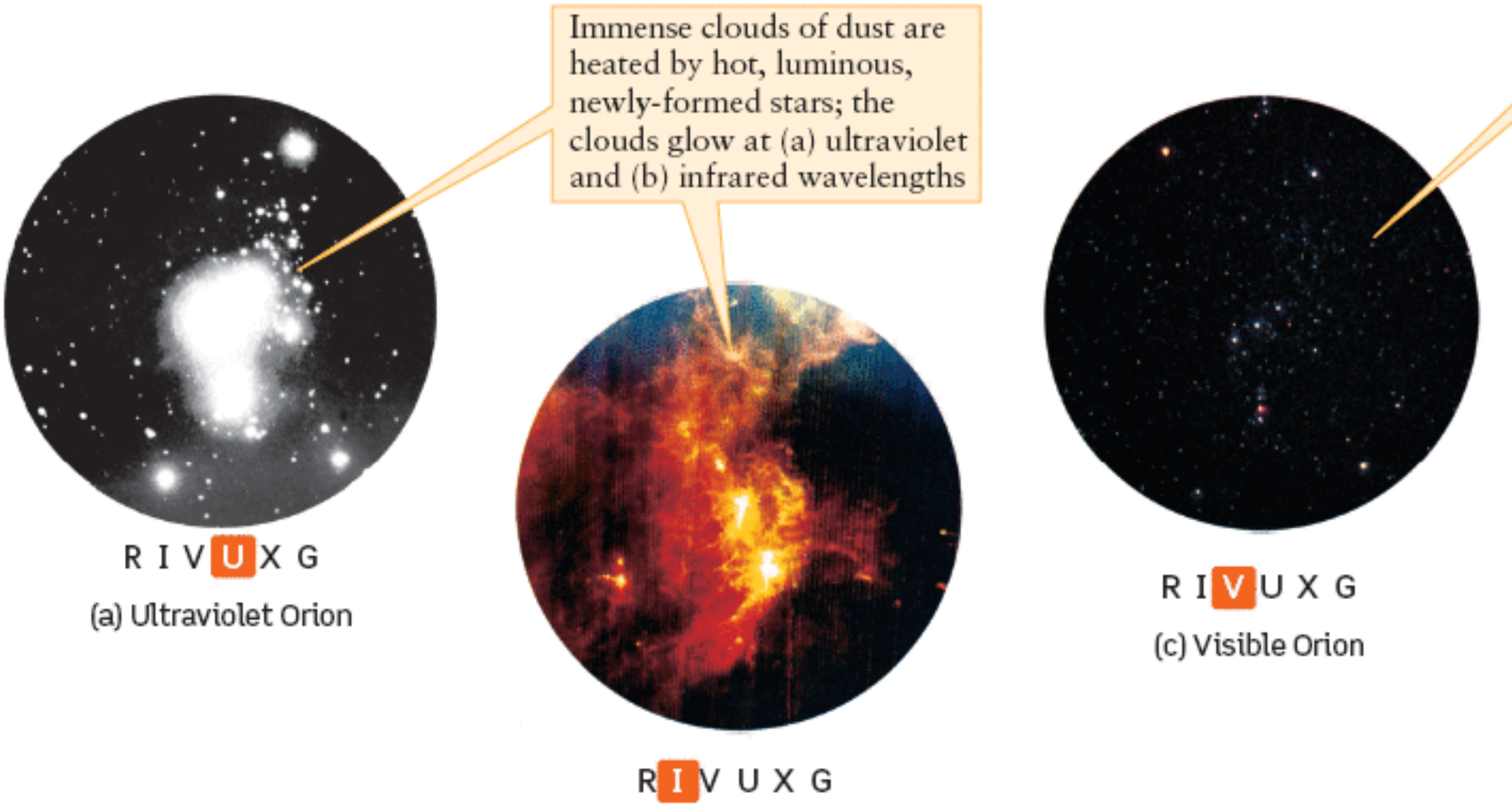
Method: First measure a stars brightness through each of the U, B and V filters. This gives the apparent brightnesses of b_U, b_B and b_V.

Then compare the relative brightnesses by taking the ratios b_V/b_B and b_B/b_U. These ratios indicate the temperature of the stars surface.

Measuring Temperatures with Filters



Measuring Temperatures with Filters



(a) Ultraviolet Orion

(b) Infrared Orion

(c) Visible Orion

Spectra of Stars

Absorption spectra in stars are produced in the following way:

A star produces a **continuum spectrum** from hot (T_{gas}) dense gas in its atmosphere. This spectrum is very close to that of a **blackbody spectrum** with a temperature of T_{gas}.

The stars continuum radiation goes through cooler parts of its upper atmosphere where **photons of only certain wavelengths are absorbed.**

The **wavelengths** of the absorption lines are **characteristic of the elements and the ionization level** of the stars absorbing gas.

Stellar Classification

To bring some order in the zoo of stellar spectra astronomers have grouped stars according to the appearance of their spectra. These **classifications of stars according to the appearance of their spectra** are called **spectral classes**.

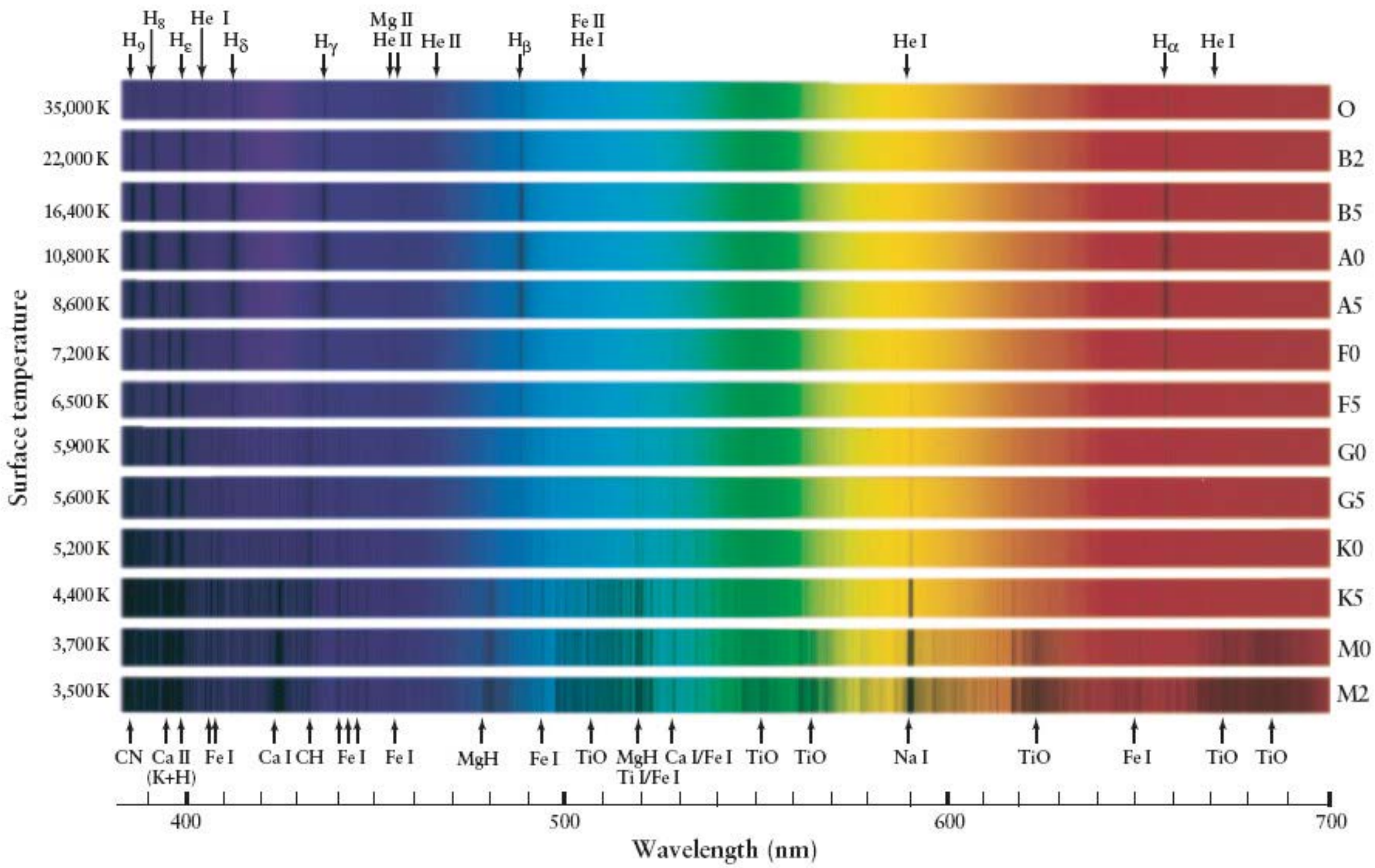
The **spectra classes** are labeled:

O B A F G K M L T

A refined scheme adds a number ranging from 0 to 9 to each letter. This subdivision of the spectral class is called **spectral type**.

In the late 1800's a team of women at the Harvard College Observatory undertook the task of classifying the spectra of hundreds of thousands of stellar spectra.

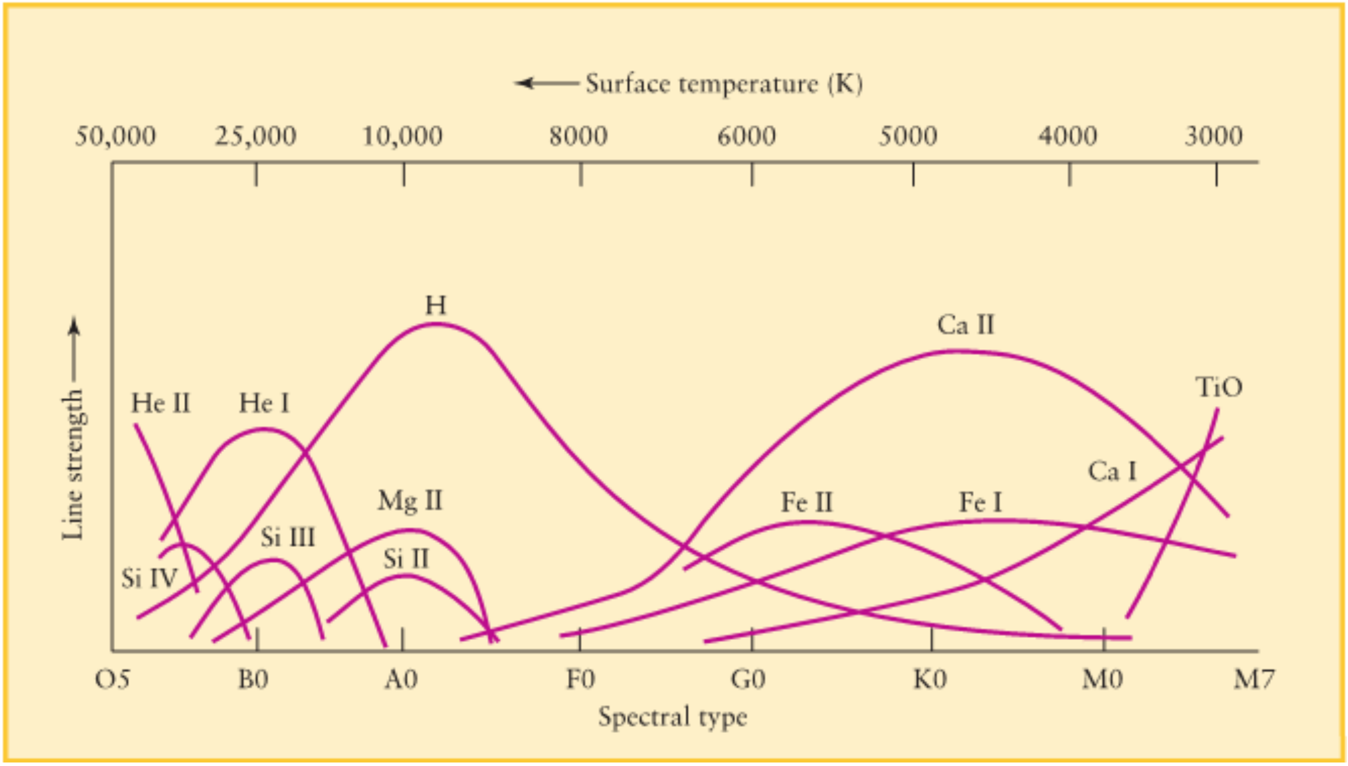
Stellar Spectra and Temperature



For T > 10,000 K most H atoms are ionized so the Balmer lines are very weak in very hot stars.

For T < 4,000 K most H atoms have electrons in the n = 1 level and the Balmer lines are very weak in very cool stars.

Stellar Spectra and Temperature



Each curve peaks at the surface temperature for which that chemical’s absorption line is strongest. For example, hydrogen (H) absorption lines are strongest in A stars with surface temperatures near 10,000 K. Roman numeral I for neutral atoms, roman numeral II for 1 e^- removed, III for 2 e^- removed …

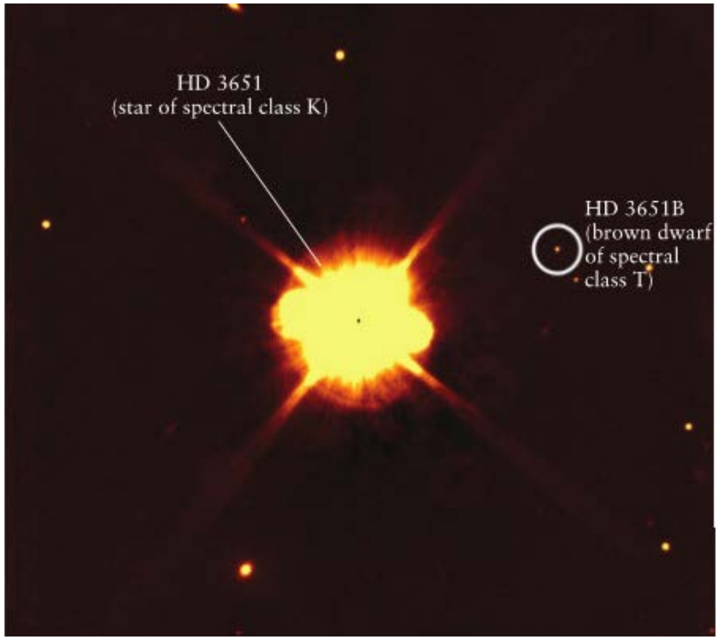
Brown Dwarfs

Brown Dwarfs are a starlike objects that are not massive enough to sustain hydrogen fusion in their core. They have temperatures lower than those of spectral class M stars.

They are primary heated by Kelvin-Helmoltz contraction.

Since they are so cool **their spectra peak in the infrared**.

Brown Dwarf spectra have a rich variety of **absorption lines produced by molecules**.



Infrared image of brown dwarf HD3561B. The star HD 3561 is of spectral class K, with a surface temperature of about 5200 K. HD 3651 is orbited by a brown dwarf with a surface temperature between 800 and 900 K and a luminosity just 1/300,000 that of the Sun.

Star Radii

Stefan - Boltzmann Law : $F = \sigma T^4$

Inverse Square Law : $F = \dfrac{L}{4\pi R^2}$

F = flux at the stars surface in W m^{-2}

L = stars luminosity in W

R = radius of stars emitting surface in meters

T = temperature of stars surface in kelvins

σ = Stefan - Boltzmann contant $= 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

Star Radii

$L = 4\pi R^2 \sigma T^4$ Equation (1)

$L_\odot = 4\pi R_\odot^2 \sigma T_\odot^4$ Equation (2)

Dividing equation 1 by equation 2 we have:

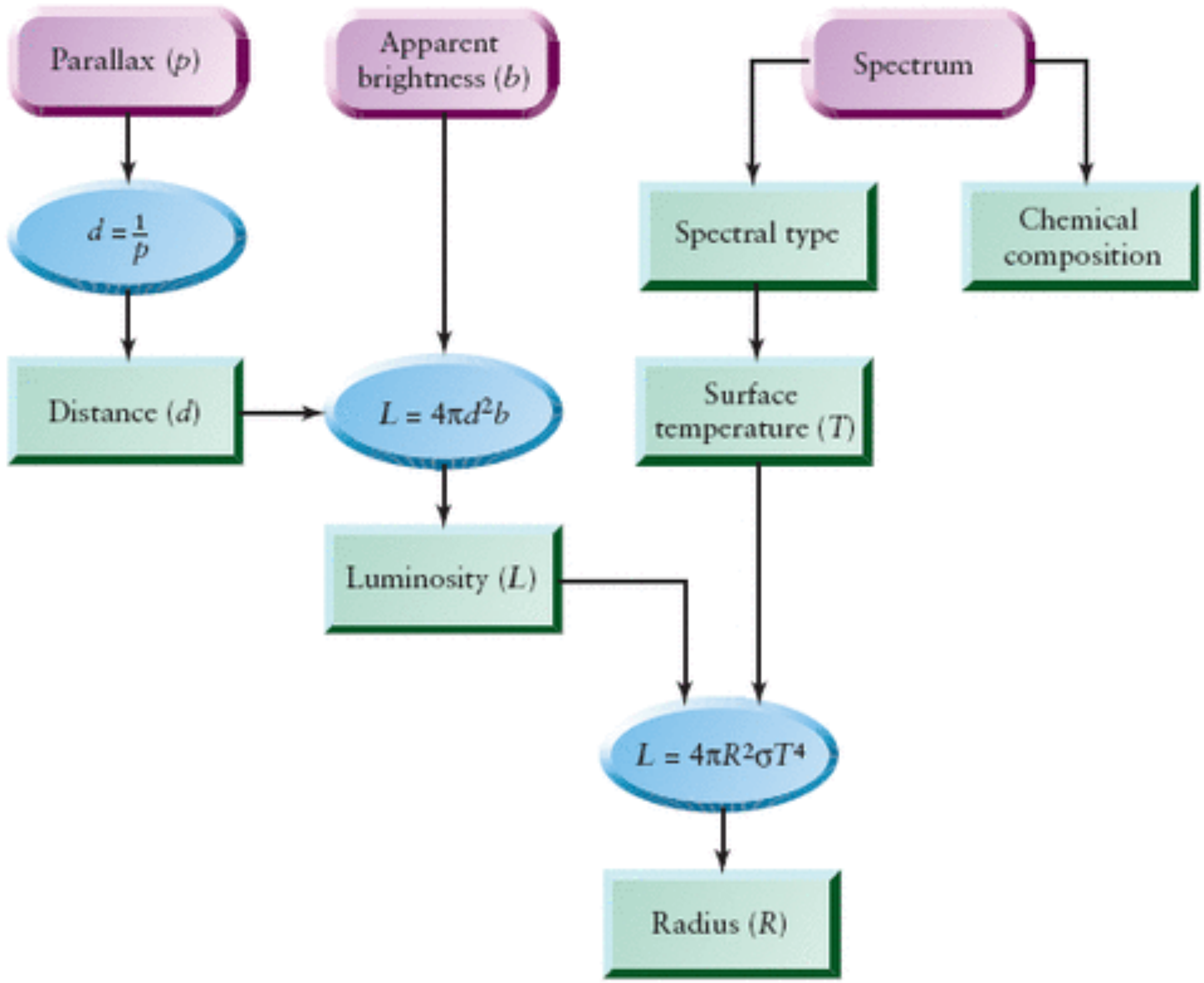
$L/L_\odot = (R/R_\odot)^2 (T/T_\odot)^4$ Equation (3)

Solving for $R/R_\odot$ we have:

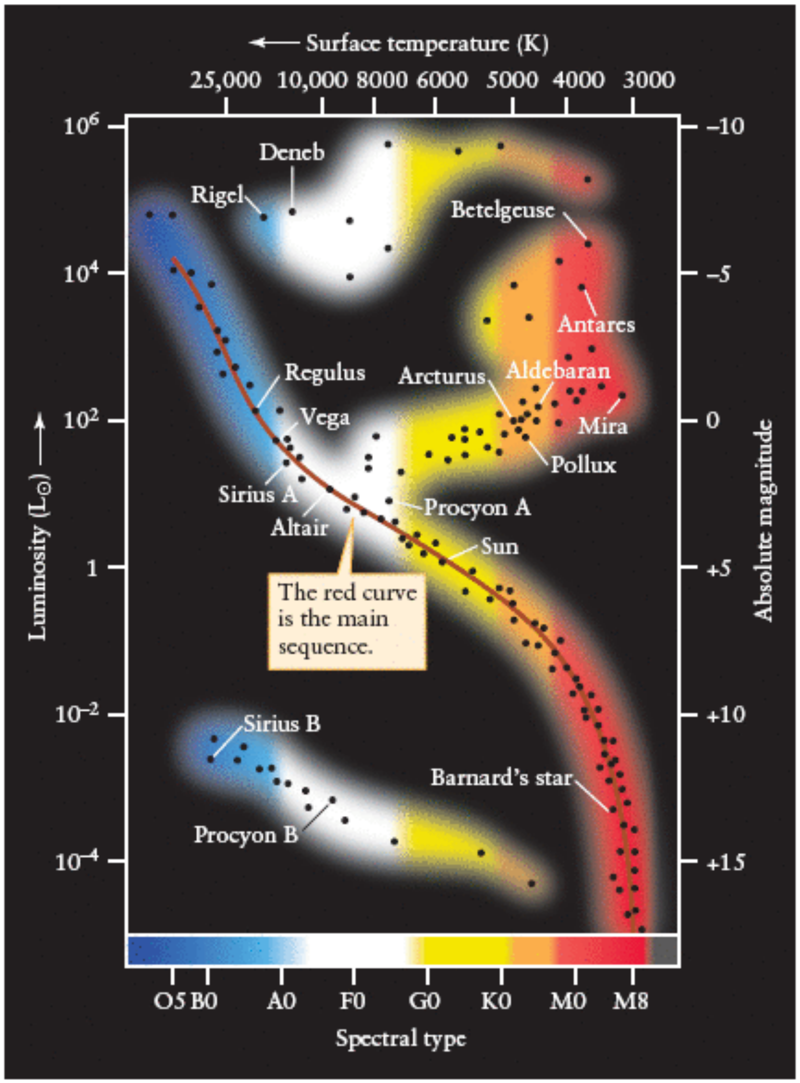
$R/R_\odot = \sqrt{L/L_\odot}(T_\odot/T)^2$

Example: The bright reddish star Betelgeuse in the constellation Orion is 60,000 times more luminous than the Sun and has a surface temperature of 3500 K. How much larger is Betelgeuse's radius from the Sun's radius ? ($T_\odot$=5,800 K)

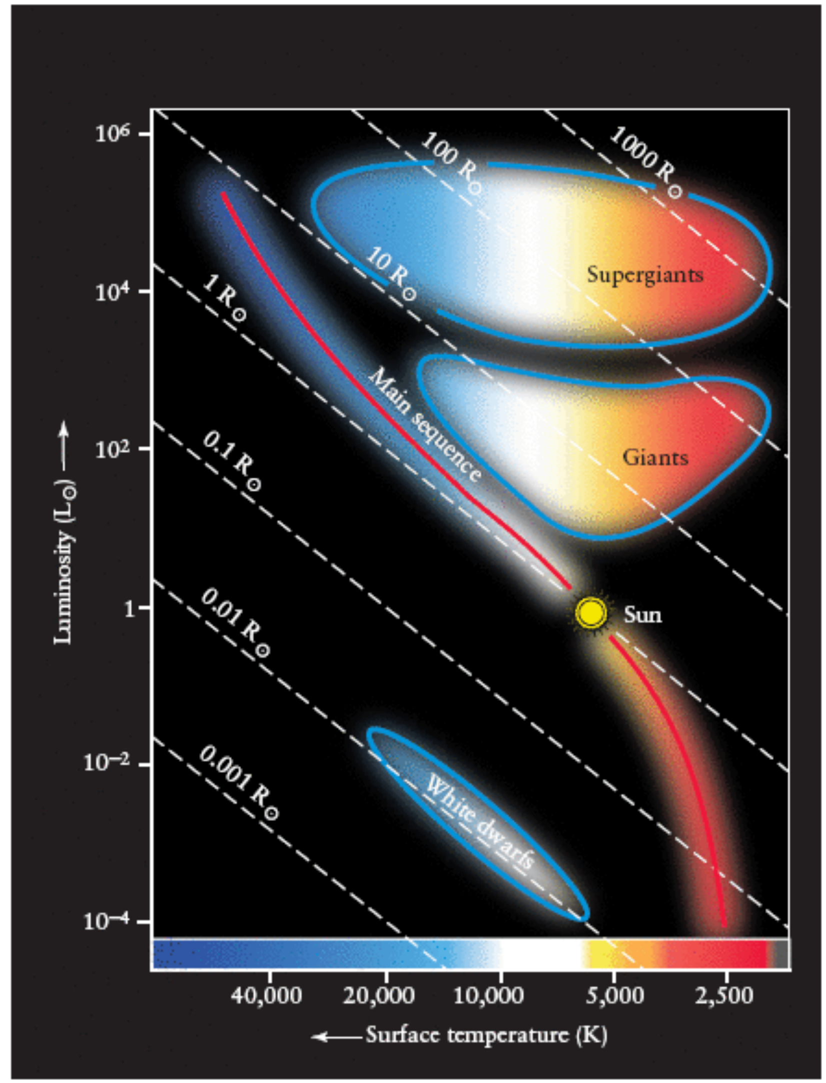
Measuring the Properties of Stars



Hertzsprung-Russel Diagram of Stars



(a) A Hertzsprung-Russell (H-R) diagram



(b) The sizes of stars on an H-R diagram

Categories of Stars

Main-sequence stars: hydrogen fusion is taking place in their cores. About 90% of the stars (including the Sun) in the night sky lie along the main sequence.

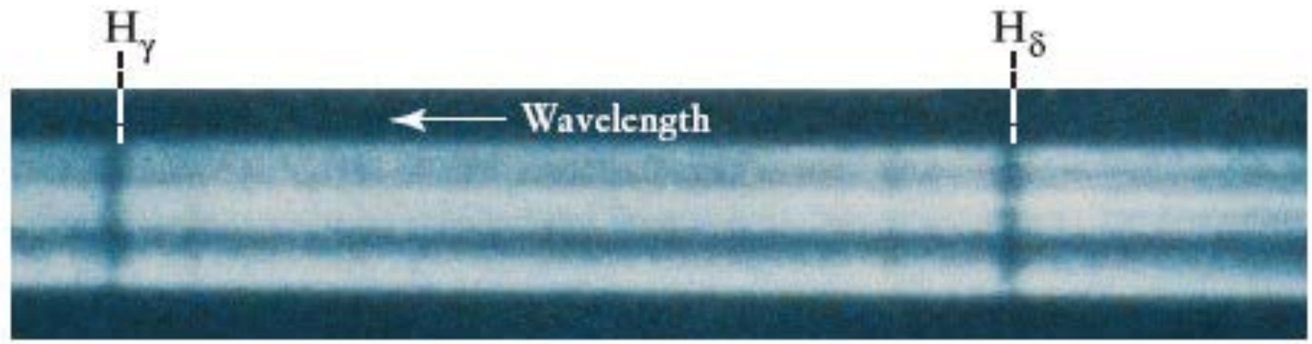
Giant stars: luminosities of 100–1000 $L_\odot$ and temperatures of 3000–6000 K. Red giants have T : 3000–5000 K.

Supergiant stars: considerably bigger and brighter than typical red giants, with radii of up to 1000 $R_\odot$.

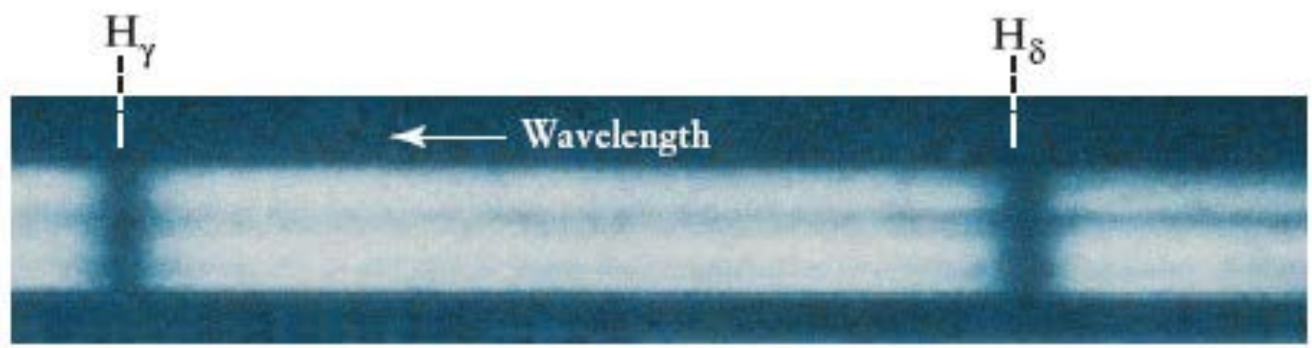
White Dwarfs: A low-mass star that has exhausted all its thermonuclear fuel and contracted to a size roughly equal to the size of the Earth (*has-been star*).

Brown Dwarfs: Starlike (~Jupiter-size, $M < 0.08M_\odot$) objects that are not massive enough to sustain hydrogen fusion in their core (*never-will-be star*).

Absorption Line Widths



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



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

Absorption Line Widths

The widths of the absorption lines in stellar spectra depends on the density and pressure of the gas causing the absorption.

The widths of the absorption lines (especially the H lines) indicate the category (ie. main sequence, giant, supergiant) the star belongs to.

In the 1930s W. W. Morgan and P. C. Keenan of the Yerkes Observatory of the University of Chicago classified stars into **luminosity classes** depending on the widths of their lines.

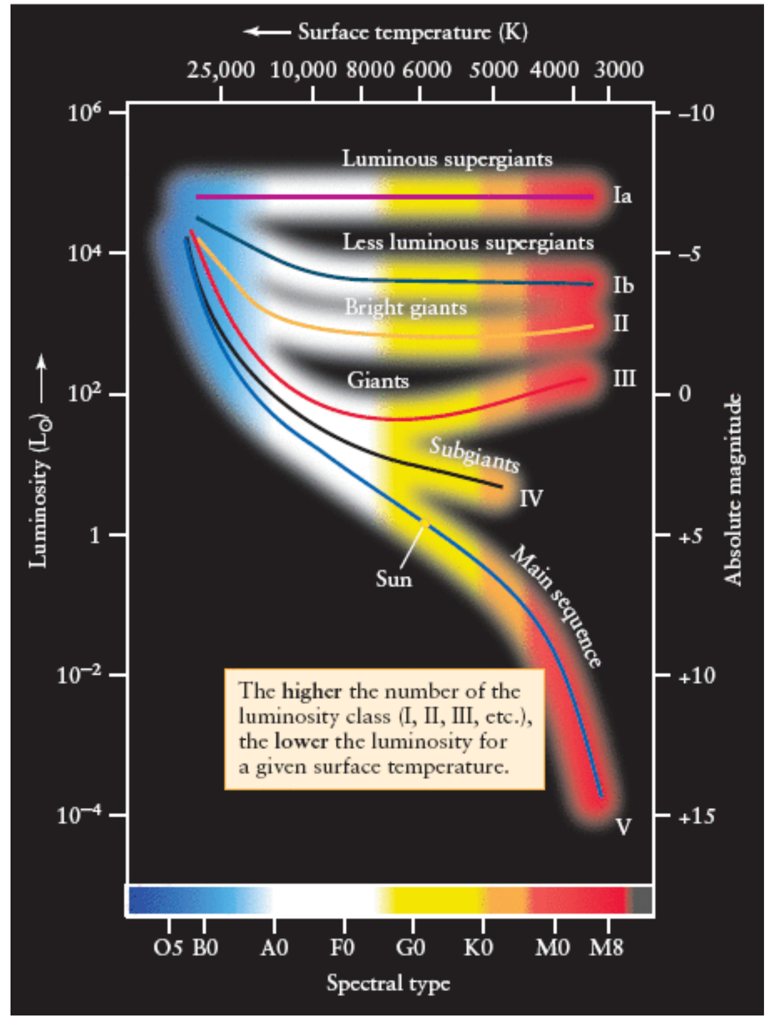
Luminosity Classes: V (Main sequence), IV (Subgiant), III (Giant), II (Bright giant), Ib(Less luminous supergiant) and Ia(Most Luminous supergiant)

Spectral Type and Luminosity Class

Combining the **spectral type** (which gives the stars temperature) with the **luminosity class** (which indicates on what branch of the H-R diagram the star lies one can estimate the stars luminosity.

Examples: What is the luminosity of

-a G2 V star ?
-a M0 II star ?
-a B0 Ia star ?

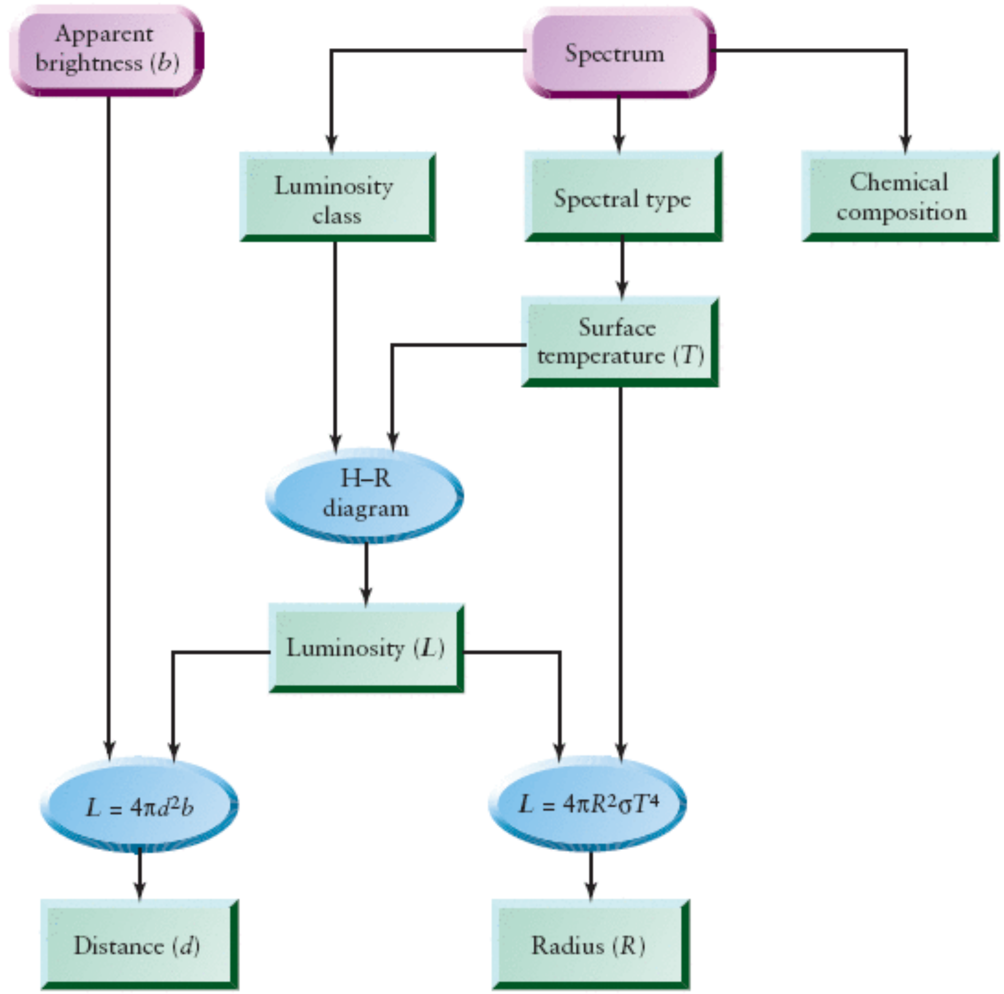


H-R diagram with Luminosity Classes.

Spectroscopic Parallax

From a stars spectrum one can obtain the **spectral type** and **luminosity class** which provide estimates of the temperature (T) and luminosity (L) of the star.

From T, L and the apparent brightness (b) one can infer the distance (**spectroscopic parallax**) and radius of the star.

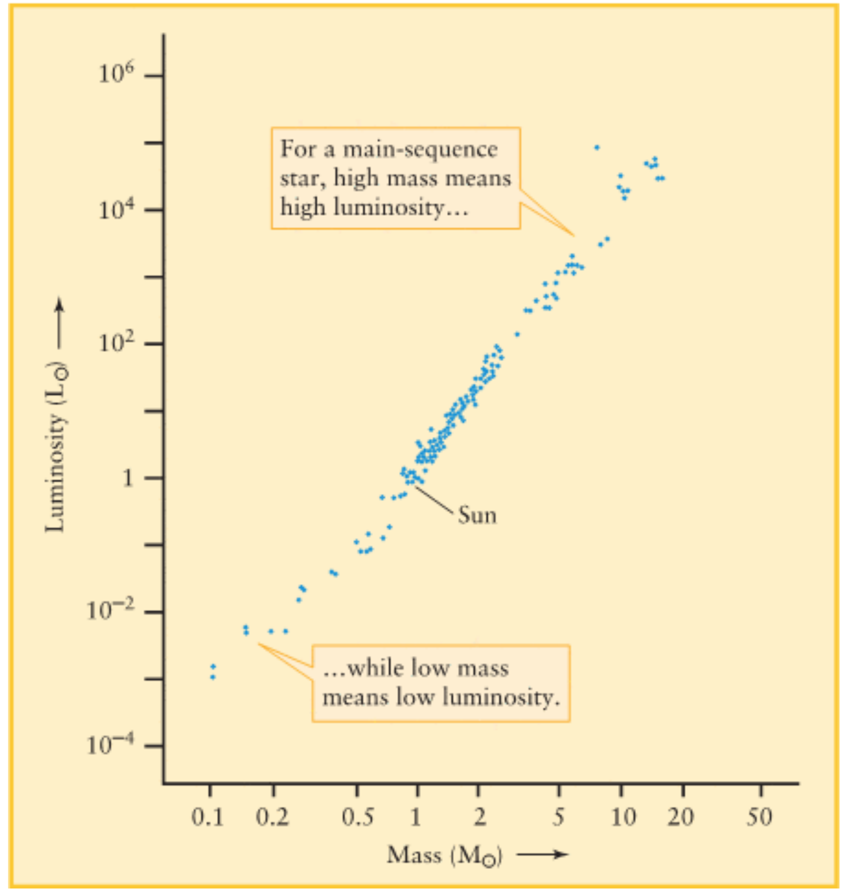


Mass-Luminosity for Main Sequence Stars

Luminosity increases with mass for main sequence stars.

Combining this result with the main sequence branch on the H-R diagram we conclude:

The greater the mass of a main-sequence star, the greater its luminosity, its surface temperature, and its radius.

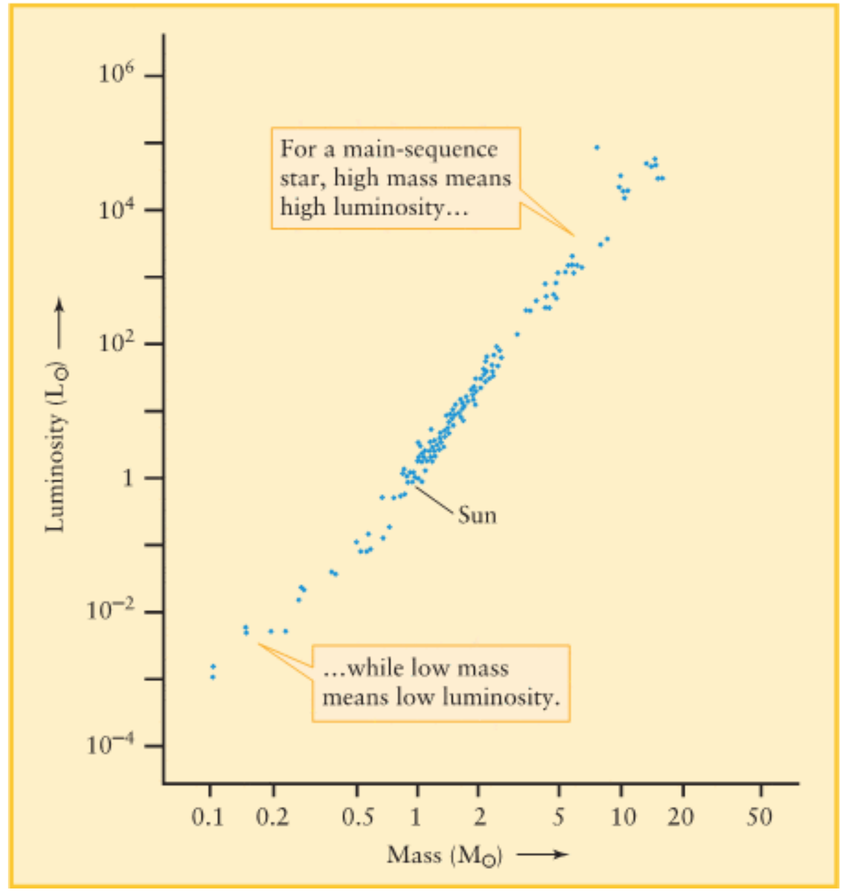


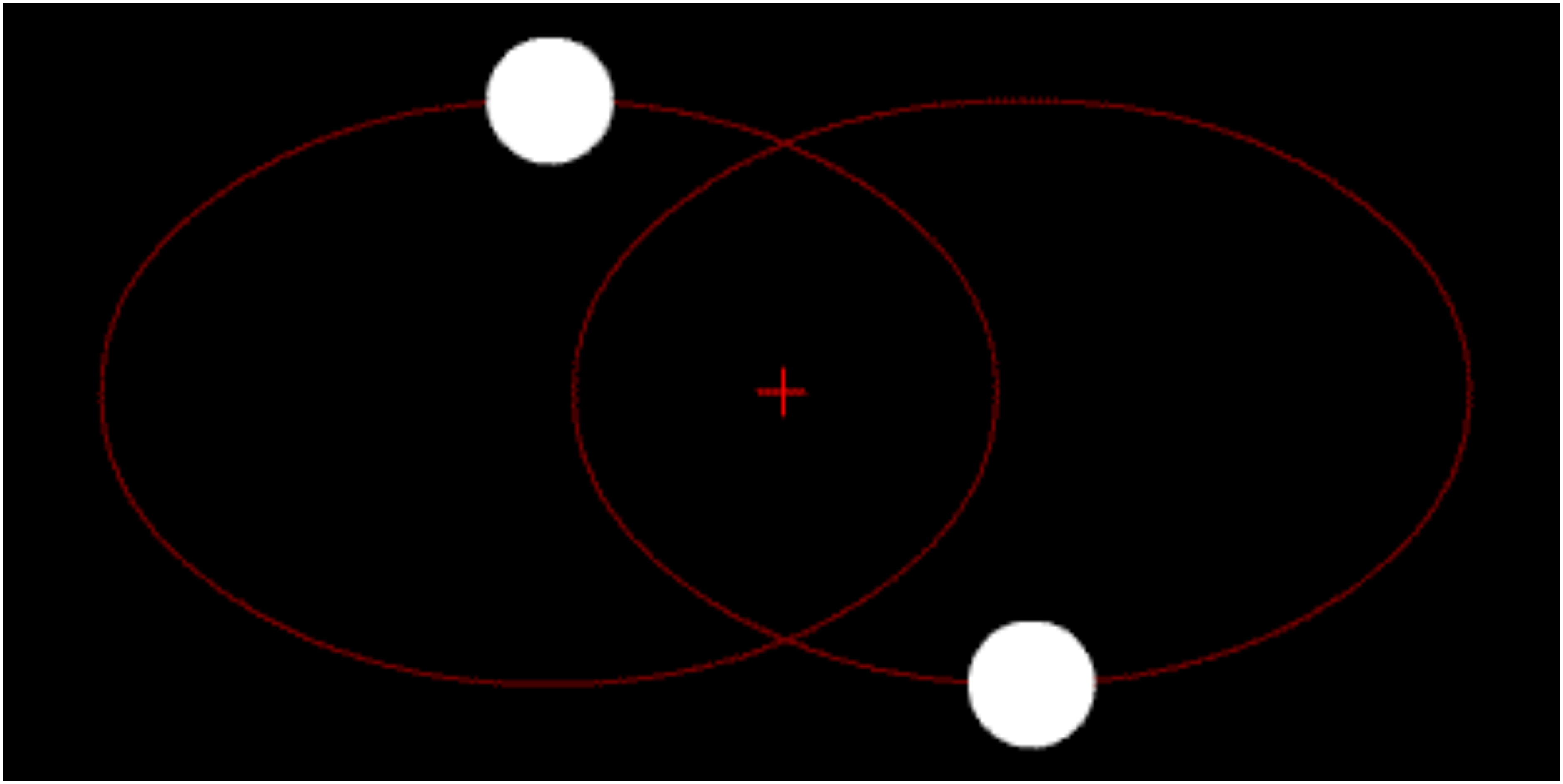
Mass-Luminosity for Main Sequence Stars

Explaining the M-L correlation: The more massive a star the larger the pressure, density and temperature in its core. This leads to a larger fusion reaction rate and thus a larger luminosity.

Brown dwarfs ($M < 0.08M_{\odot}$) also obey a mass luminosity relation.

The more massive brown dwarfs collapse more rapidly thus radiate energy more rapidly and are more luminous.





Double Stars

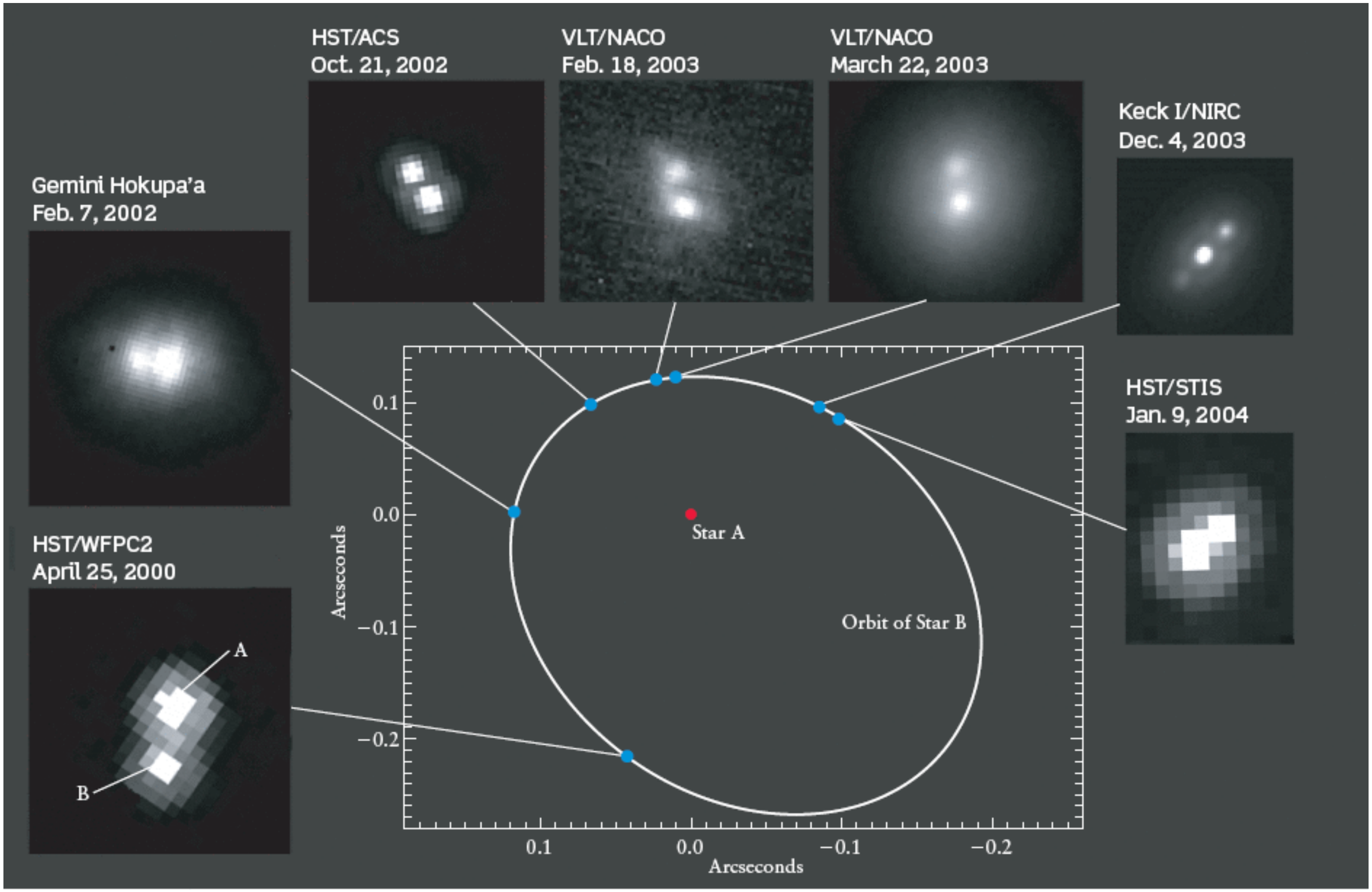
Double star: A pair of stars located at nearly the same position in the night sky. Some, but not all, double stars are binary stars.

Optical double star: **Two stars** that lie along nearly the same line of sight but are actually **at very different distances from us**.

Binary stars: Two stars orbiting about each other. The brighter star is called the primary and the other is its companion star or secondary. A double star can be either an optical double of a binary star.

Visual Binary: a binary star for which the **angular separation between the two components is great** enough to permit them to be observed as pair of stars.

Binary Stars

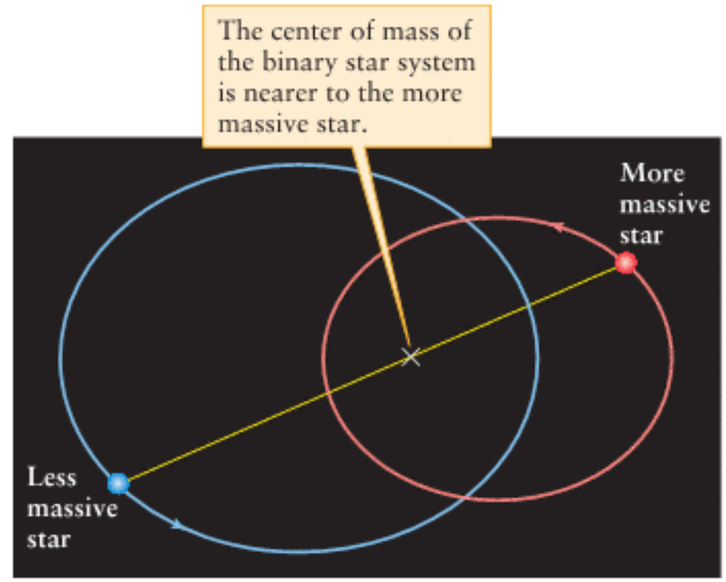


Binary Star 2MASSW J0746425 +2000321

Kepler's Third Law for Binary Systems

$$M_1 + M_2 = \frac{a^3}{P^2}$$

$$\frac{M_1}{M_2} = \frac{a_2}{a_1}$$



(b) A binary star system

P = period of orbit, in years

$a = a_1 + a_2$, in AU (a_1, a_2 are the semimajor axes of the orbits of M_1, M_2 , respectively

M_1, M_2 = mass of stars, in solar masses

Spectrum Binaries

One can also use spectroscopy to determine if a star is a binary.

If the spectrum contains absorption lines associated with different temperatures and luminosities one can infer that they are looking at more that one star.

spectrum binary: A binary star whose binary nature is deduced from the presence of two sets of incongruous spectral lines.

Spectroscopic Binaries

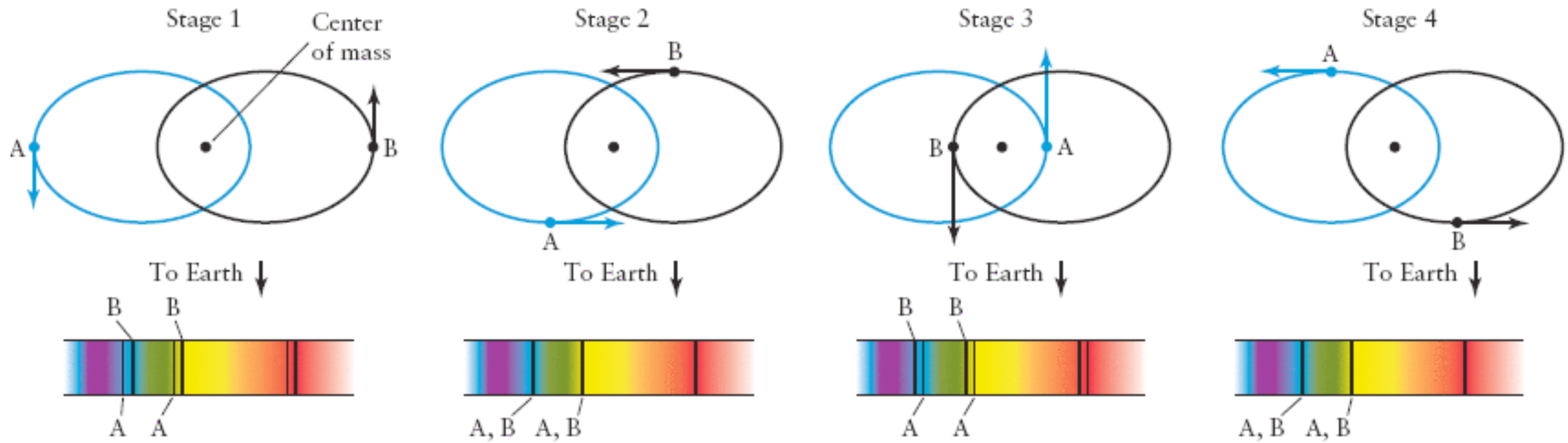
One can also use the Doppler effect to determine if a star is a binary.

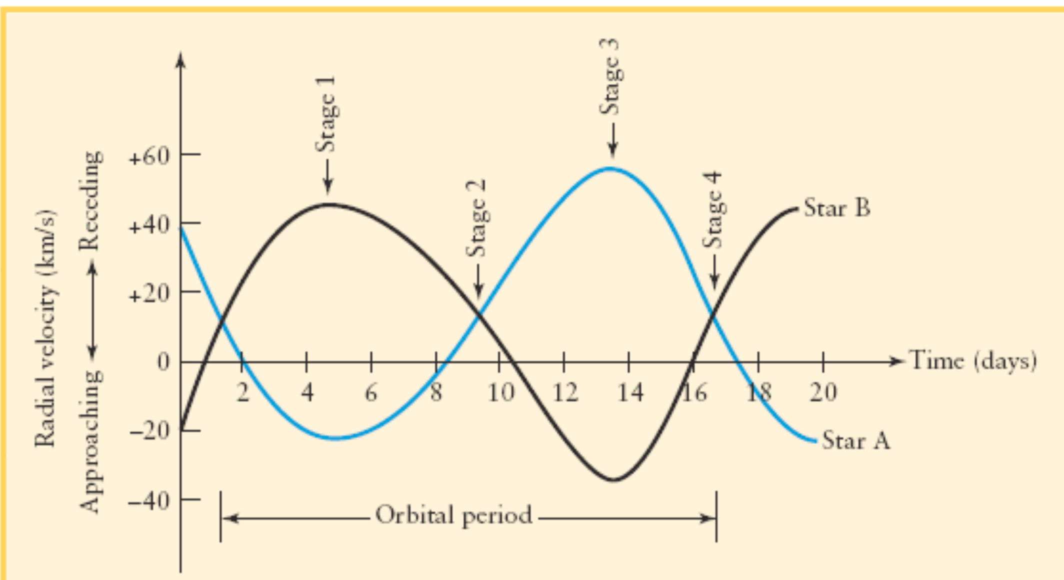
If the spectrum contains absorption lines that periodically shift in wavelength one can infer that they are looking at more that one star.

spectroscopic binary: A binary star system whose binary nature is deduced from the periodic Doppler shifting of lines in its spectrum.

If the spectrum of only one star of the binary is detectable it is called a **single-line spectroscopic binary**.

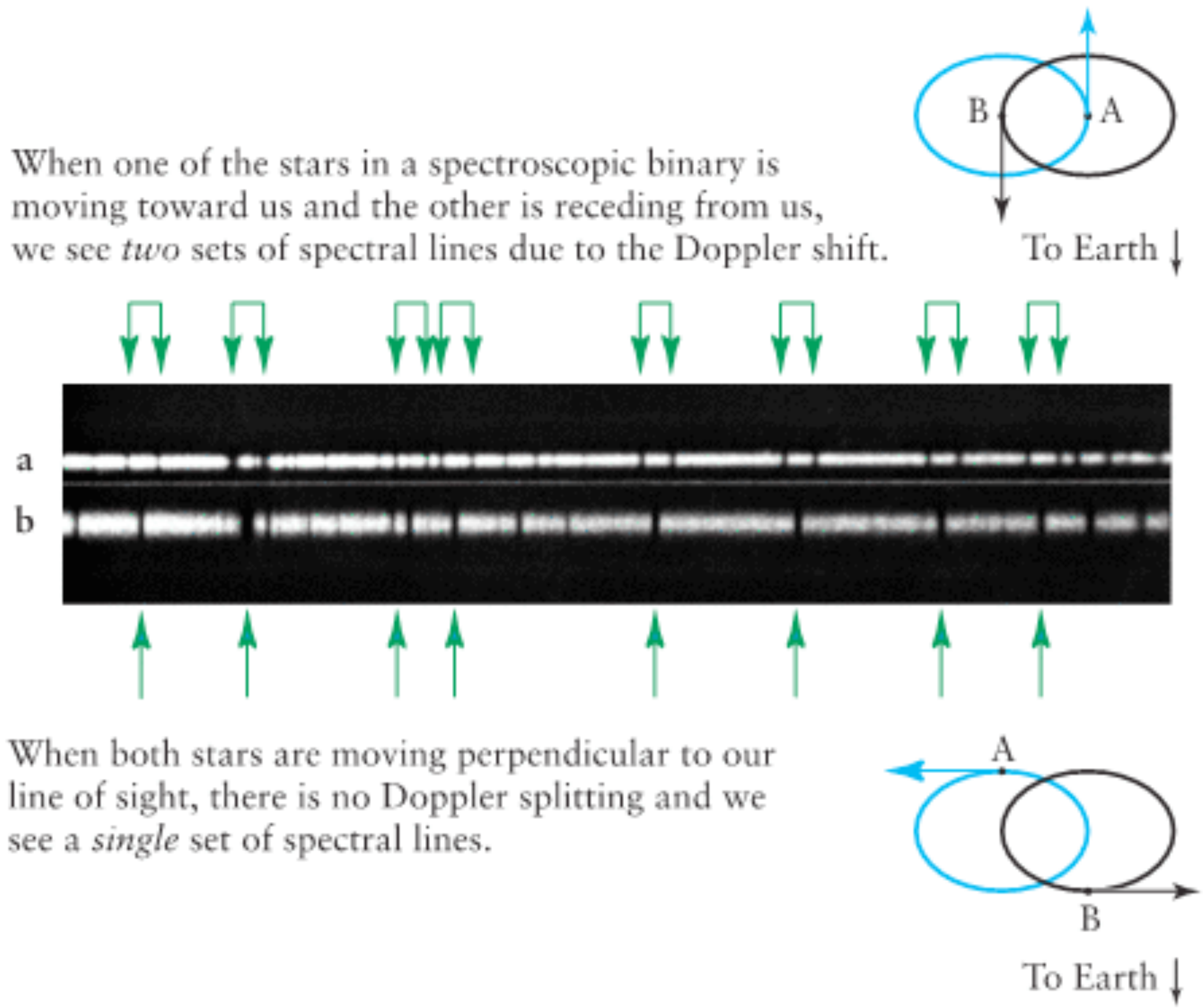
Spectroscopic Binaries





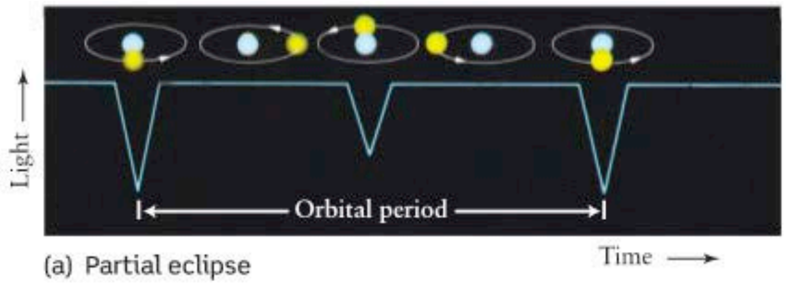
Radial Velocity Curves of Spectroscopic binary system HD 171978

Spectroscopic Binaries

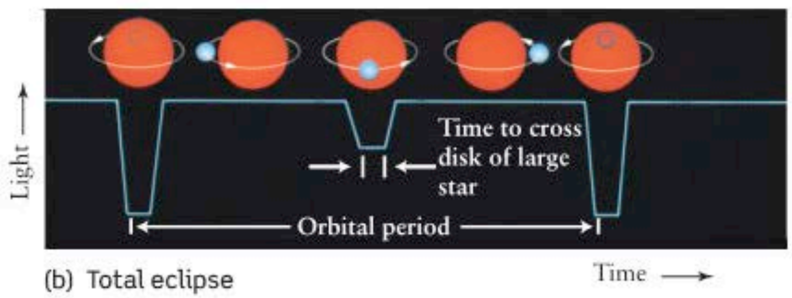


Radial Velocity Curves of Spectroscopic binary system κ Arietis

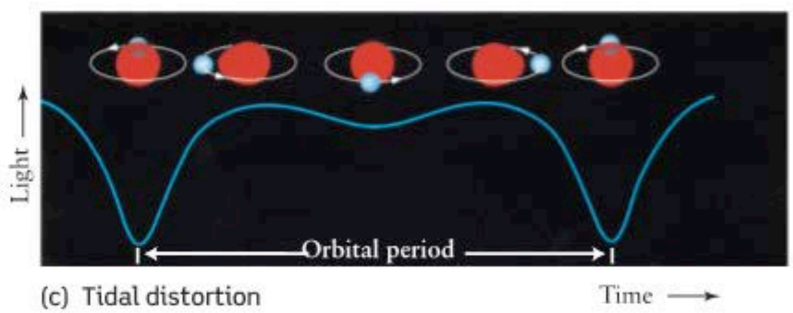
Eclipsing Binaries



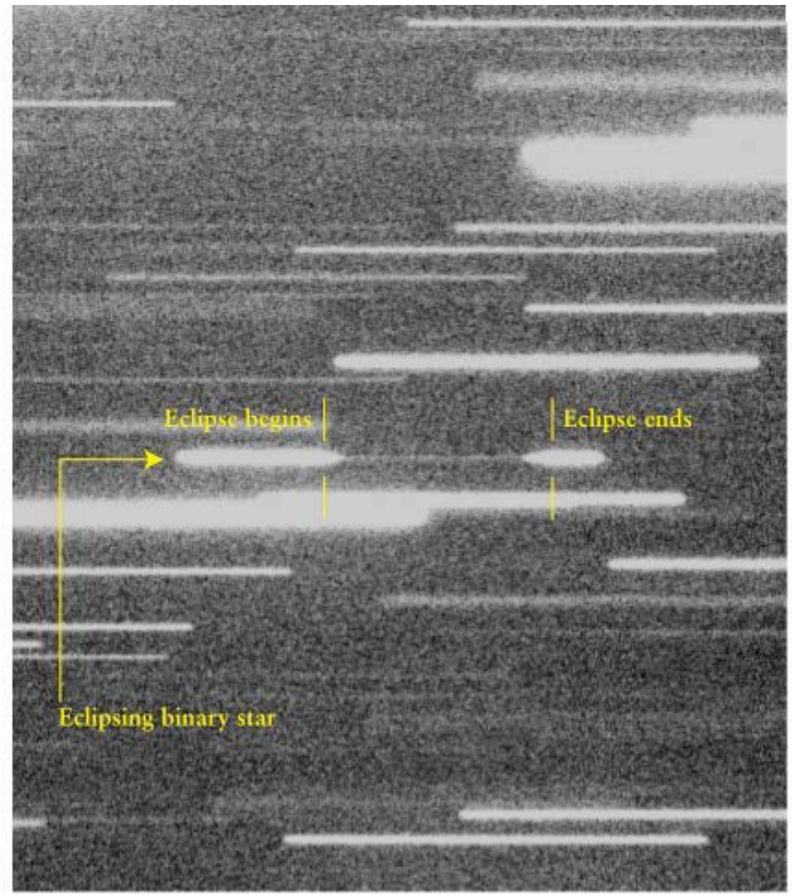
(a) Partial eclipse



(b) Total eclipse



(c) Tidal distortion



(d) Eclipse of a binary star