Stellar Properties
(Numbering differs on handout)

1. Distance (nearby stars) (17.1)
2. Apparent mag./ Flux (17.2)
3. Luminosity/ Absolute mag. (17.2)
4. Surface Temp./Core Temp. (17.3)
5. Spectral Type & color (17.3)
6. Size (radius) (17.4)
7. Position on H-R diagram (17.5)
8 Luminosity Class (17.6, p.456)
9. Mass (17.7,17.8)
10. Distance (far away stars) (17.6)
11. Radial & Tangential velocity (17.1)
12. Composition (17.3)
13. Lifetime & age (17.8)

For each property listed to the left I will describe:

a) The value for the Sun
b) Range of values for other stars
c) How it's measured
d) Theory behind interpretation of measurement.

Table 17-5
Measuring the Stars

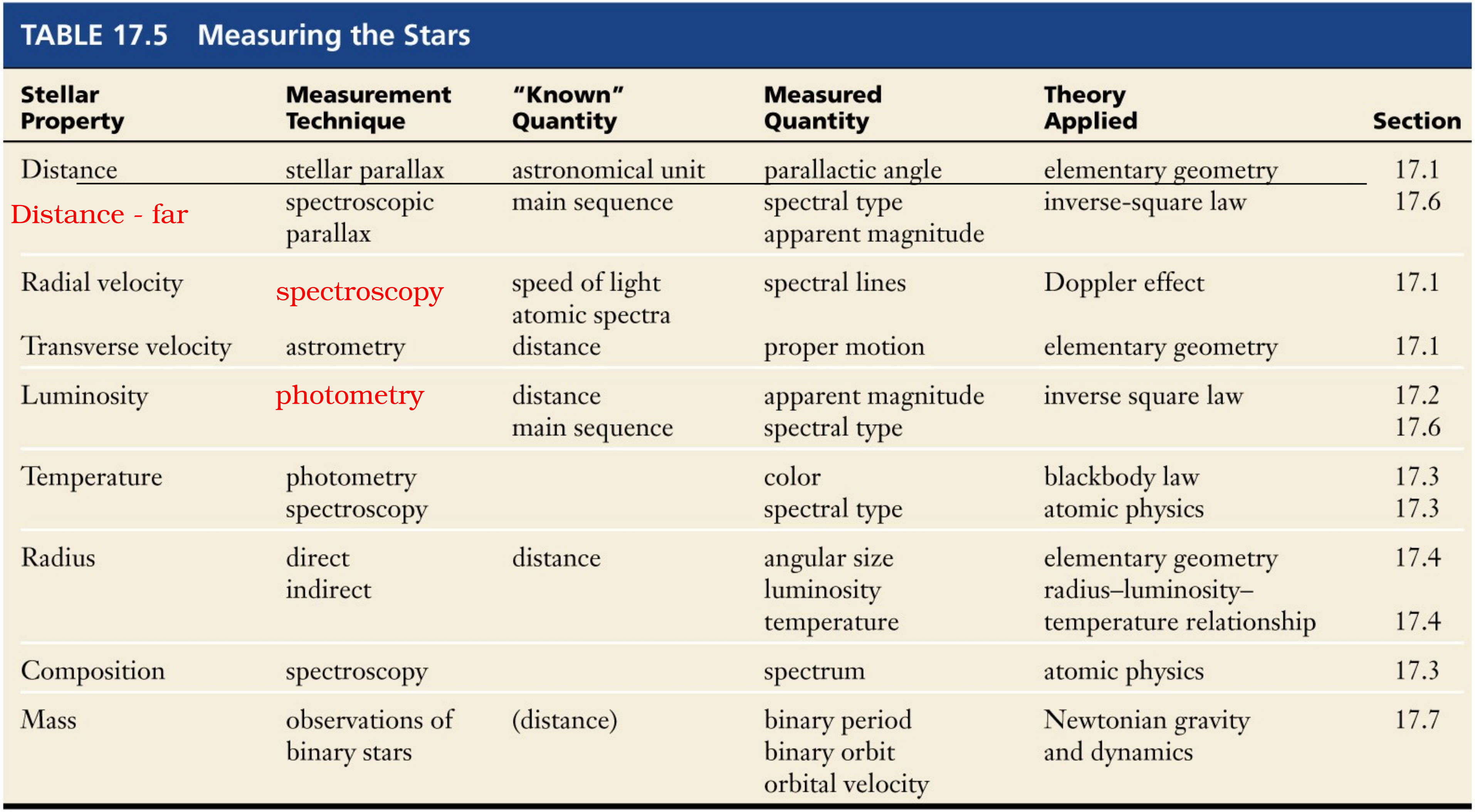


TABLE 17.5 Measuring the Stars

Stellar Property	Measurement Technique	"Known" Quantity	Measured Quantity	Theory Applied	Section
Distance	stellar parallax	astronomical unit	parallactic angle	elementary geometry	17.1
Distance - far	spectroscopic parallax	main sequence	spectral type apparent magnitude	inverse-square law	17.6
Radial velocity	spectroscopy	speed of light atomic spectra	spectral lines	Doppler effect	17.1
Transverse velocity	astrometry	distance	proper motion	elementary geometry	17.1
Luminosity	photometry	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

Table 17-6
Key Properties of Some Well-Known Main-Sequence Stars

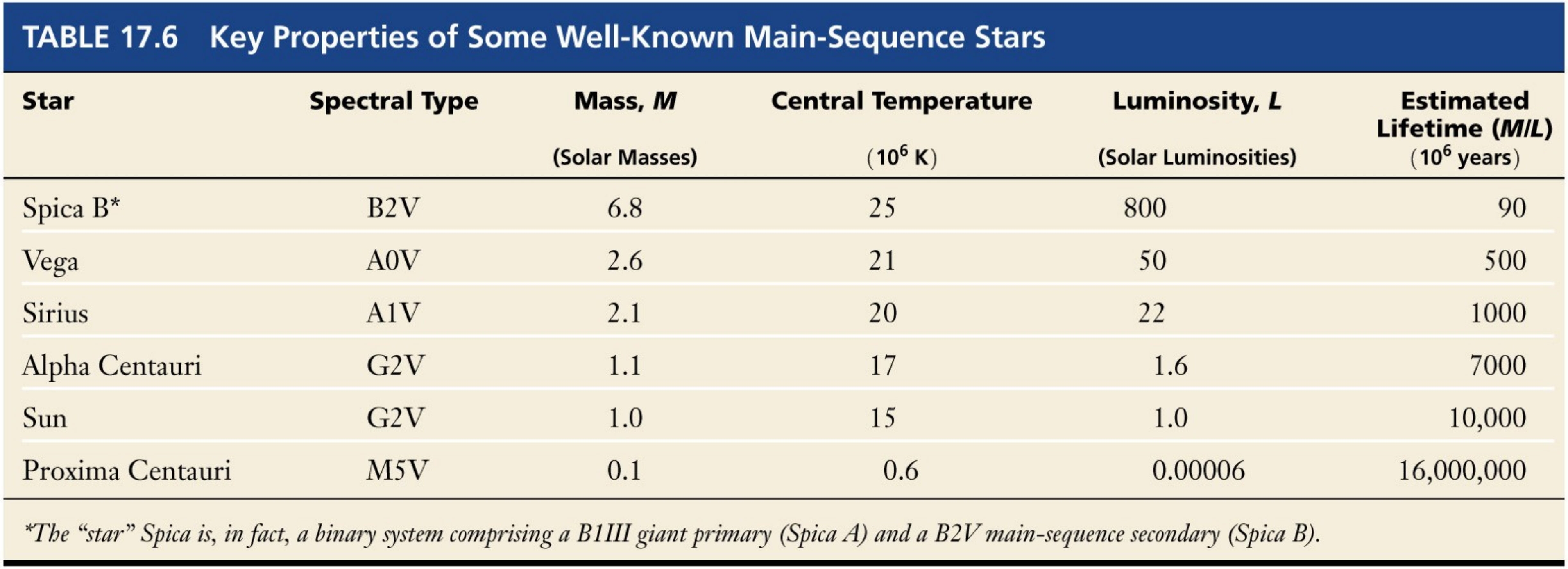


TABLE 17.6 Key Properties of Some Well-Known Main-Sequence Stars

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).*

1. Distances to nearby stars

a) Value for Sun.*

93,000,000 miles or 150,000,000 km.

This is only 1.5 X 10^{-5} LY.

b) Range of values for other stars.

Closest: 4.3 LY for Proxima Centauri. (4.22 LY)

Farthest: Stars exist in galaxies which have distances out to the edge of the observable universe (about 10,000,000,000 LY). However, the technique of "Stellar Parallax" is limited by the resolution of our imagers. It can only be measured out to ~200 pc (600 LY) from the ground, The HIPPARCOS satellite "measured parallaxes to over 1000 pc, encompassing over a million stars." (See Hipparcos image, slide 6.)

c) How its measured (next page)

d) Theory behind interpretation of measurement. (next page)

* green text means information from Astronomy Today 5th Ed.

1. Distances to nearby stars *(cont.)*

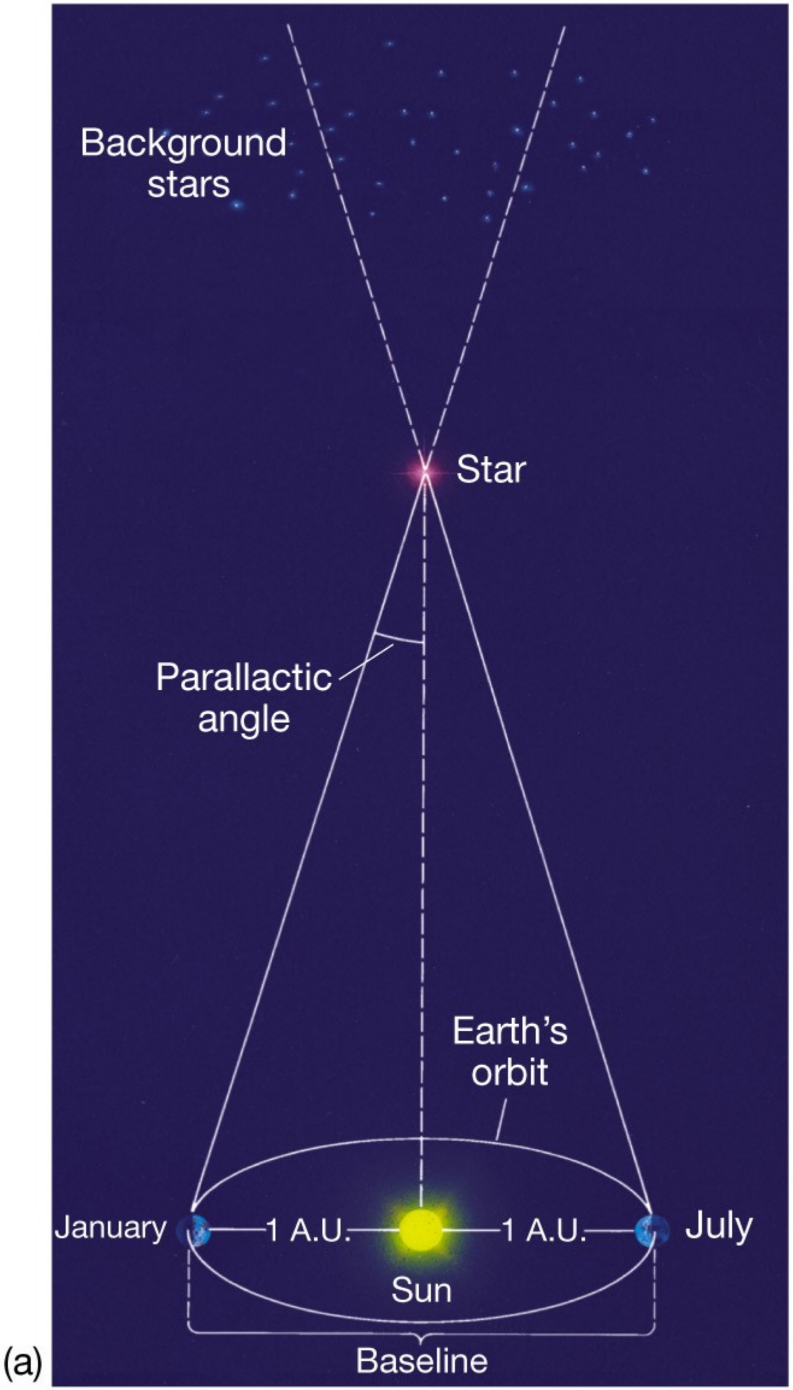
c) How it's measured

Trigonometric parallax: image a nearby star (on film or CCD) repeatedly as the Earth orbits the Sun at a distance of 1 AU (1.5×10^{11} m). The star will appear to trace out an ellipse relative to background stars. The semi-major axis of that ellipse, measured in arcseconds, is the parallax, π, of the star. The farther the star, the smaller the parallax.

Spectroscopic parallax: [See slides 57-60] If the luminosity of a star can be determined (from spectra), and its brightness is known (from photometry), its distance can be calculated.

d) Theory behind interpretation of measurement.

The theory is simple geometry, not physics. See Fig. 17-1. $D = 1/\pi$ where D is distance (in parsecs) and π is the parallax angle (in arcseconds). [See Slide 7.]



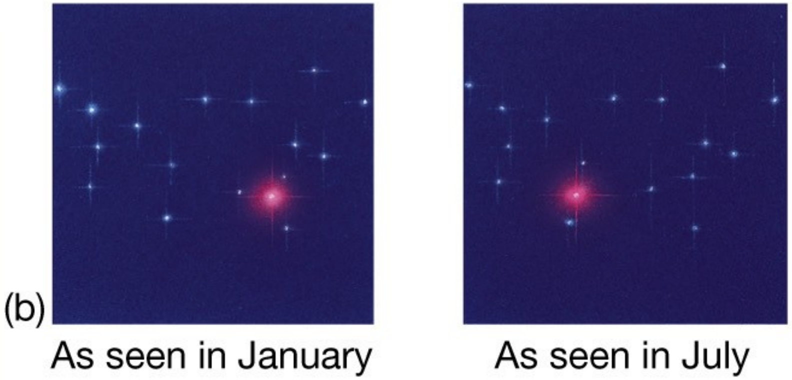
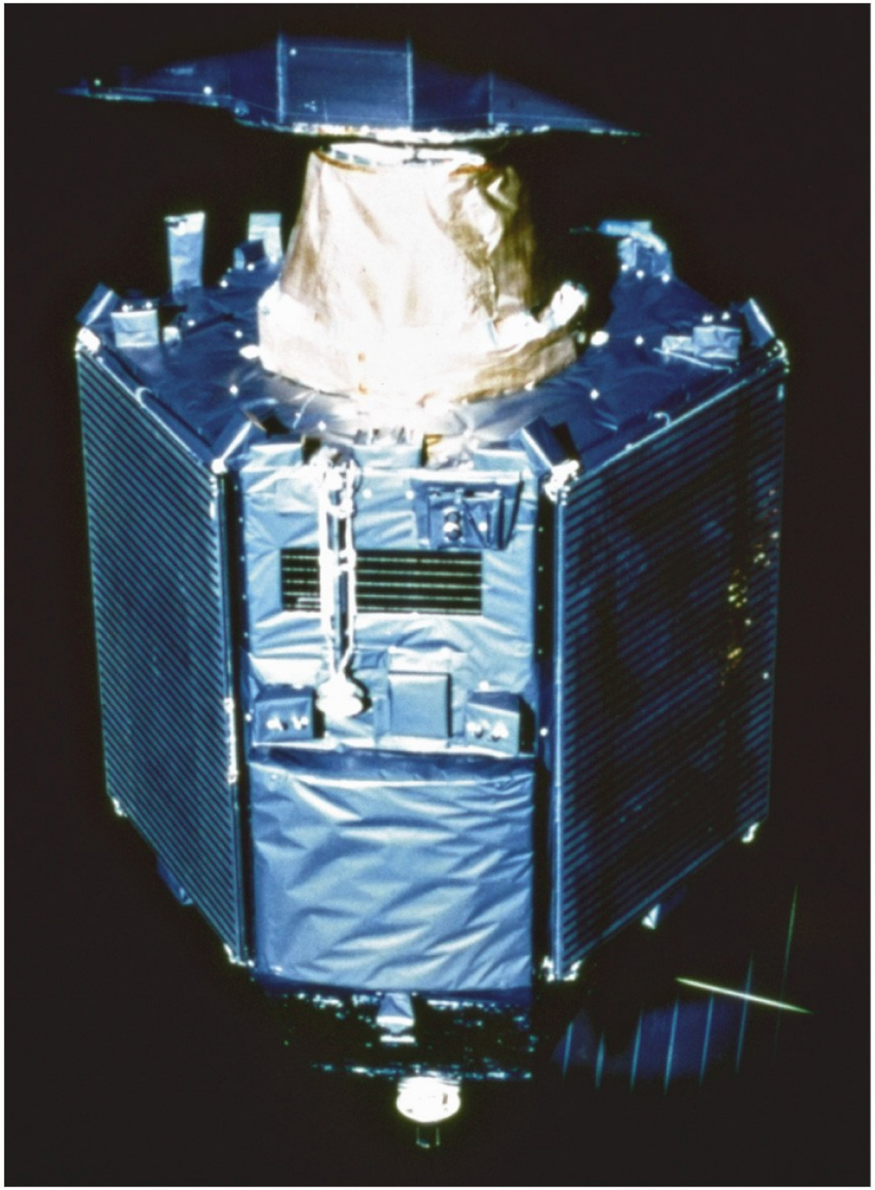


Figure 17-1
Stellar Parallax

Note that the parallax (here "parallactic angle") is ½ of the angular shift of the star between January and July.

Discovery 17-2
The *Hipparcos* Mission



Hi Precision PARrallax COllecting Satellite.
118,000 stars with a median precision of +-1 mas at d=1000 pc.
Another 2,500,000 stars at lower precision.
[See solar apex movie.]

GAIA
distances to 1 *billion* stars out to 9000 pc!

Launched Oct 2013.
Reached L2 in Jan 2014.
Now gathering data!
Extended mission to 2025

GAIA mission

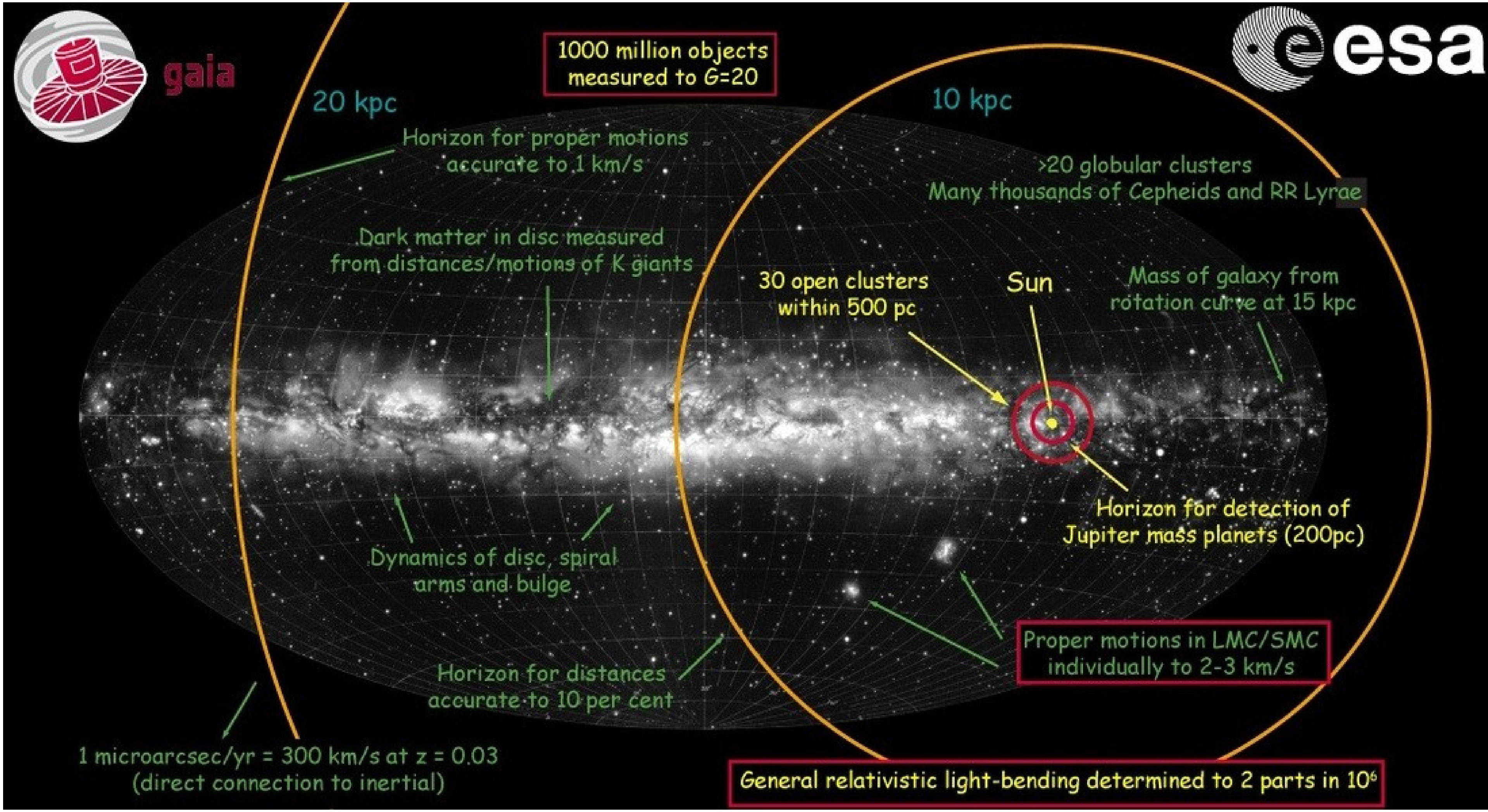


Figure 17-17
Stellar Distances and the “Distance Ladder”

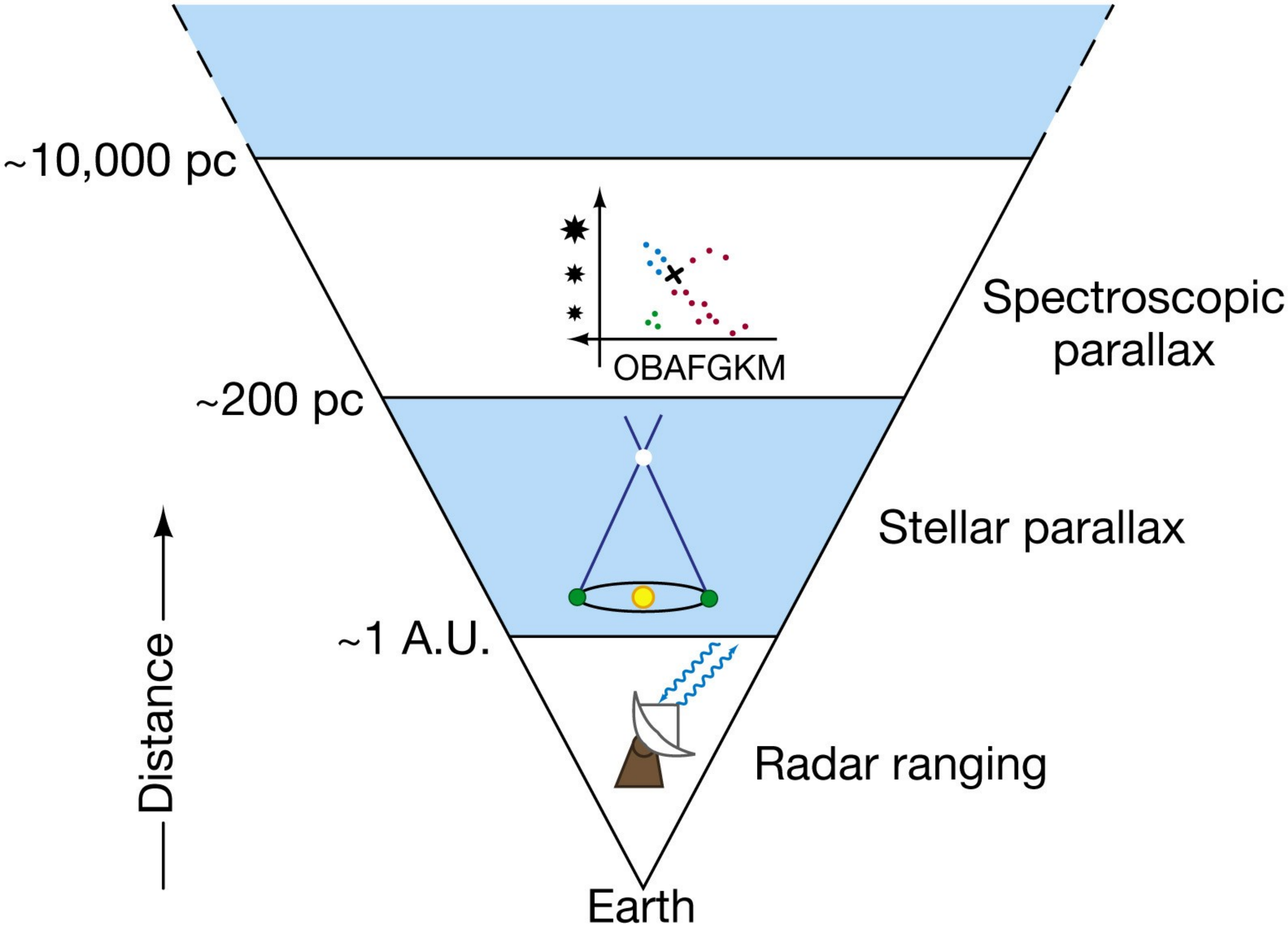
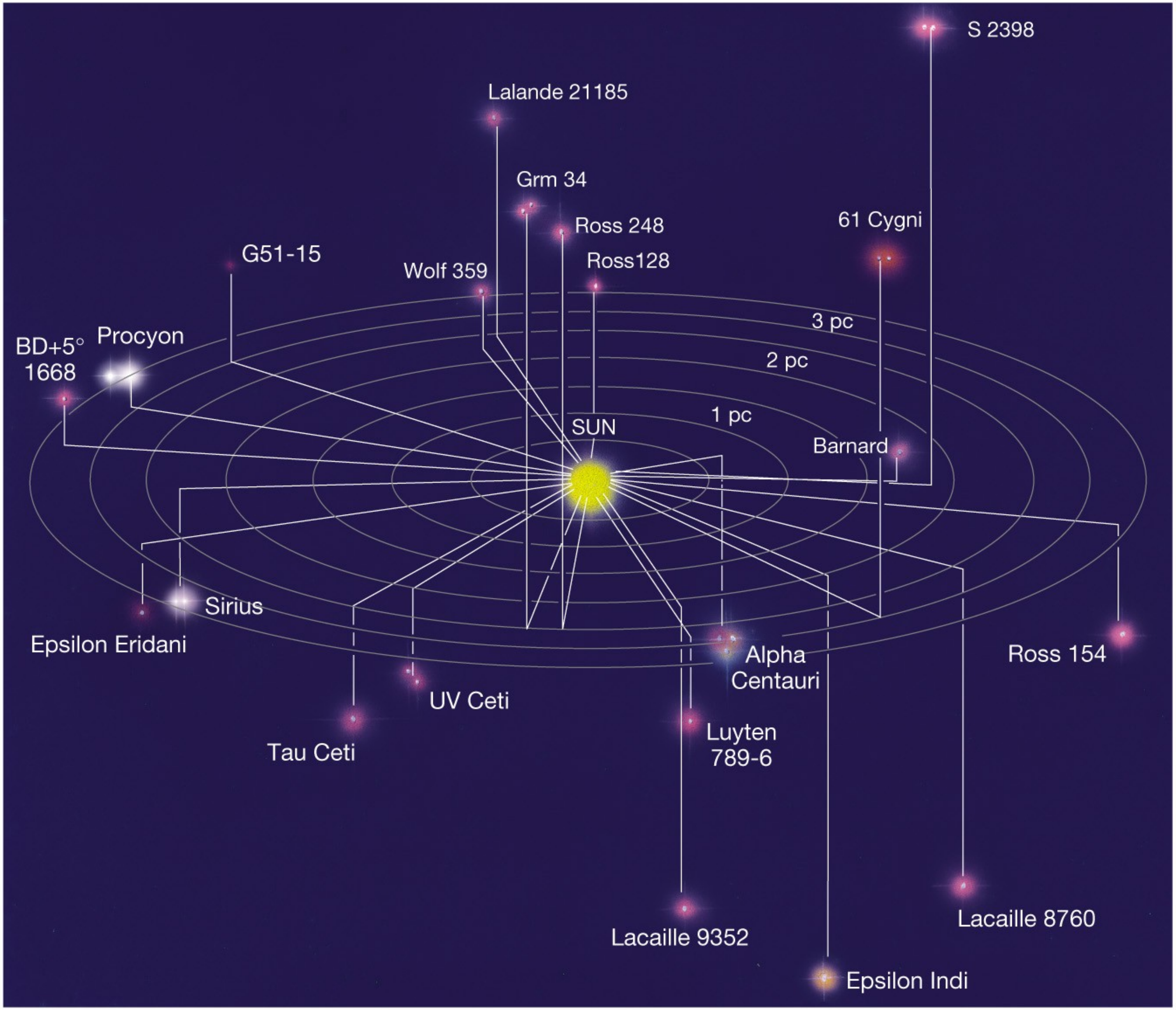


Figure 17-2: The Solar Neighborhood



2. Apparent magnitude, m, and flux, F

a) Values for the Sun

m = -26.7, F = Solar Constant = 1360 W/m^2

b) Range of values for other stars

Sun is brightest (-26.7), we can observe others as faint as m=+30.0.

Next brightest star is -1.5 (Sirius).

Planets can appear even brighter, and the Moon is -12.5.

c) How its measured

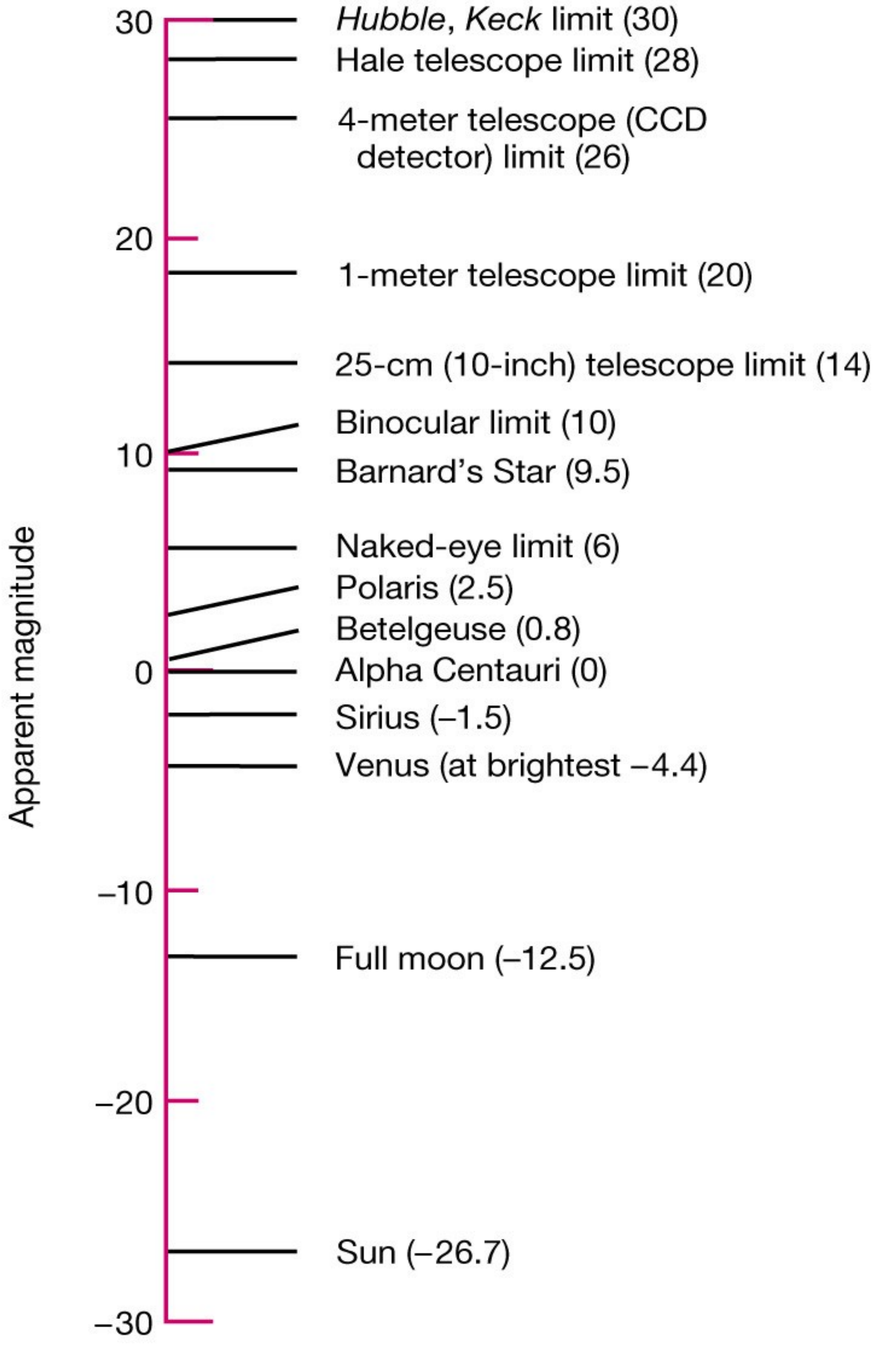
Use photometry to get a flux (counts per second). Apparent magnitude is then given by m = -2.5 log (flux/reference flux).

d) Theory behind interpretation of measurement.

The counts that we receive in a detector tell us the intensity or flux of photons at the Earth. Flux is not an intrinsic property of the star unless it is measured at its surface, in which case it obeys Stefan's law: $F = \sigma T^4$ (where σ=5.67x10^{-8} W/m^2K^4)

Figure 17-7
Apparent Magnitude

(lower case m)



Stars A and B have same *m*, flux or brightness, but different Luminosity

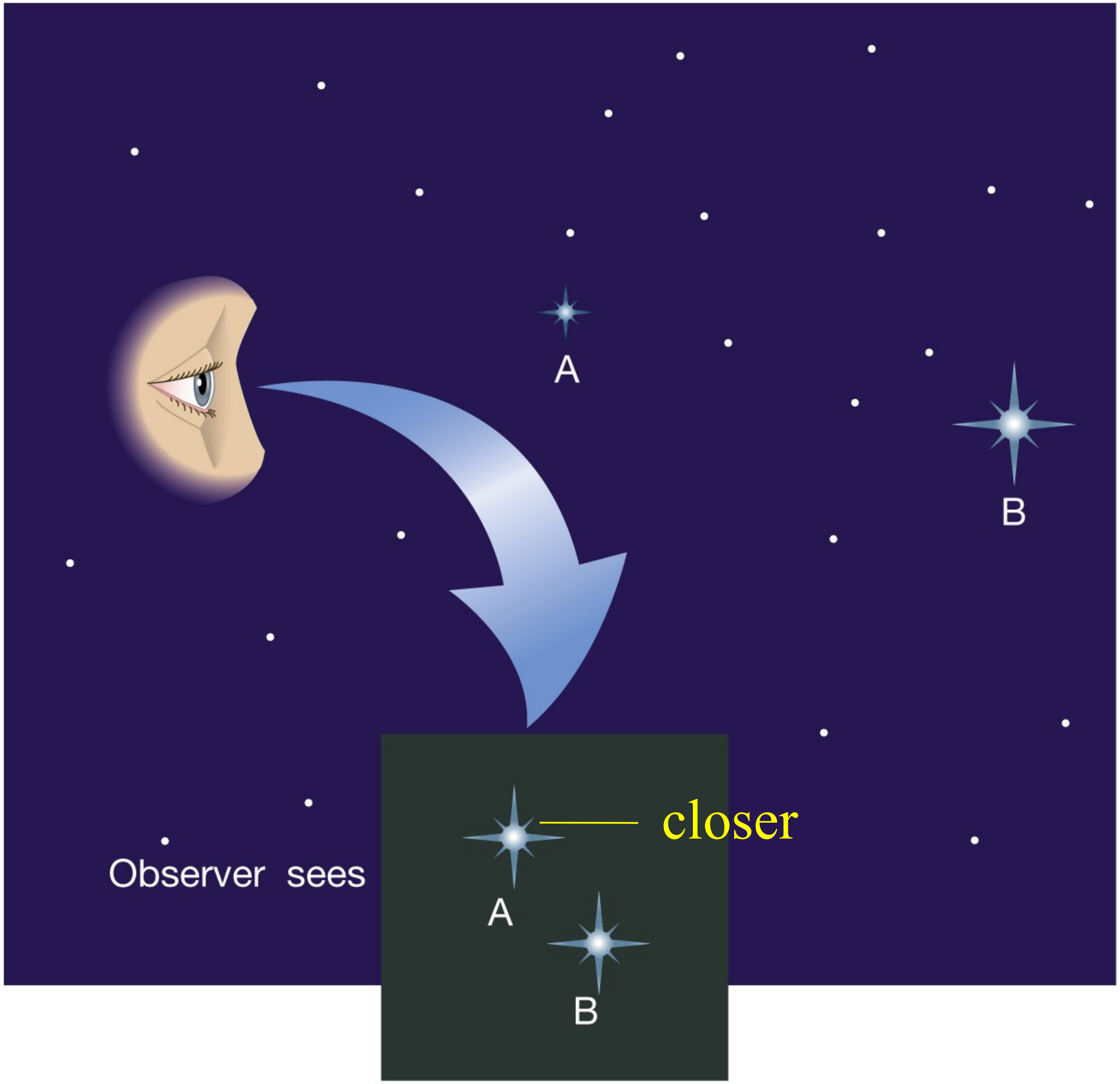
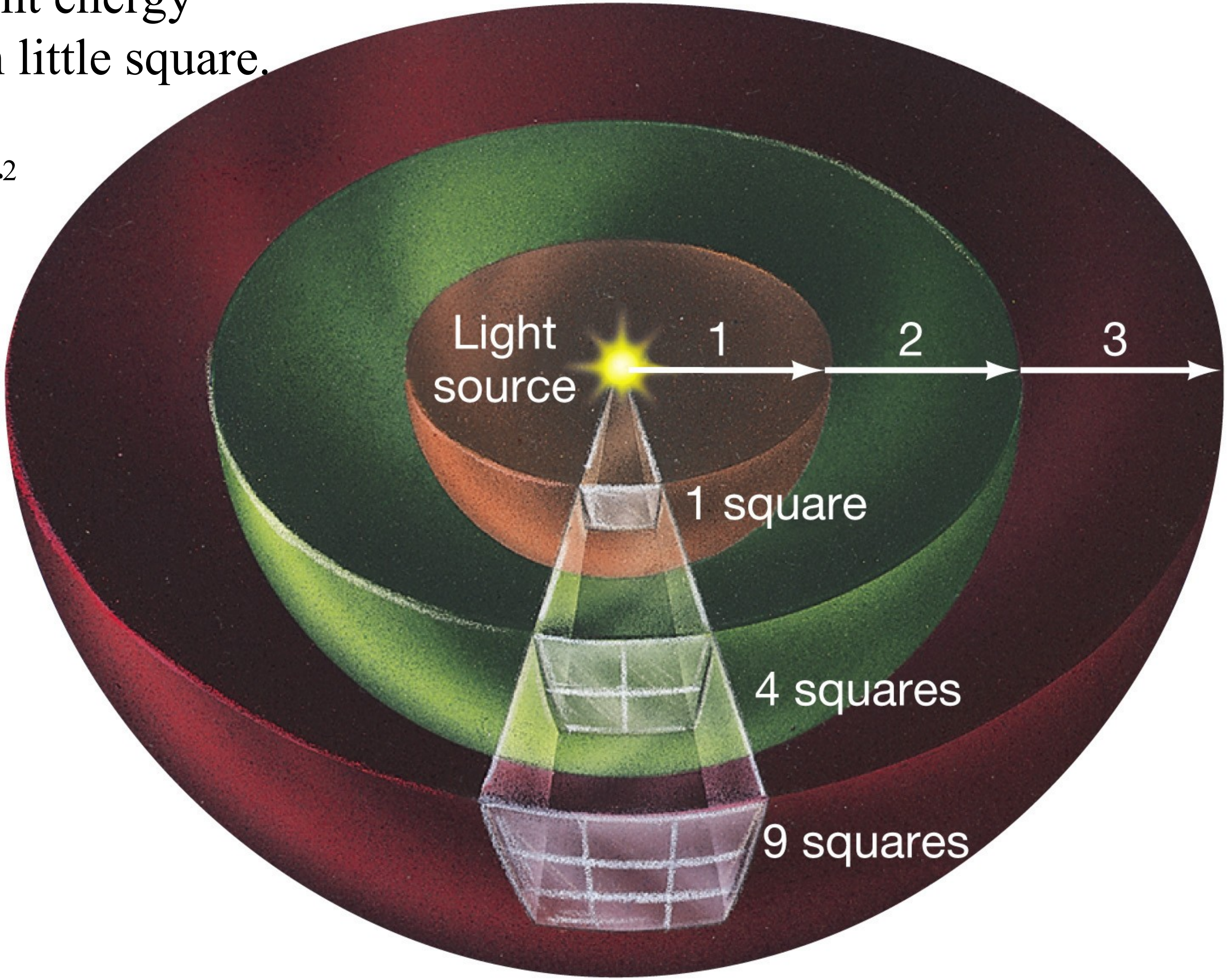


Figure 17-5
Inverse-Square Law for Flux

F = light energy rcvd in little square.

$F \sim 1/r^2$



3. Luminosity and Absolute Magnitude

a) Values for the Sun

$L = 3.9 \times 10^{26}$ W = 1 $L_\odot$

$M_\odot = 4.83$

b) Range of values for other stars

Red dwarf (M-type) stars have the lowest L among main sequence stars, $L \sim .001\ L_\odot$

Blue giant (O-type) stars have the largest L among main sequence stars, $L \sim 10^5\ L_\odot$

Non-main sequence stars can be fainter (white dwarfs, neutron stars) and brighter (supergiants, novae, supernovae).

c) How it's measured

d) Theory behind interpretation of measurement.

3. Luminosity and Absolute Magnitude

c) How its measured

Use photometry to get the apparent brightness (flux or m), then get a distance from parallax. Solve for luminosity with

$$L = 4\pi d^2 (flux)$$

OR take a spectrum which gives the spectral type and luminosity class. This allows one to roughly locate the star on the H-R diagram (a plot of L vs spectral type). Read off L.

To convert from L to absolute magnitude, M, you use some nasty looking equations [$M=-2.5\log(L/Lref)$, or $M=m-5\log(d/10pc)$]. But the basic idea is that M is defined as the relative magnitude that a star would have if its distance was d=10 pc. We call 10 pc the Standard Reference Distance (SRD).

3. Luminosity and Absolute Magnitude

d) Theory behind interpretation of measurement.

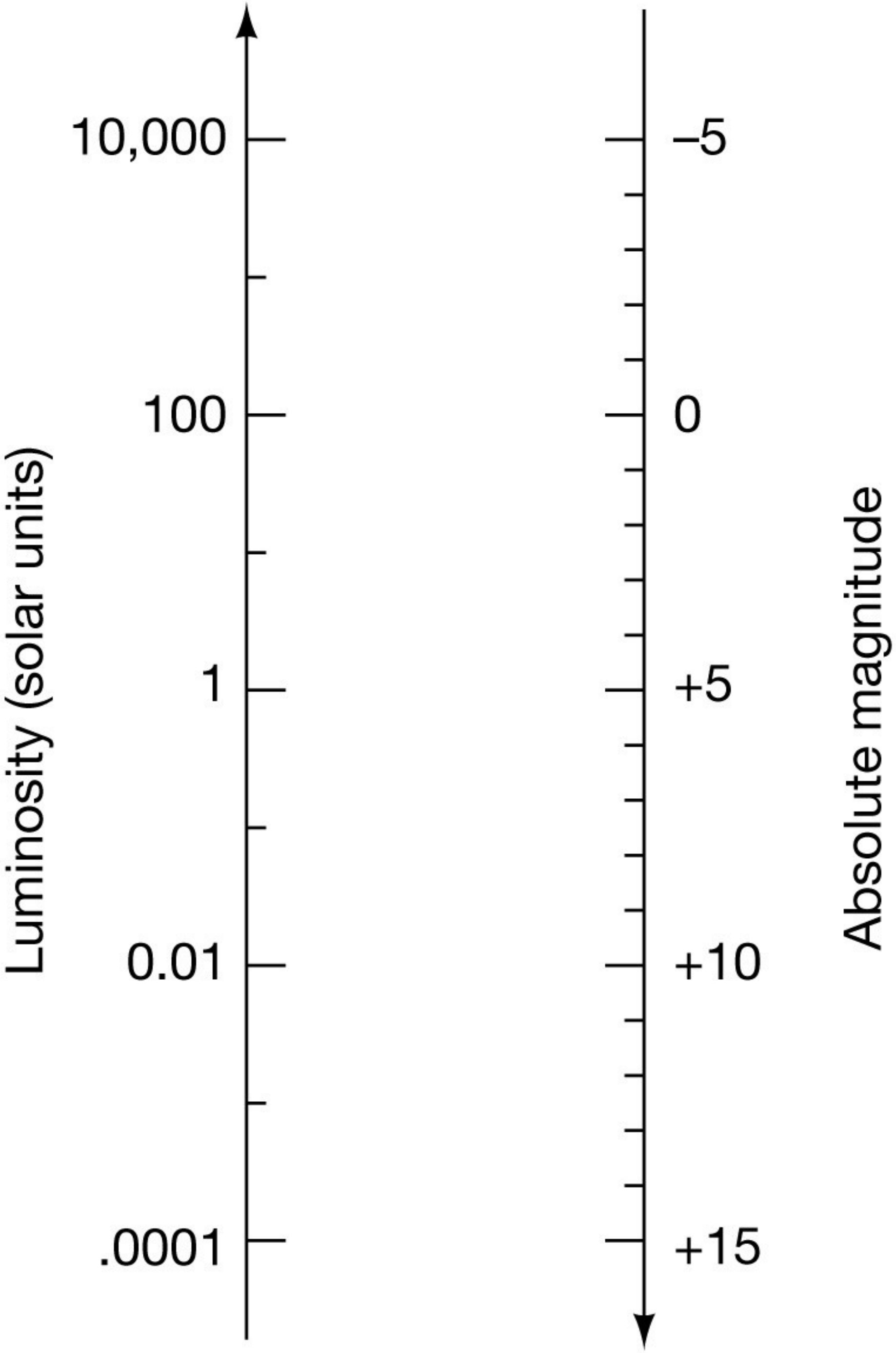
Luminosity, L is the total amount of light energy leaving the object – in all directions! This is the "power" of the star; an intrinsic property, unlike flux which depends on distance. L relates to flux and distance as follows:

$$L = 4\pi d^2 (flux)$$

Absolute Magnitude, *M* is another measure of luminosity which uses the magnitude system (1 step = 2.512X, etc.). The absolute magnitude, *M*, of a star is equal to its relative magnitude, *m*, if the star were placed at the distance d=10 pc. $m<M$ if the star is closer than 10pc. $m>M$ if the star is farther than 10 pc.

M is related to the relative magnitude and the distance by:

$$M=m-5\log(d/10pc)$$



More Precisely 17-1
More on the Magnitude Scale

4. Surface (and core) temperature

a) Values for the Sun

Tsurface= 5800 K

Tcore= 15×10^6 *K*

b) Range of values for other stars

Tsurface ranges from 3000 to 50000 K for main sequence stars.

T*core* ranges from about 9×10^6 to 600×10^6 (C fusion).

c) How it's measured

Tsurf:

a) use multi-color photometry (i.e. image through color filters). The colors correlate with surface temperature (blue=hot, red=cool).

b) take a spectrum and measure the strengths of many different absorption lines.

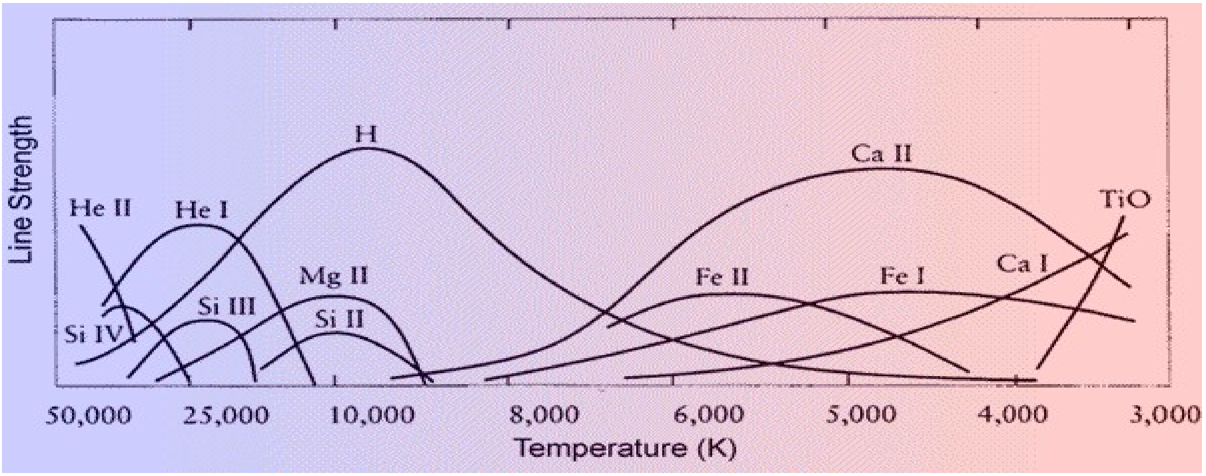
4. Surface and core temperature

d) Theory behind interpretation of measurement.

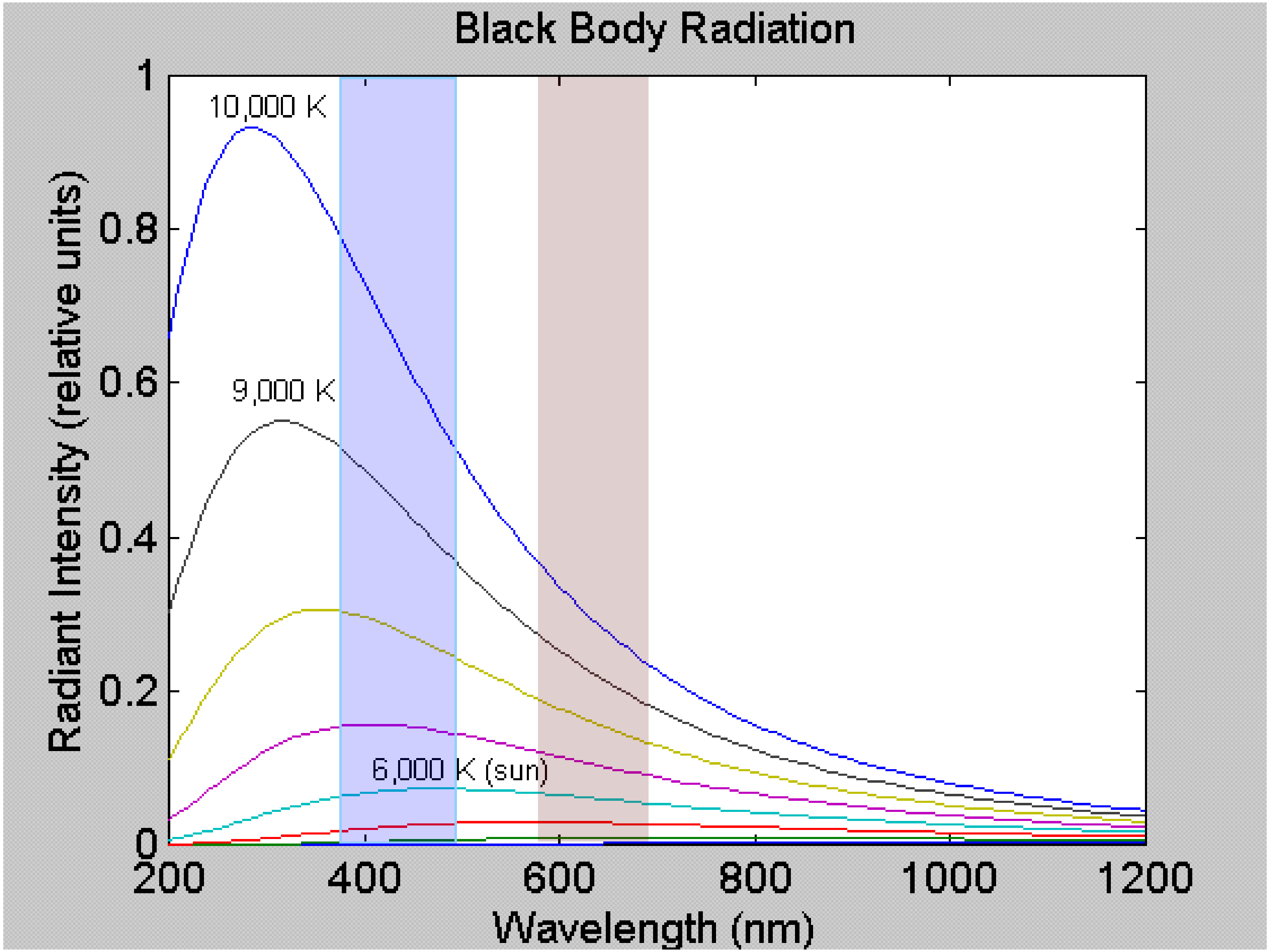
Tsurf:

a) Wien's law – for a blackbody, each temperature produces a unique continuous spectrum with a unique peak wavelength (λmax). The shape of this spectrum across the filter bandwidths determines the colors measured.

b) atomic physics – the *line strength* of absorption lines created by a given element depends on the gas temperature. (See the "Balmer thermometer" below.)



Blackbody Curves and B and V filters



Compare with Fig 17-9 which shows intensity vs frequency.

Table 17-1
Stellar Colors and Temperatures

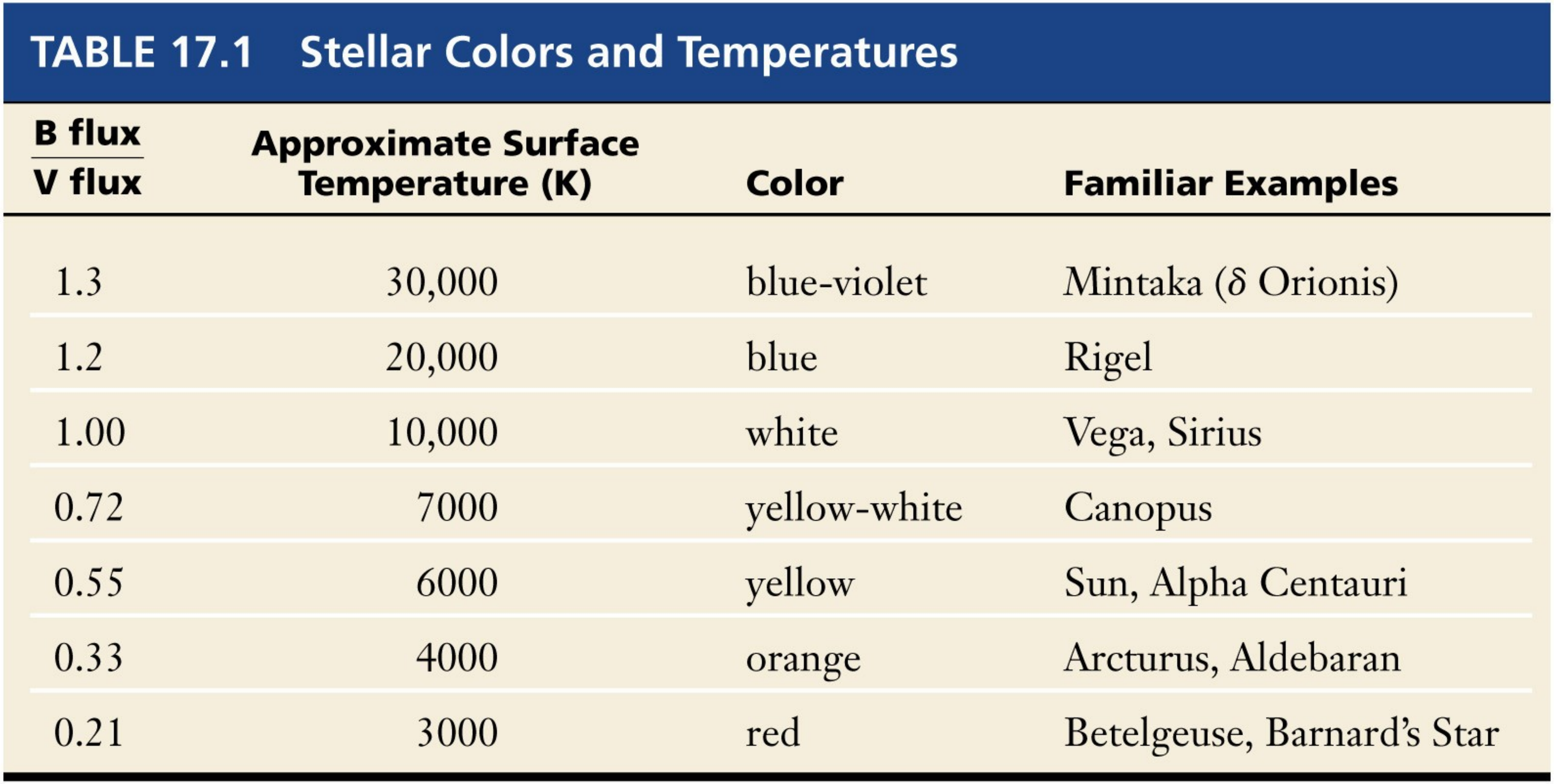


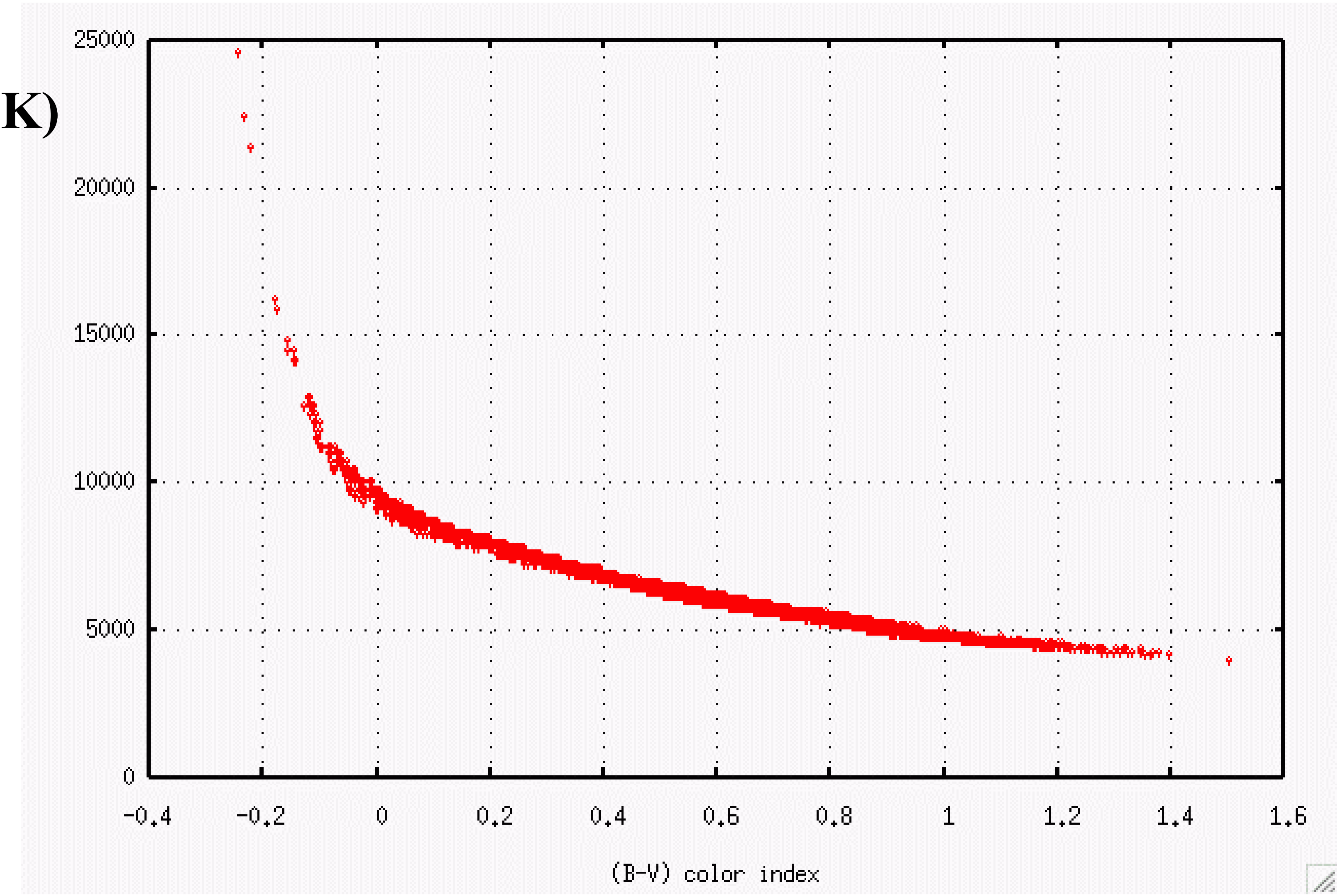
TABLE 17.1 Stellar Colors and Temperatures

$\frac{\text{B flux}}{\text{V flux}}$	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

How temperature relates to color index

……

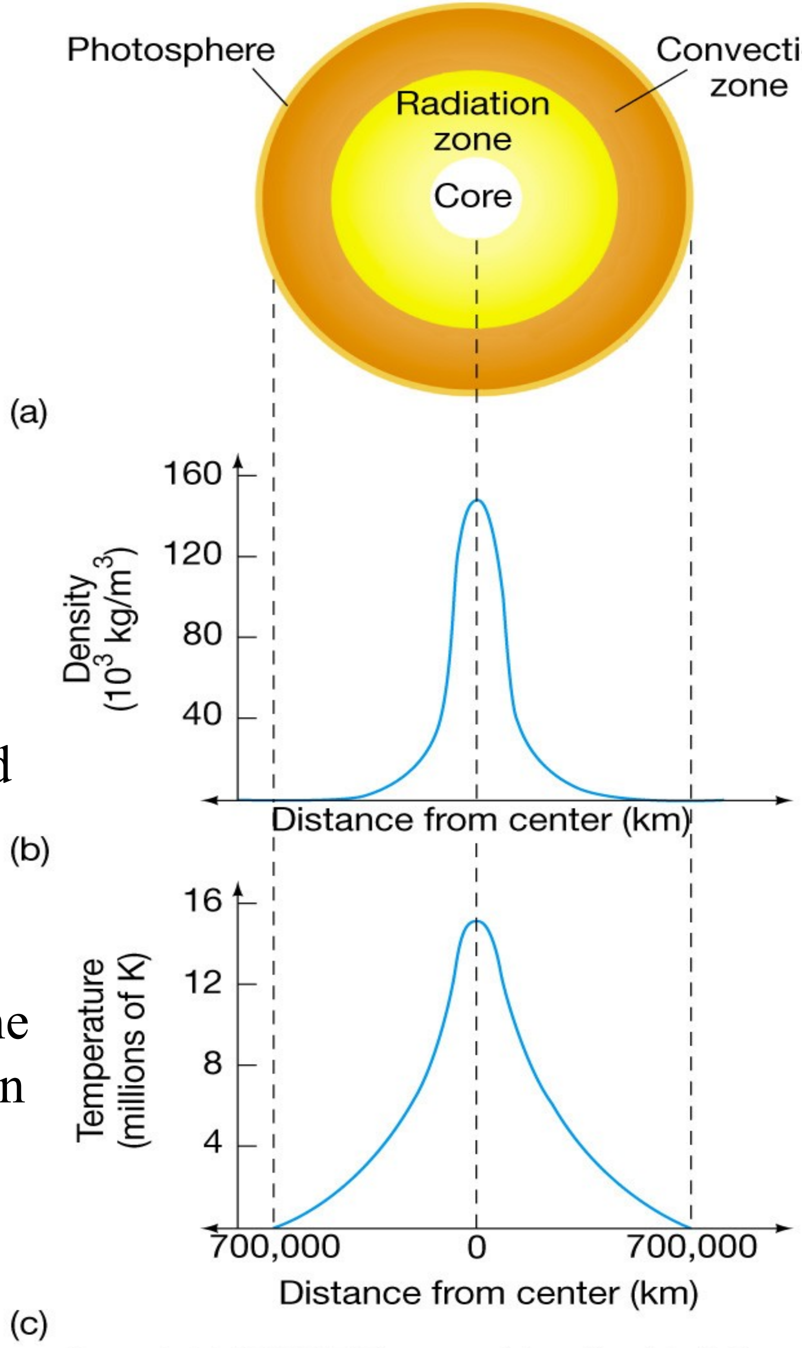
T (K)



Core temperature

is found by creating a stellar model. You observe things like radius, total mass, and luminosity, and these will constrain the model.

The model is calculated from 4 “structural” equations and knowledge of the dependence of the Hydrogen fusion rate on temperature and density.



5. Spectral types and colors

a) Values for the Sun

Spectral Type = G2 V

Color = yellow-white (qualitatively), B/V = 0.55 (quantitatively). (B-V=0.65 actual color index).

b) Range of values for other stars

Spectral types are OBAFGKM, so range is from O to M

Colors range from red to blue (qualitatively), B/V ranges from 0.2-1.3.

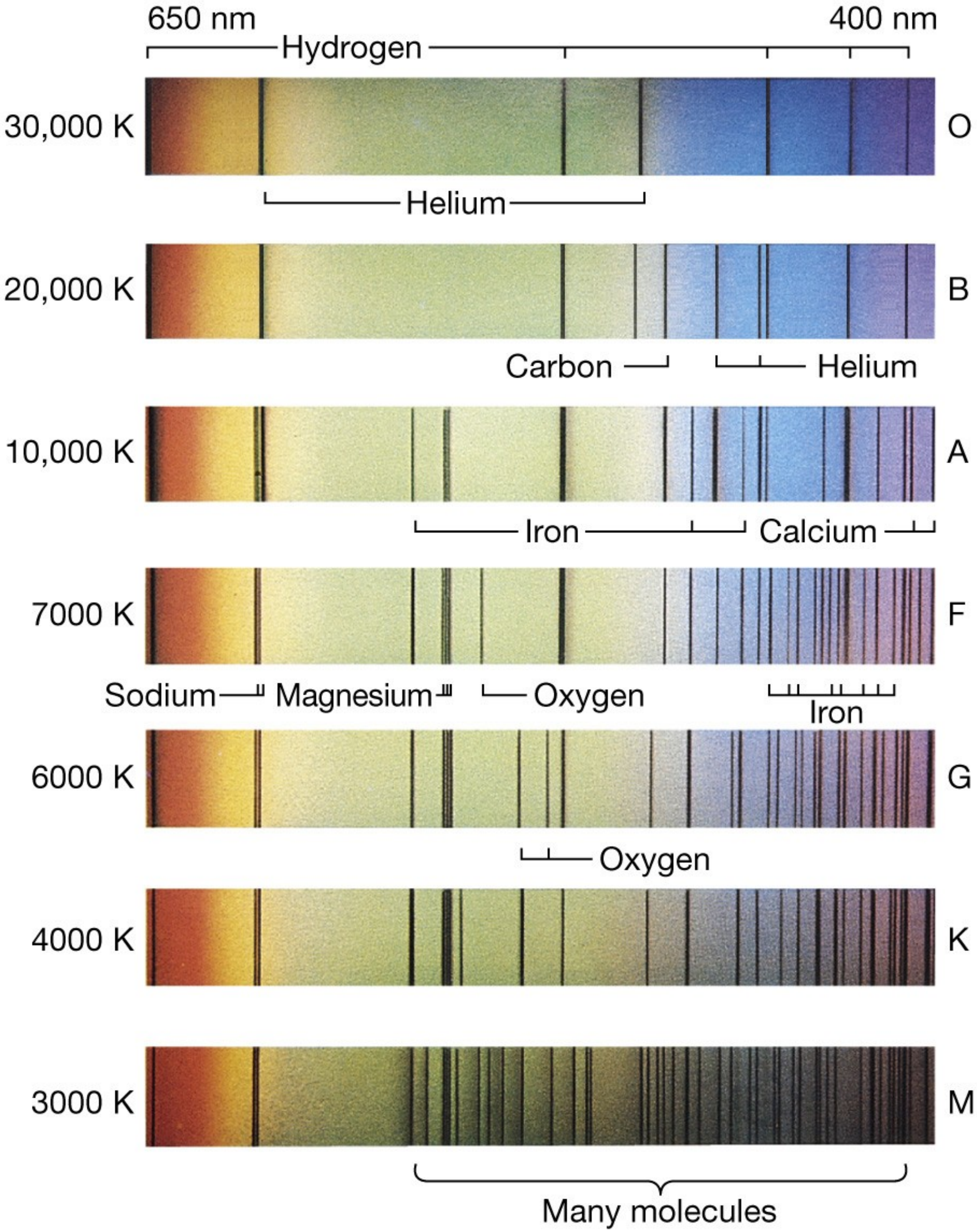
(B-V = -0.4 to 2.1)

c) How it's measured

Spectral Types: spectroscopy, measure absorption line strengths.

Colors: use multi-color photometry (ie. record images or counts through color filters).

Figure 17-10
Stellar Spectra



5. Spectral types and colors

d) Theory behind interpretation of measurement.

Spectral Types: the letters O,B,A, etc were originally arranged based on H line strength (no theory). Later, atomic theory (e.g, the Bohr model) was used to arrange the spectral types in order of decreasing surface temperature. (See the "Balmer thermometer".)

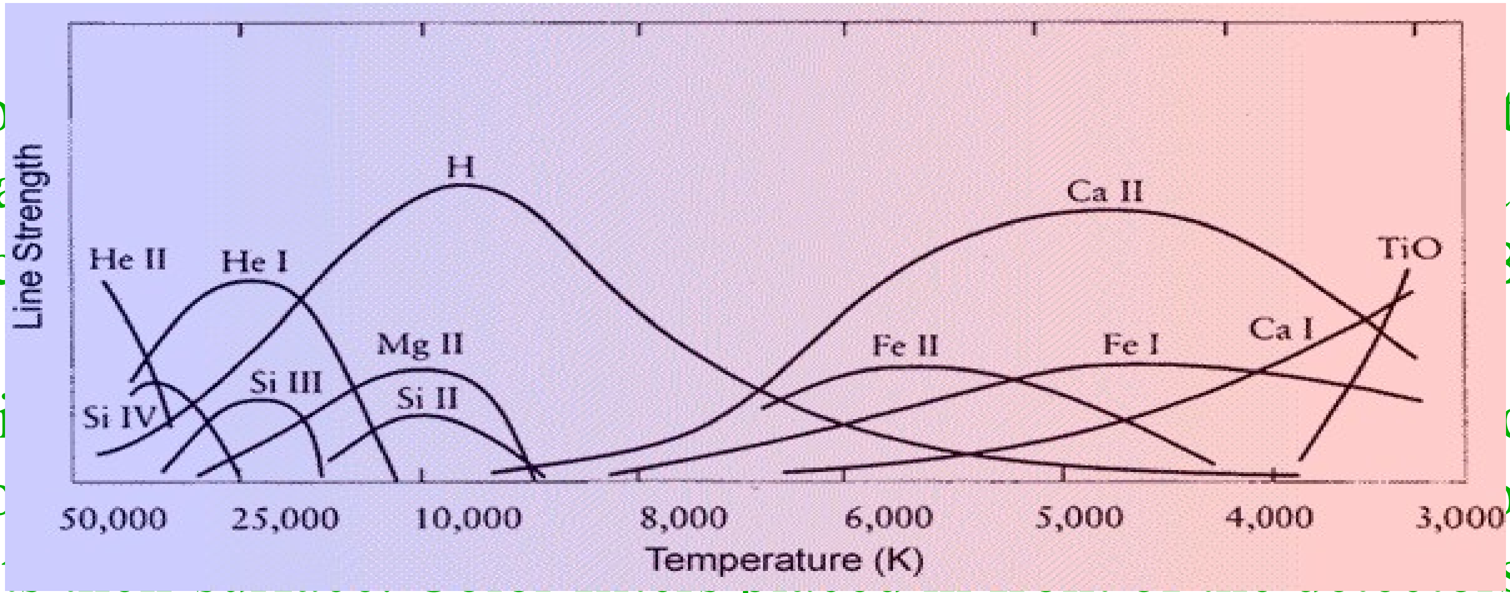
Colors: perceived colors are explained with the physiology of the eye (specialized cone cells in the retina respond to either R, G, or B and the brain combines these signals to give us the sensations of ROYGBIV.)

Quantitative colors, namely B/V or B-V, are measured with photometry. The counts in photometers or CCDs are proportional to the flux of light that hits their surface. Color filters placed in front of the detectors allow a narrow range of frequencies to pass, so that counts are proportional to the light we call "blue" or "red" or "UV", etc.

5. Spectral types and colors

d) Theory behind interpretation of measurement.

Spectral Types: the letters O,B,A, etc were originally arranged based on H line strength (no theory). Later, atomic theory (e.g, the Bohr model) was used to arrange the spectral types in order of decreasing surface temperature. (See the "Balmer thermometer".)



Colo … the eye (specia … nd the brain c … BIV.)

Quanti … ometry. The co … f light that hi … s allow a narrow range of frequencies to pass, so that counts are proportional to the light we call "blue" or "red" or "UV", etc.

Figure 17-8
Star Colors

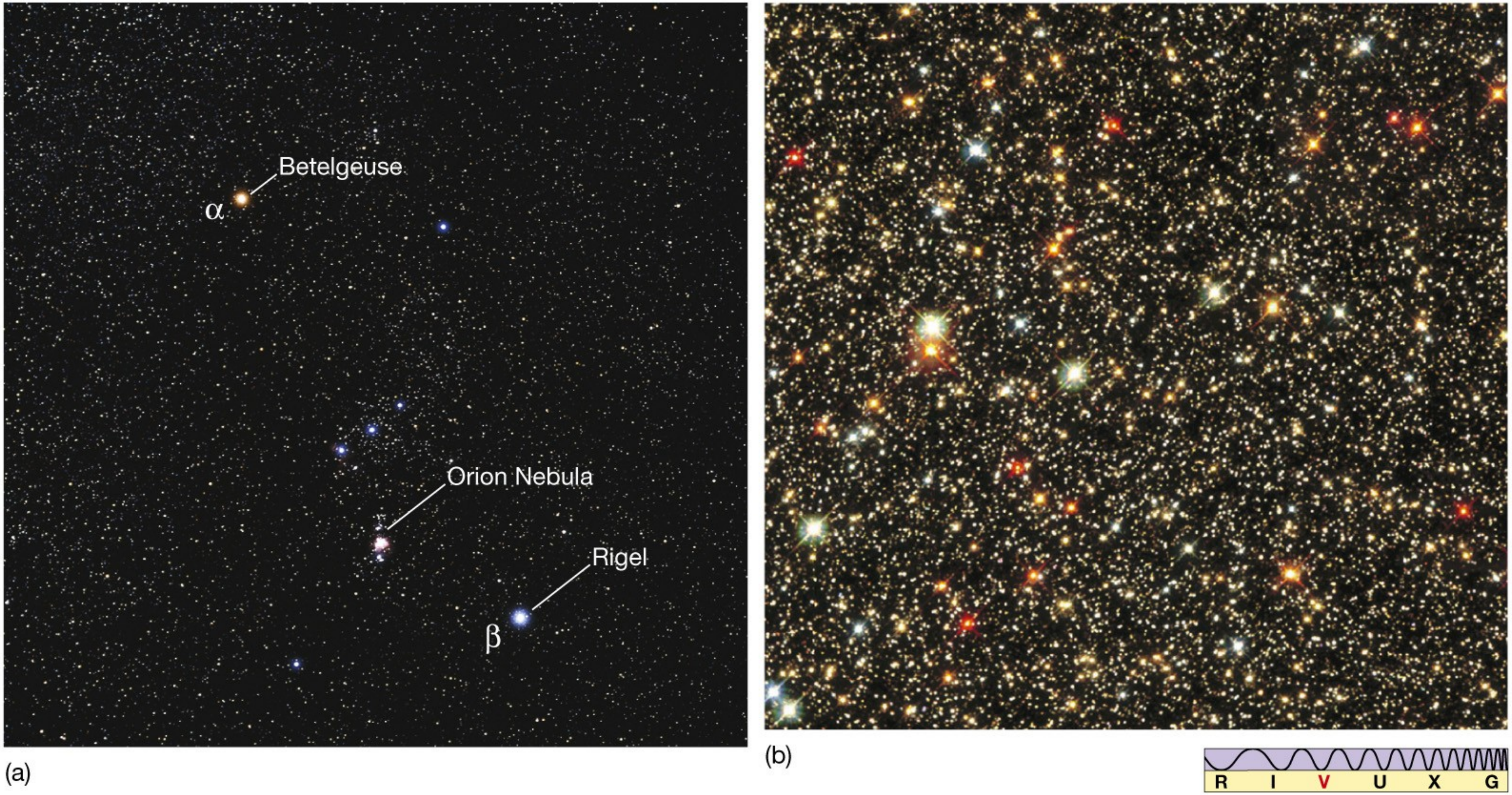


Table 17-2
Stellar Spectral Classes

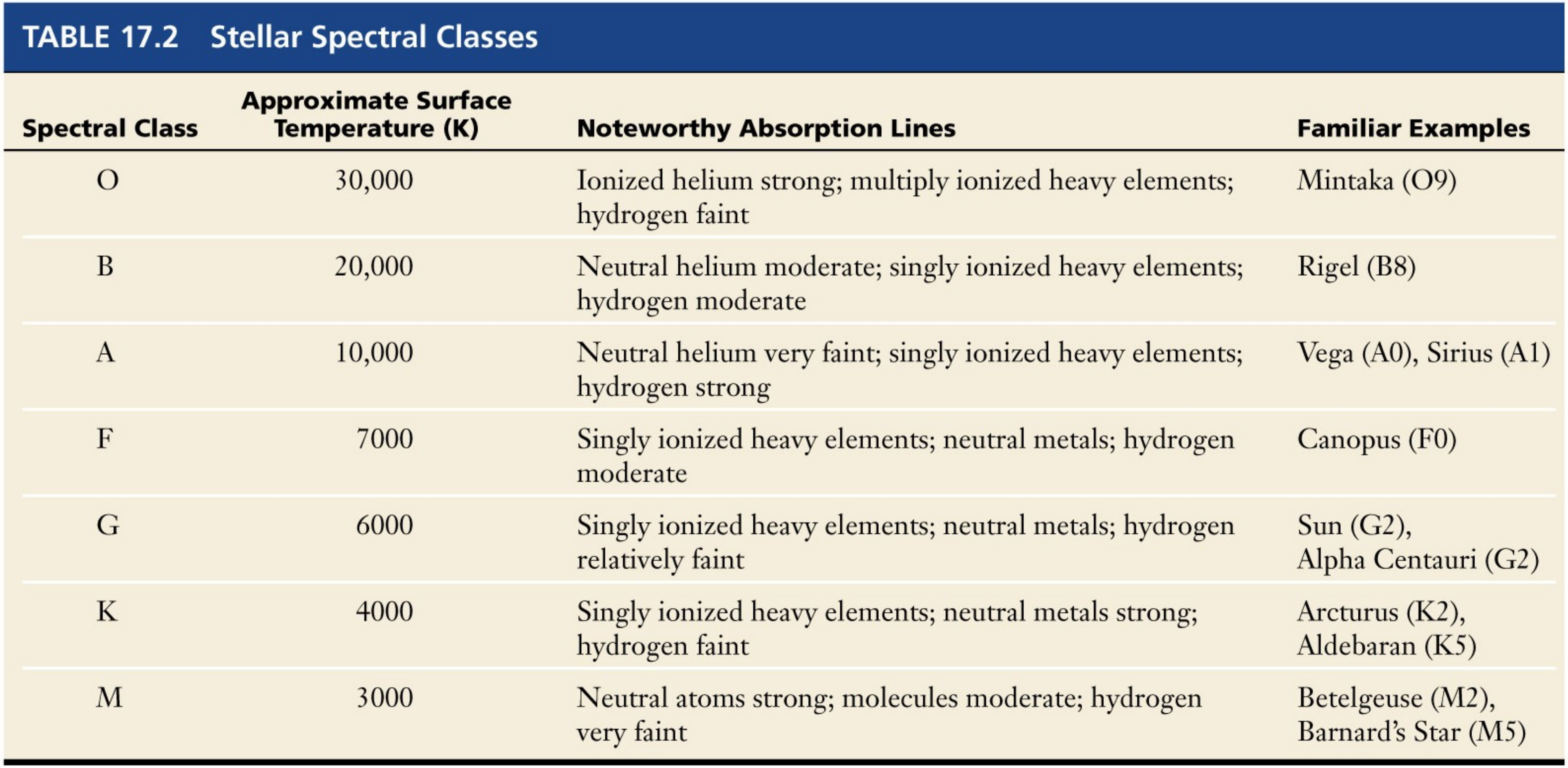


TABLE 17.2 Stellar Spectral Classes

Spectral Class	Approximate Surface Temperature (K)	Noteworthy Absorption Lines	Familiar Examples
O	30,000	Ionized helium strong; multiply ionized heavy elements; hydrogen faint	Mintaka (O9)
B	20,000	Neutral helium moderate; singly ionized heavy elements; hydrogen moderate	Rigel (B8)
A	10,000	Neutral helium very faint; singly ionized heavy elements; hydrogen strong	Vega (A0), Sirius (A1)
F	7000	Singly ionized heavy elements; neutral metals; hydrogen moderate	Canopus (F0)
G	6000	Singly ionized heavy elements; neutral metals; hydrogen relatively faint	Sun (G2), Alpha Centauri (G2)
K	4000	Singly ionized heavy elements; neutral metals strong; hydrogen faint	Arcturus (K2), Aldebaran (K5)
M	3000	Neutral atoms strong; molecules moderate; hydrogen very faint	Betelgeuse (M2), Barnard's Star (M5)

6. Radius

a) Values for the Sun

R⊙ = 7x10^5 km

b) Range of values for other stars

0.05 R⊙ - ~50 R⊙ (on main sequence)

0.005 – 1000 R⊙ (off main sequence, including white dwarfs and supergiants)

c) How it's measured

Directly: by imaging and finding distance through parallax (or another means). Interferometry can provide resolution better than the seeing limit.

Indirectly: by finding the luminosity (which requires apparent brightness and a distance to be measured with photometry and parallax), and measuring the temperature (which requires spectroscopy).

Also: eclipsing binary stars!

d) Theory behind interpretation of measurement.

Direct: angle subtended (in radians) = diameter/distance

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

6. Radius

a) Values for the Sun

$R_\odot = 7\text{x}10^5$ km

b) Range of values for other stars

0.05 $R_\odot$ - ~50 $R_\odot$ (on main sequence)

0.005 – 1000 $R_\odot$ (off main sequence, including white dwarfs and supergiants)

c) How it's measured

Directly: by imaging and finding distance through parallax (or another means). Interferometry can provide resolution better than the seeing limit.

Indirectly: by finding the luminosity (which requires apparent brightness and a distance to be measured with photometry and parallax), and measuring the temperature (which requires spectroscopy).

Also: eclipsing binary stars!

d) Theory behind interpretation of measurement.

Direct: angle subtended (in radians) = diameter/distance

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

Figure 17-11
Betelgeuse

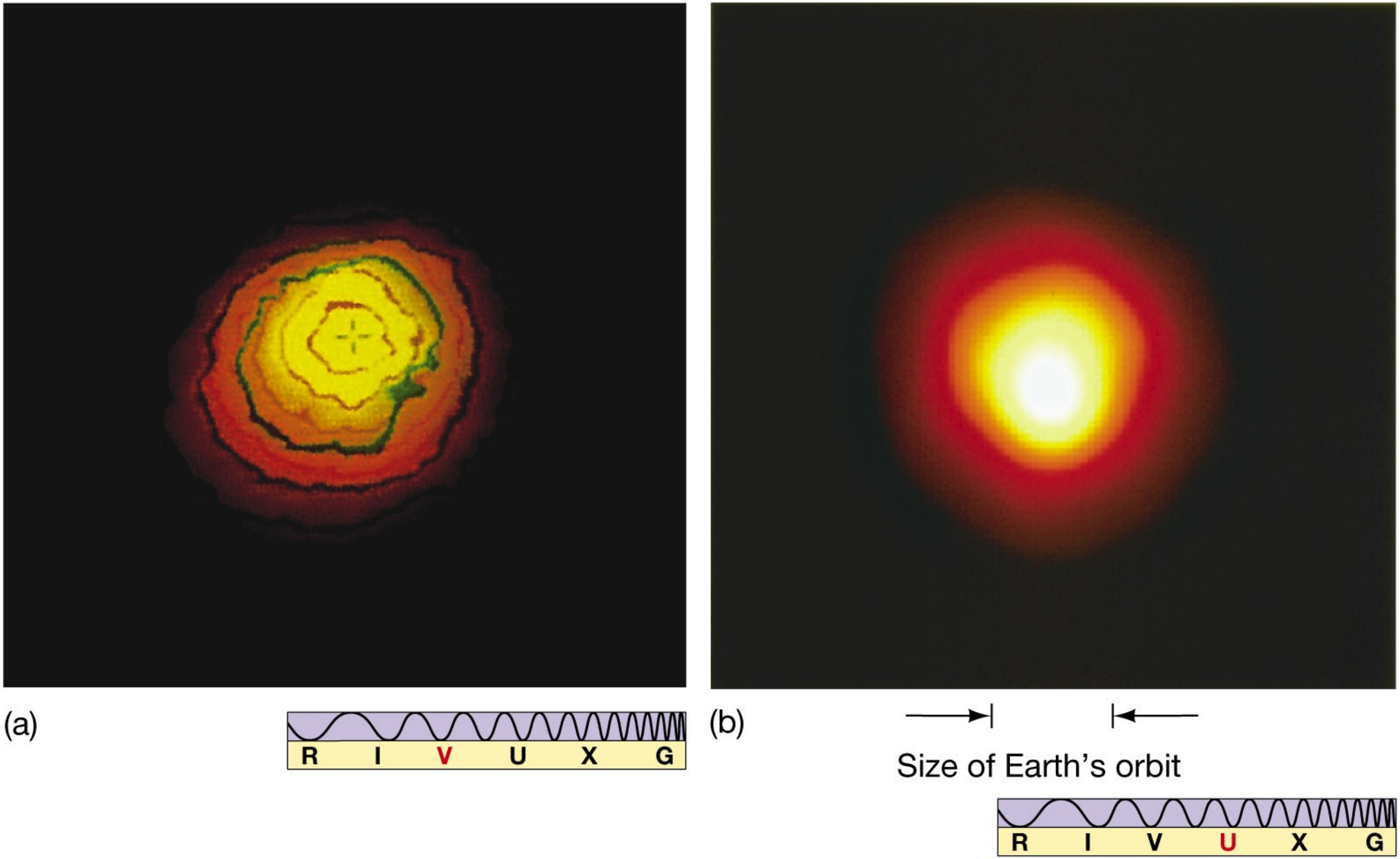
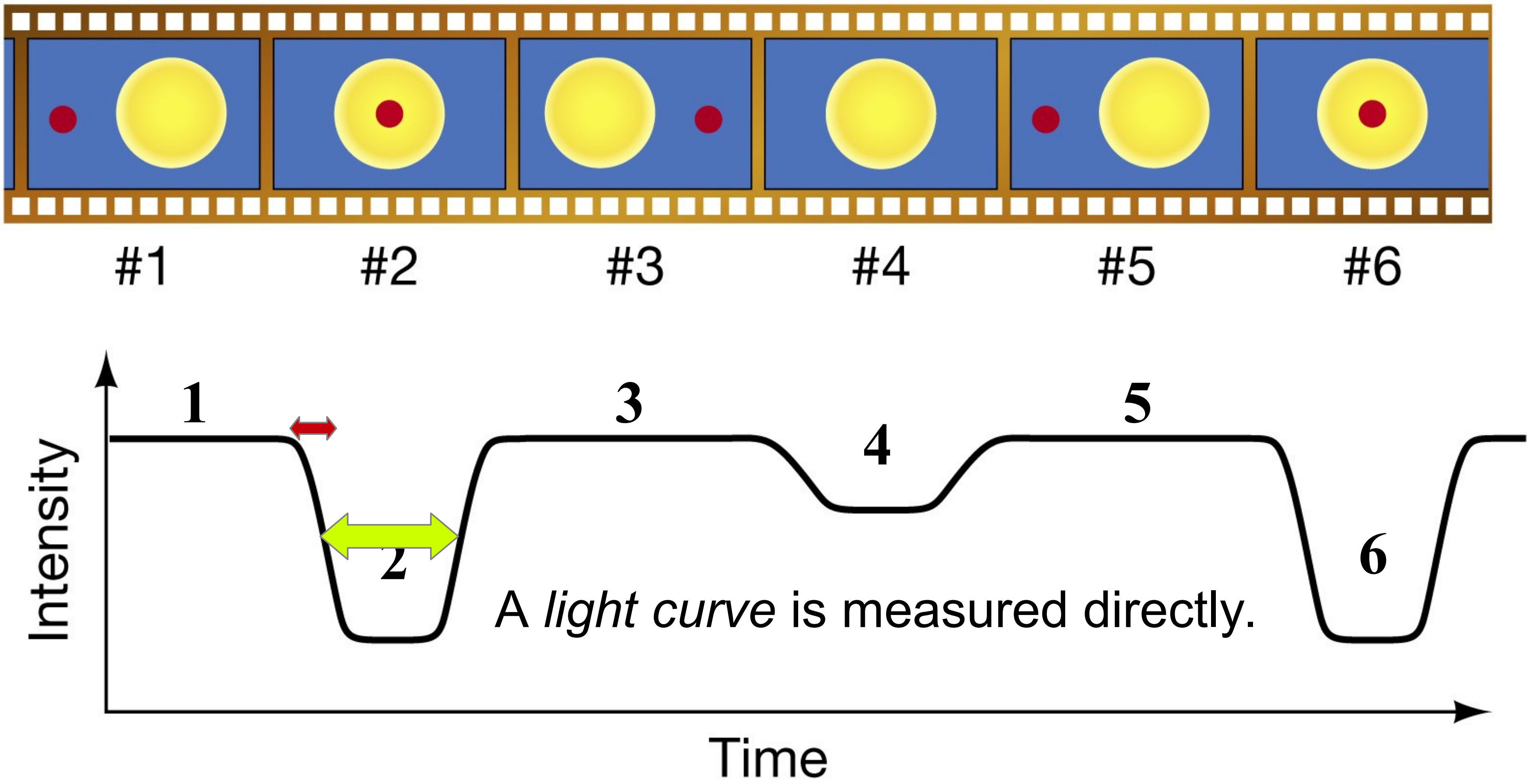
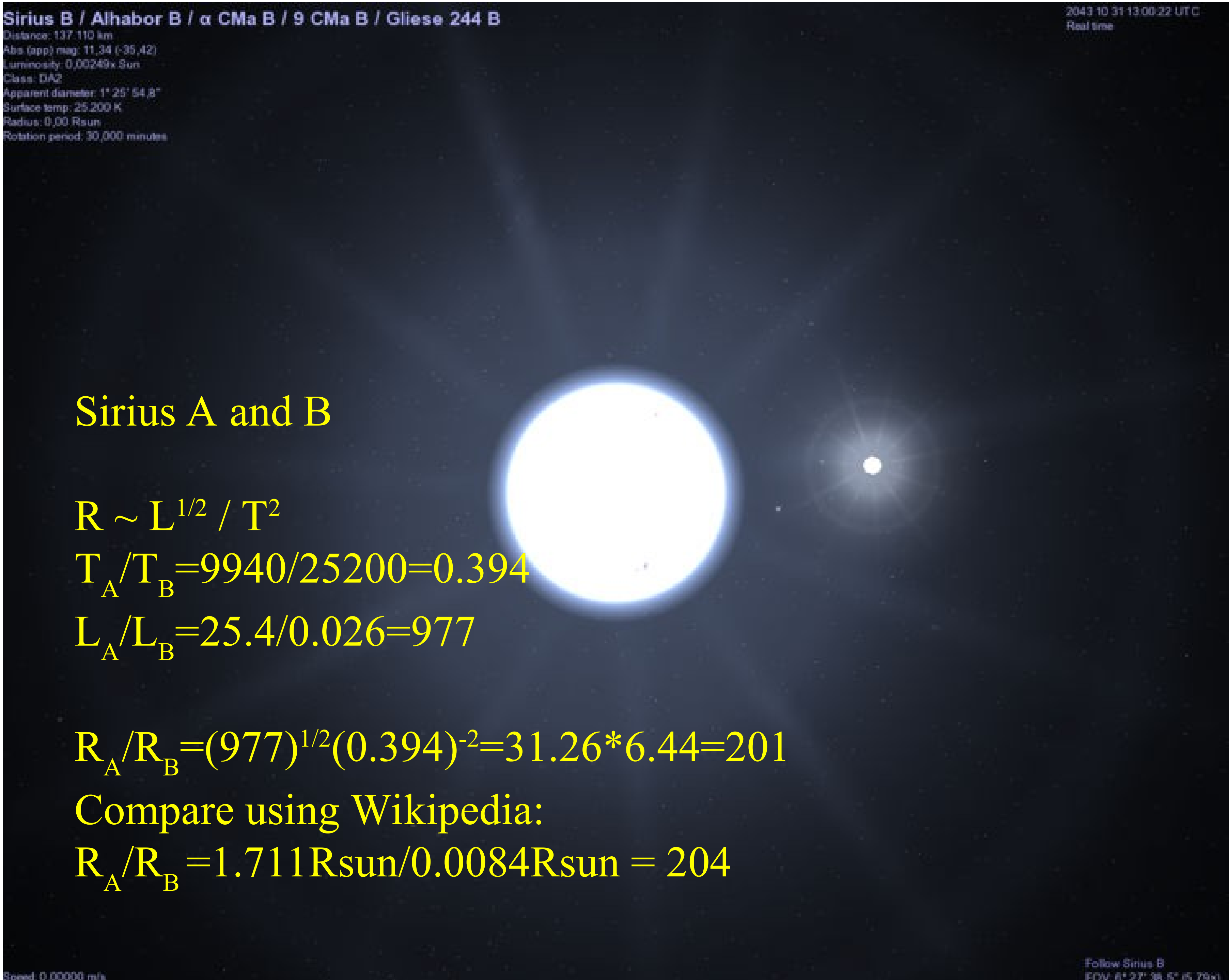


Figure 17-21
Eclipsing Binary

A 3rd way to measure a star's size ...



A *light curve* is measured directly.



Sirius B / Alhabor B / α CMa B / 9 CMa B / Gliese 244 B
Distance: 137 110 km
Abs (app) mag: 11,34 (-35,42)
Luminosity: 0,00249x Sun
Class: DA2
Apparent diameter: 1° 25' 54,8"
Surface temp: 25 200 K
Radius: 0,00 Rsun
Rotation period: 30,000 minutes

2043 10 31 13:00:22 UTC
Real time

Speed: 0.00000 m/s

Follow Sirius B
FOV: 6° 27' 38.5" (5.79x)

Sirius A and B

$R \sim L^{1/2} / T^2$

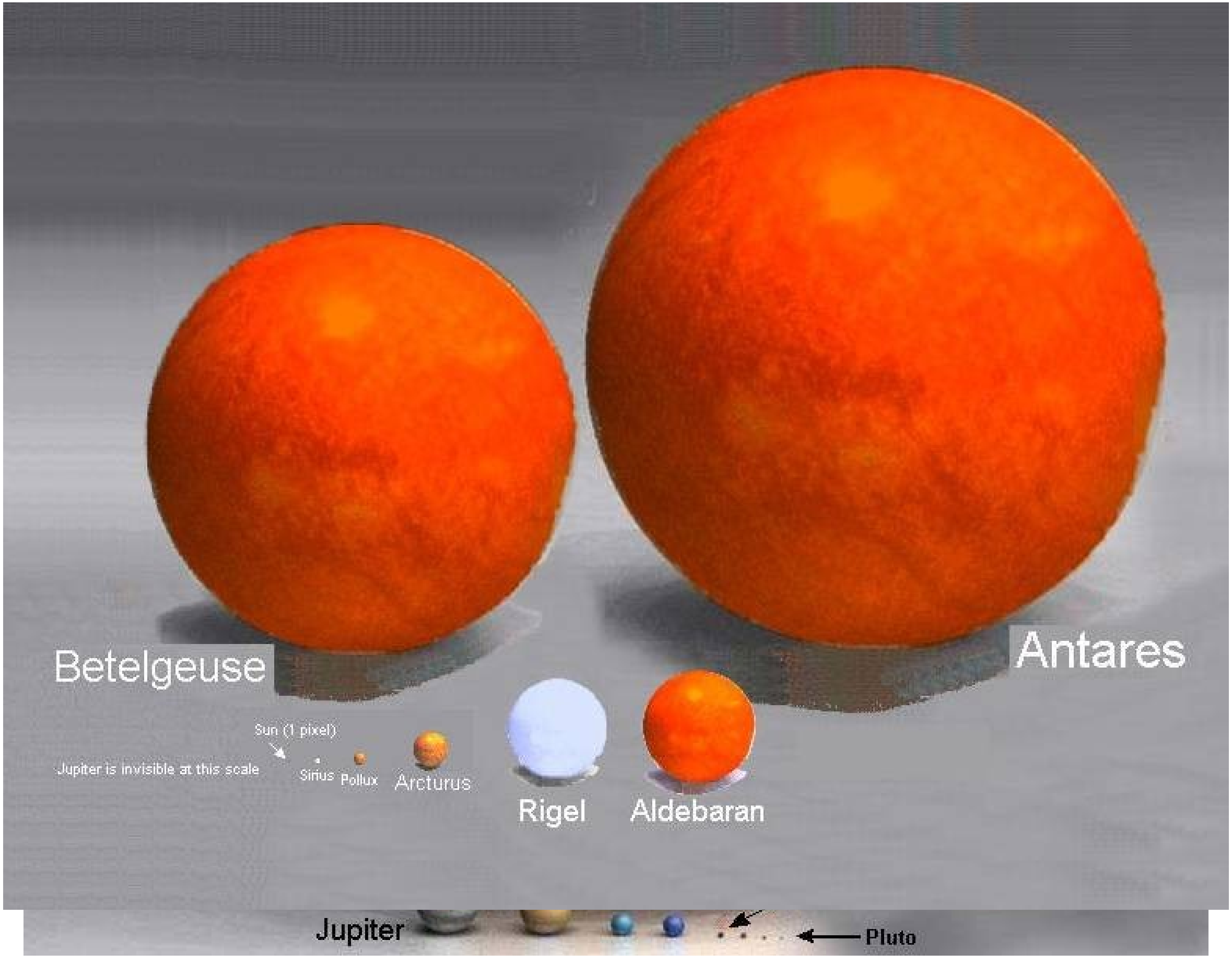
$T_A/T_B=9940/25200=0.394$

$L_A/L_B=25.4/0.026=977$

$R_A/R_B=(977)^{1/2}(0.394)^{-2}=31.26*6.44=201$

Compare using Wikipedia:

$R_A/R_B = 1.711 \mathrm{Rsun}/0.0084 \mathrm{Rsun} = 204$


Betelgeuse
Antares
Sun (1 pixel)
Jupiter is invisible at this scale
Sirius
Pollux
Arcturus
Rigel
Aldebaran
Jupiter
Pluto

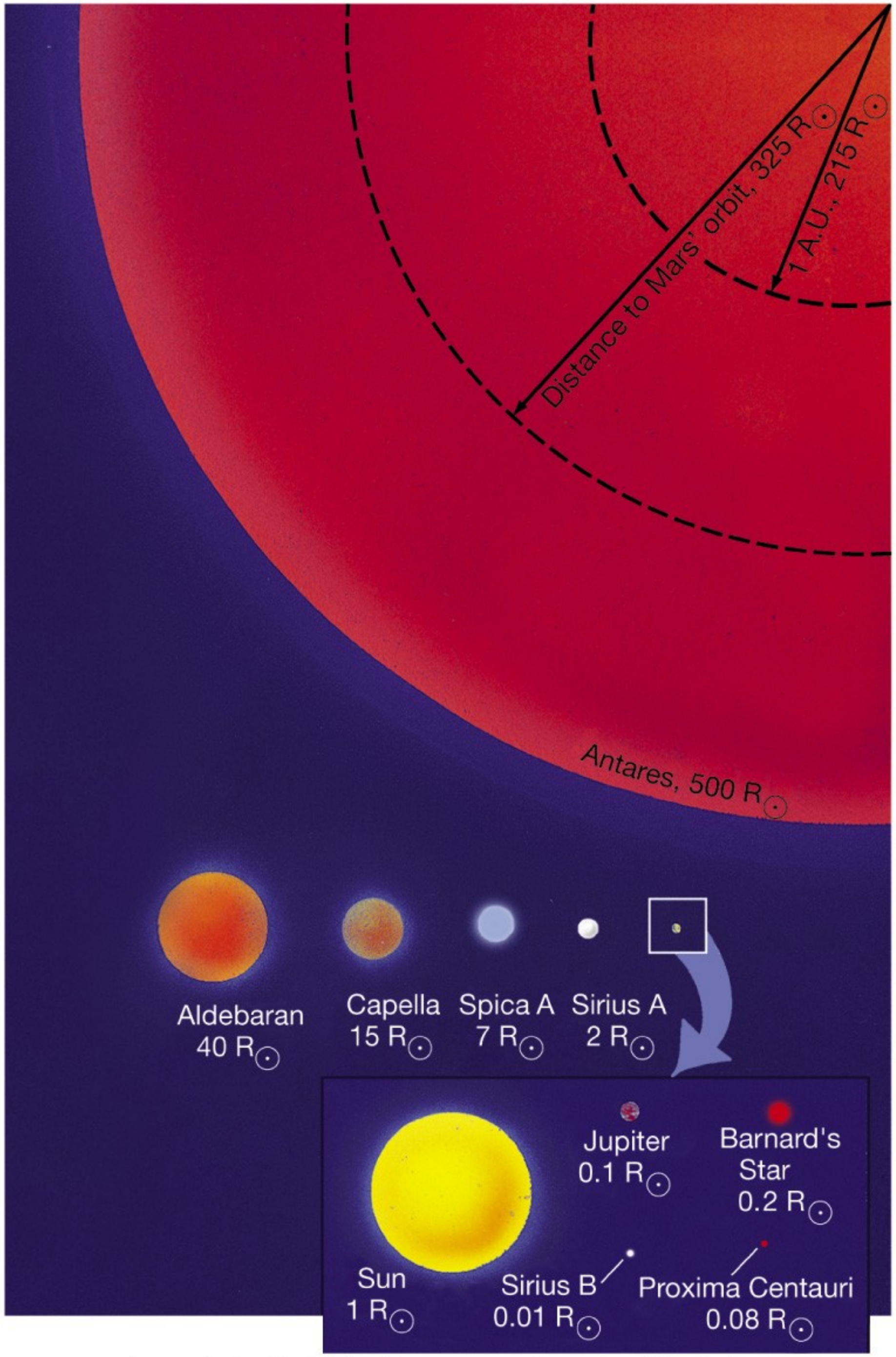


Figure 17-12
Stellar Sizes

7. H-R Diagram

or Hertzsprung – Russell diagram, is a plot of Luminosity vs spectral type. It's also called a “color-luminosity” diagram.

a) Values for the Sun

The Sun's position on the H-R Diagram is Spectral Type = G2, L=1Lsun. The Spectral Type can be replaced by surface temperature (5800 K), or color index (B/V=0.55, B-V=0.65). The Luminosity, L, can be replaced by absolute magnitude, M=+4.83.

b) Range of values for other stars

(See an H-R diagram.) The surface temperatures range from 3000-30000 K, and the luminosities range from about 0.0001 – 100,000 L⊙.

c) How it's measured

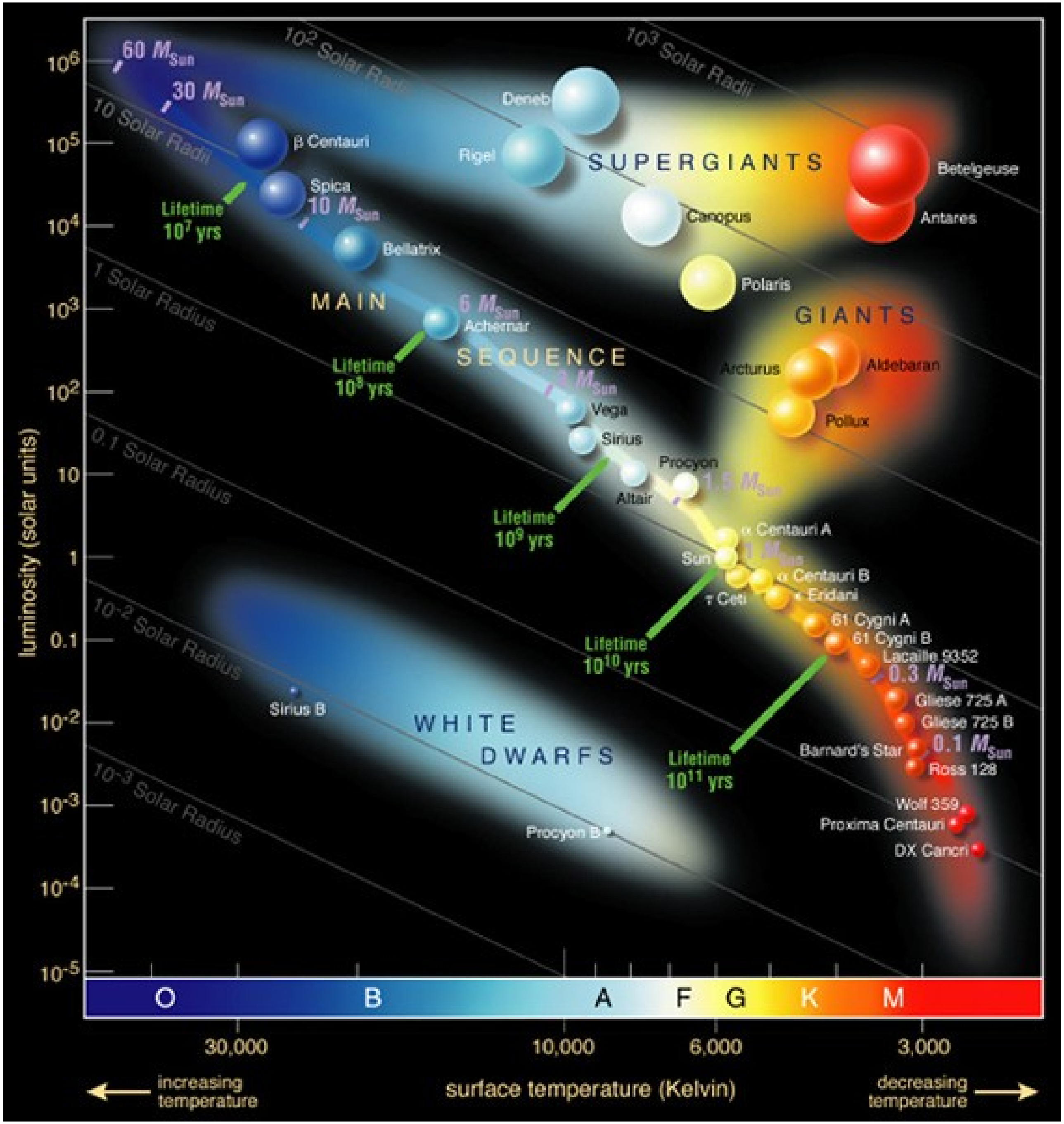
Spectroscopy is used to identify the spectral type, or surface temp. of a star. Two-color photometry can give the color index of the star. The luminosity can be found by getting a distance and a flux (or apparent magnitude).

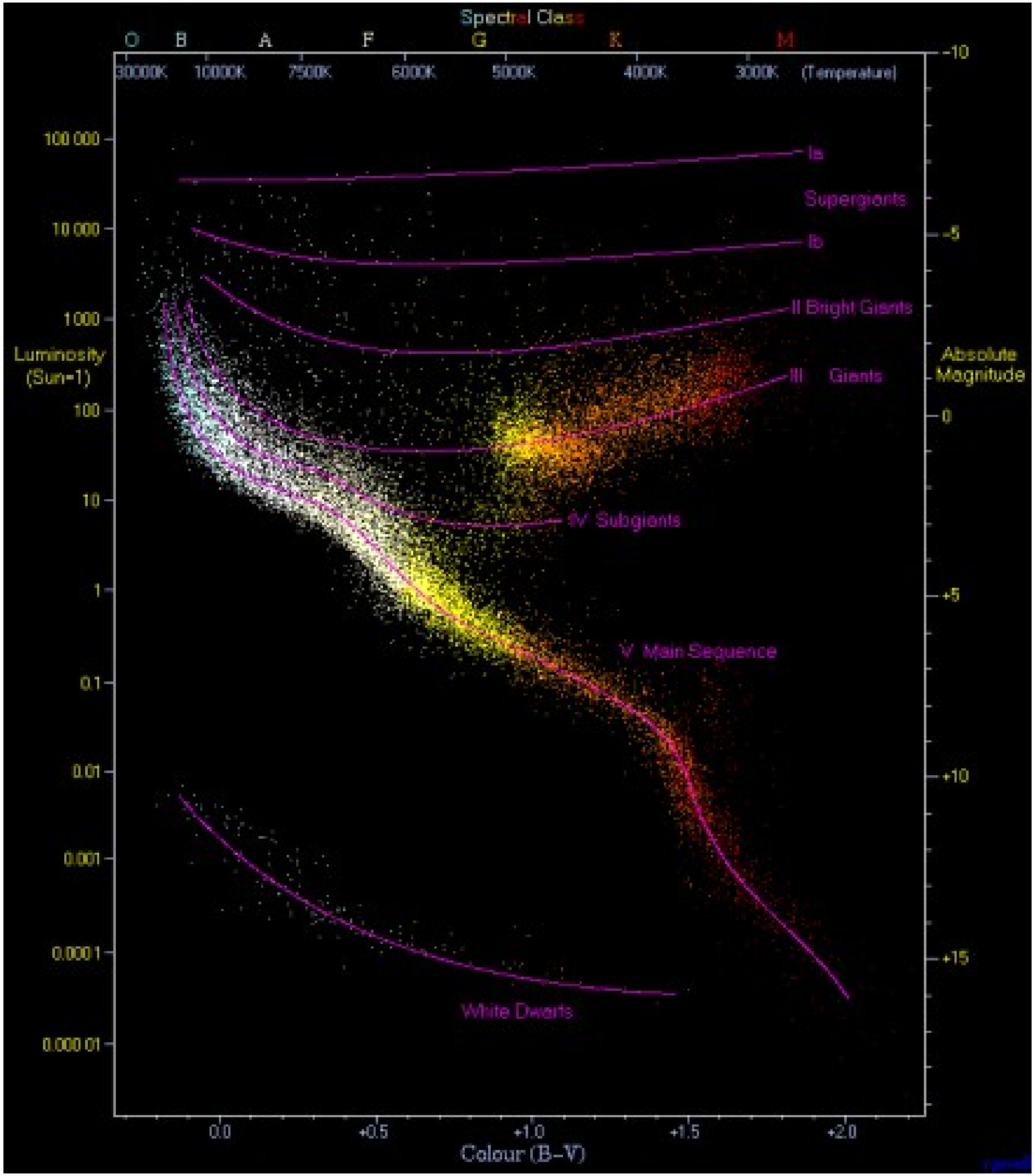
7. H-R Diagram

d) Theory behind interpretation of measurement.

The location of a star on the H-R diagram tells us about the stars mass and its stage in evolution. Stars on the Main Sequence (MS) are fusing H to He in their core, and this is the longest stage in their evolution.

A colorful H–R Diagram





H–R Diagram

Different axes:

$L \rightarrow M_{abs}$

T,Class → B-V

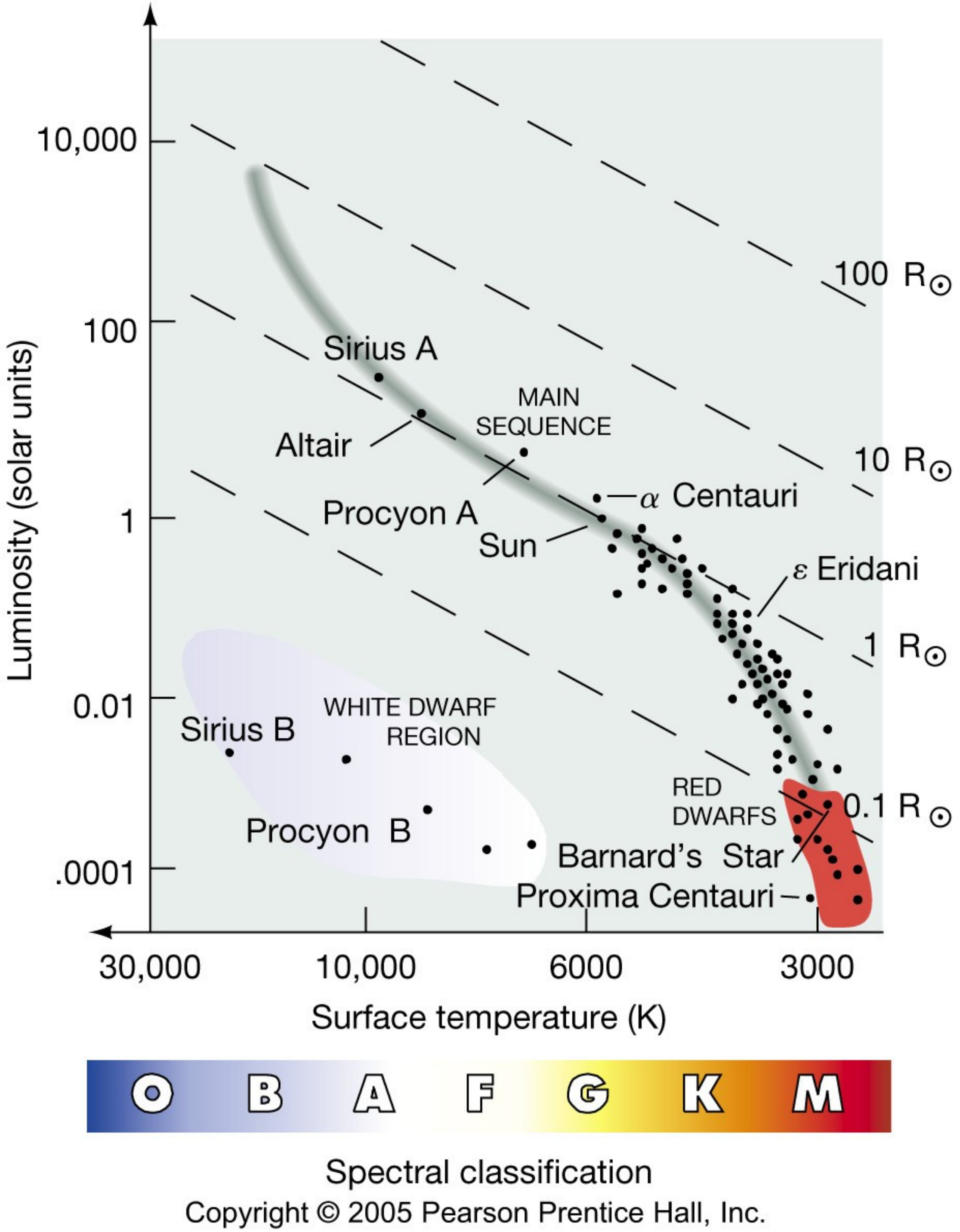
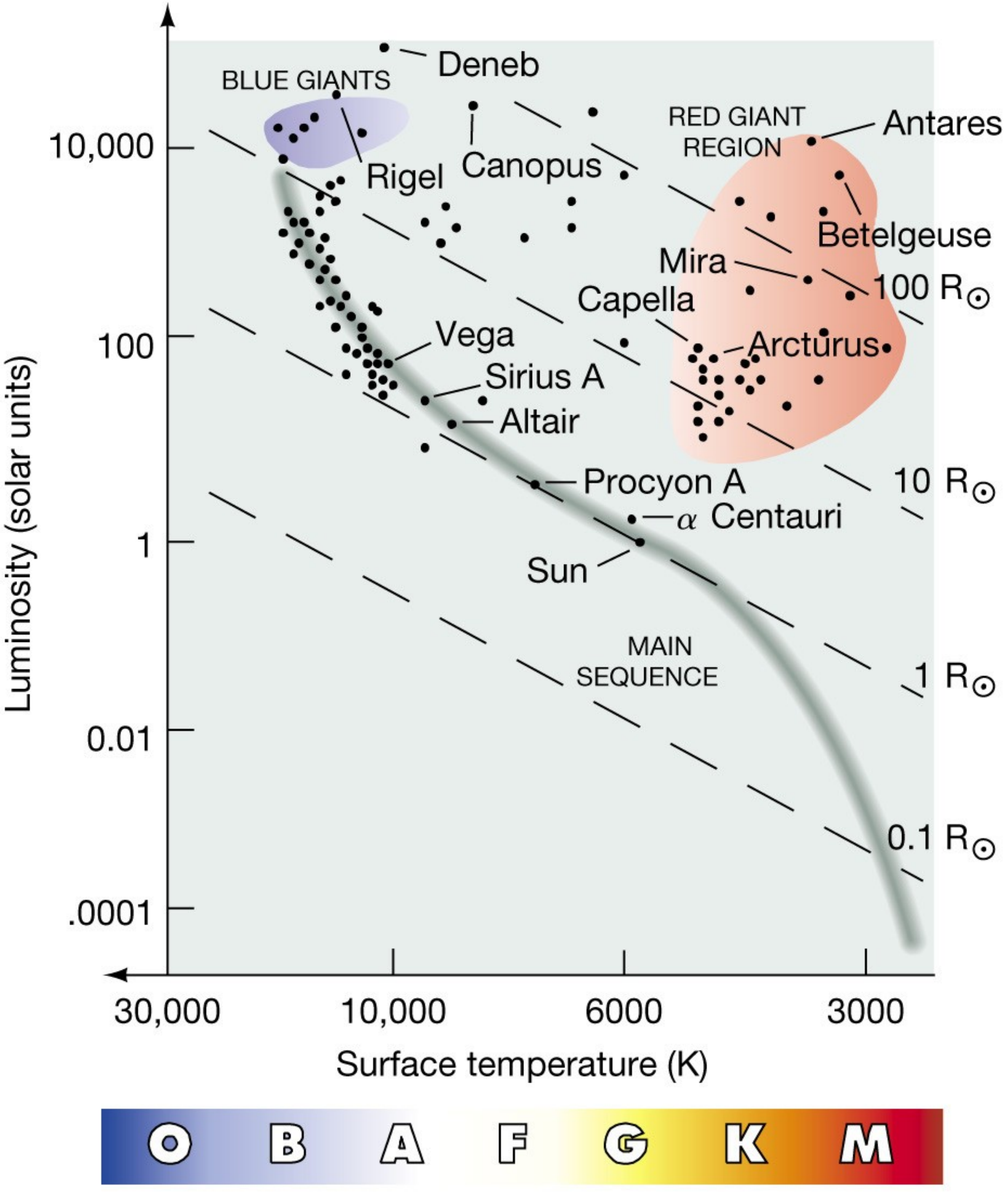


Figure 17-14
H–R Diagram of Nearby Stars

Note lines of equal radius.

Two stars of the same surface temp do not always have the same radius!

Figure 17-15 H–R Diagram of Stars that look bright in our sky.



8. Luminosity Class

a) Values for the Sun

V (dwarf)

b) Range of values for other stars

V, IV, III, II, Ib,Ia (dwarf to supergiant)

c) How it's measured

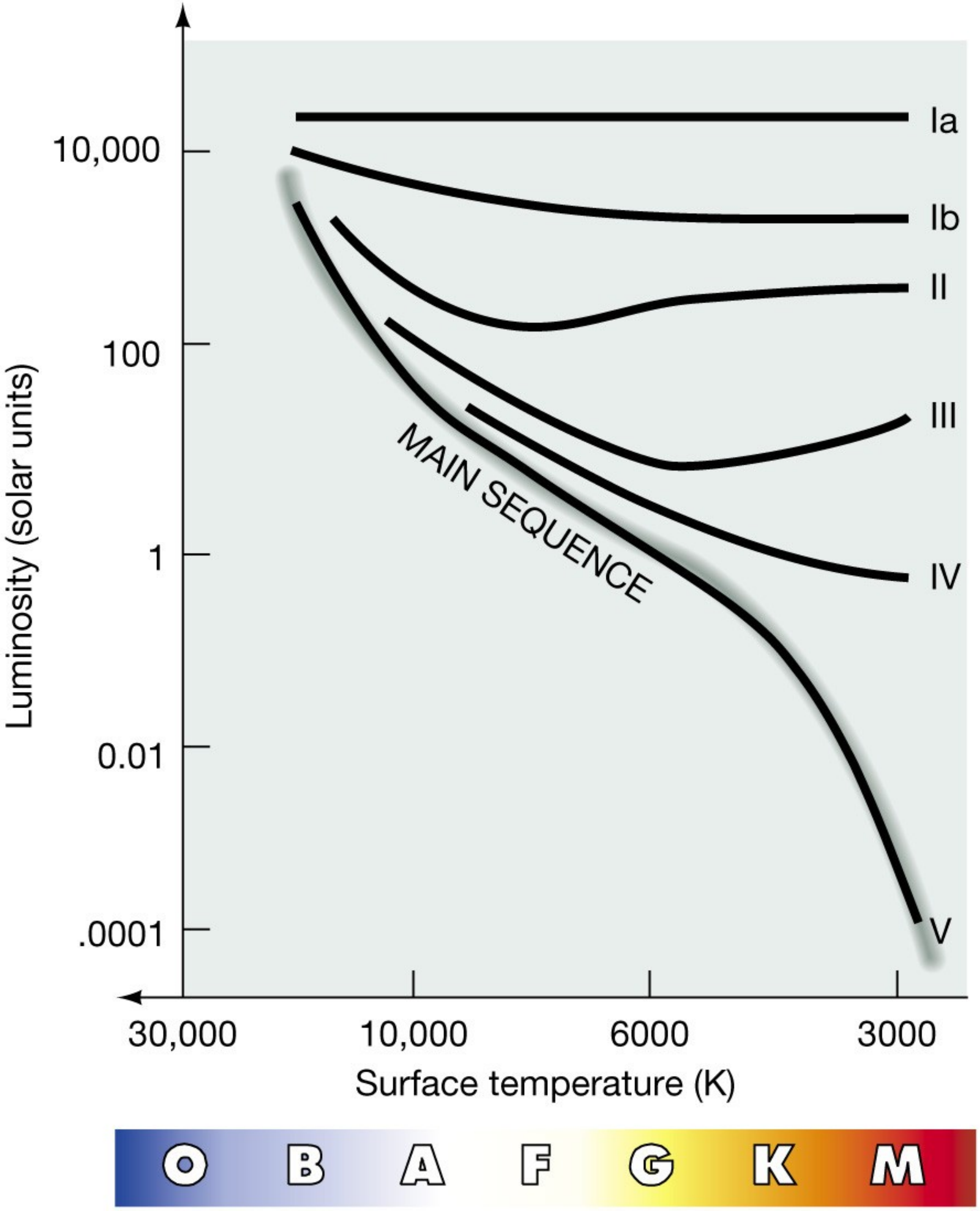
Spectroscopy is used to carefully measure the widths of absorption lines. The wider the line, the smaller the star. The small stars are class V dwarfs, the biggest are bright supergiants. Thus, luminosity class indicates radius as well as luminosity.

(Radius can also be measured from eclipsing binaries.)

d) Theory behind interpretation of measurement.

A compact star will have a higher surface gravity than a big star. This causes greater pressure broadening of the absorption lines.

Figure 17-18
Luminosity Classes



Spectral classification

Table 17-3
Stellar Luminosity Classes

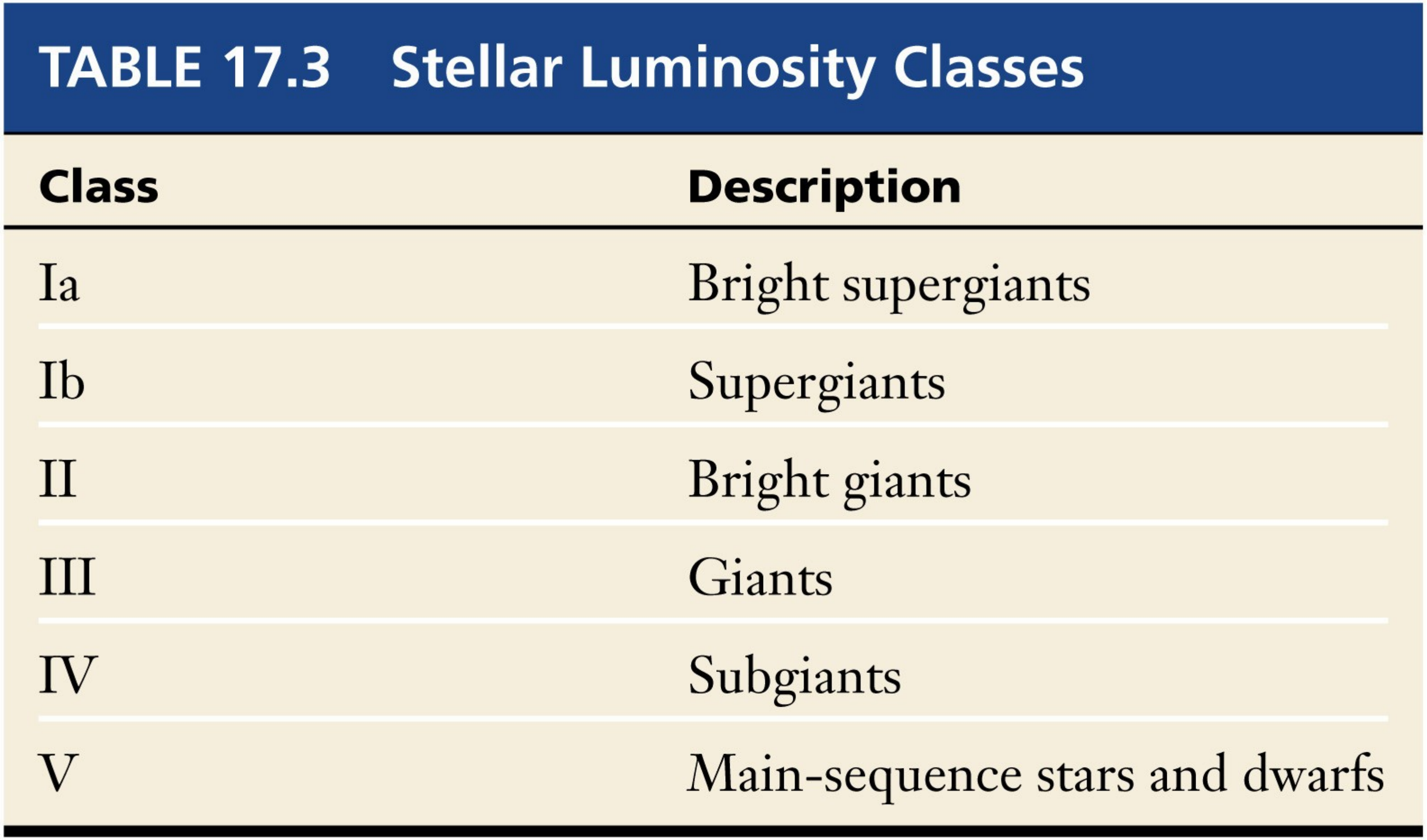


TABLE 17.3 Stellar Luminosity Classes

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

Table 17-4
Variation in Stellar Properties within a Spectral Class

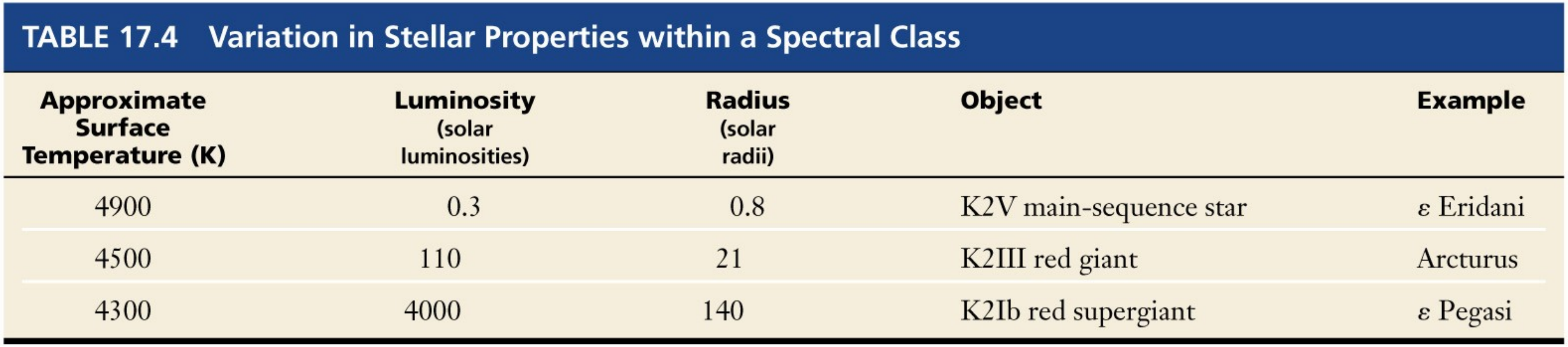


TABLE 17.4 Variation in Stellar Properties within a Spectral Class

Approximate Surface Temperature (K)	Luminosity (solar luminosities)	Radius (solar radii)	Object	Example
4900	0.3	0.8	K2V main-sequence star	ε Eridani
4500	110	21	K2III red giant	Arcturus
4300	4000	140	K2Ib red supergiant	ε Pegasi

9. Mass

a) Values for the Sun

Msun = $2x10^{30}$ kg

b) Range of values for other stars

0.08 Msun - ~50 Msun

c) How it's measured

Observations of binary stars. Example: for eclipsing binaries, get the period from the light curve (photometry), get the true speeds from the doppler effect (spectra), get the mass ratios from the speed ratios: $m_1/m_2 = v_2/v_1$.

Or, for visual binaries (those where two stars can be resolved), one can get the relative masses from the relative sizes of the orbits: $m_1/m_2 = r_2/r_1$.

d) Theory behind interpretation of measurement.

Kepler's 3rd law (with Newton's modification):

$$P^2=4\pi^2 R^3/G(m_1+m_2)$$

Figure 17-19
Visual Binary

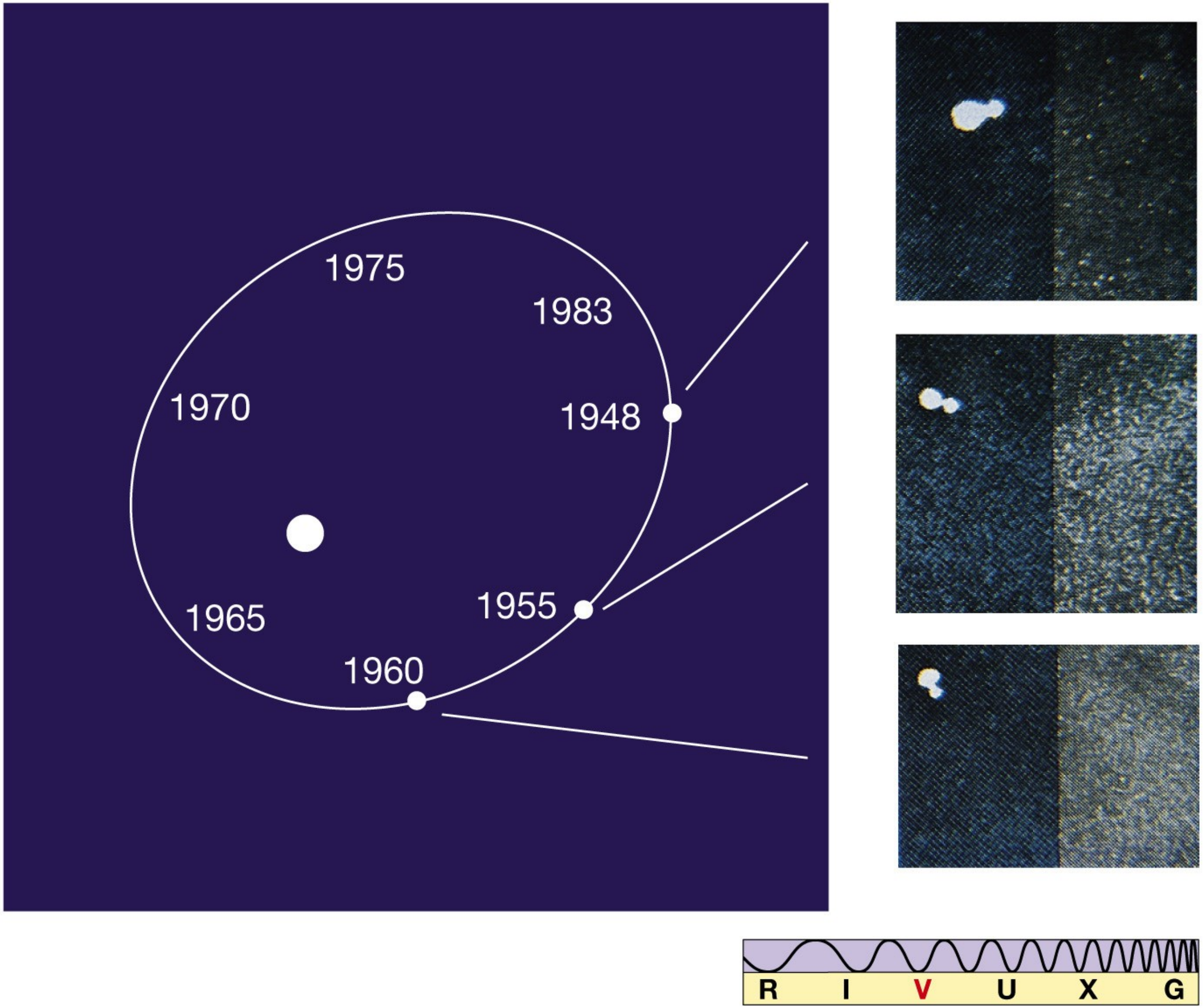


Figure 17-20
Spectroscopic Binary

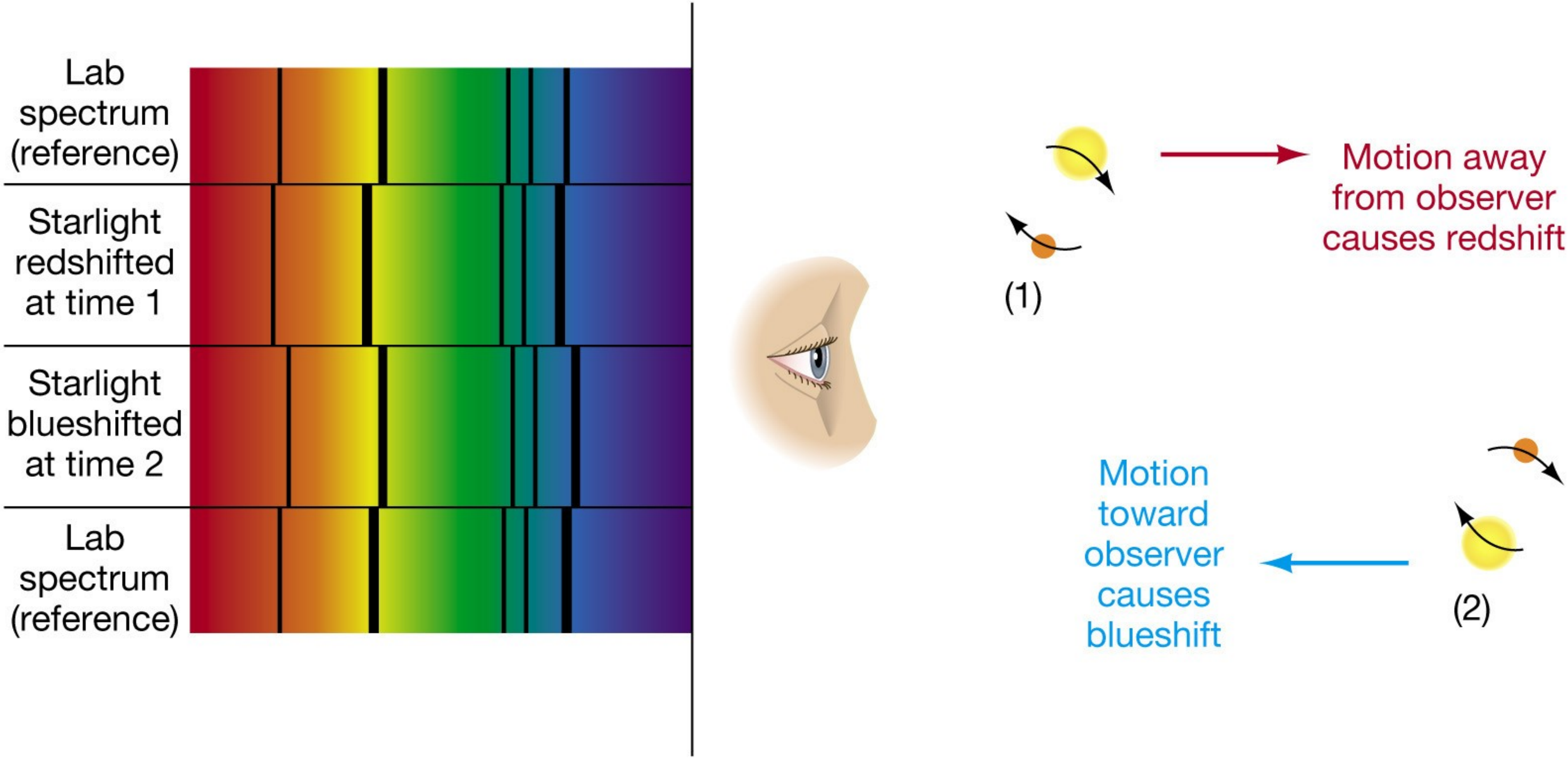
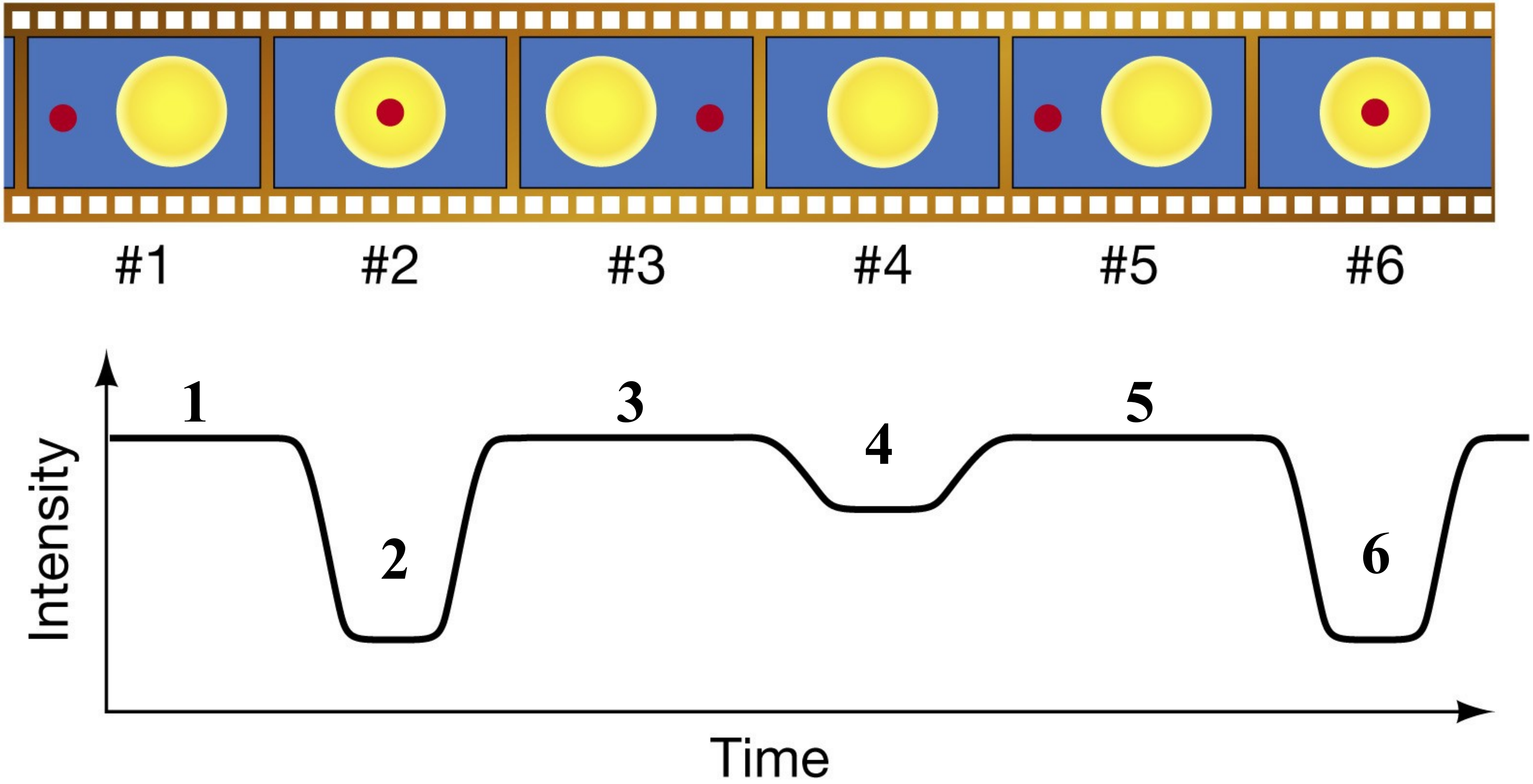


Figure 17-21
Eclipsing Binary



Mass – Luminosity relationship for M.S. Stars.

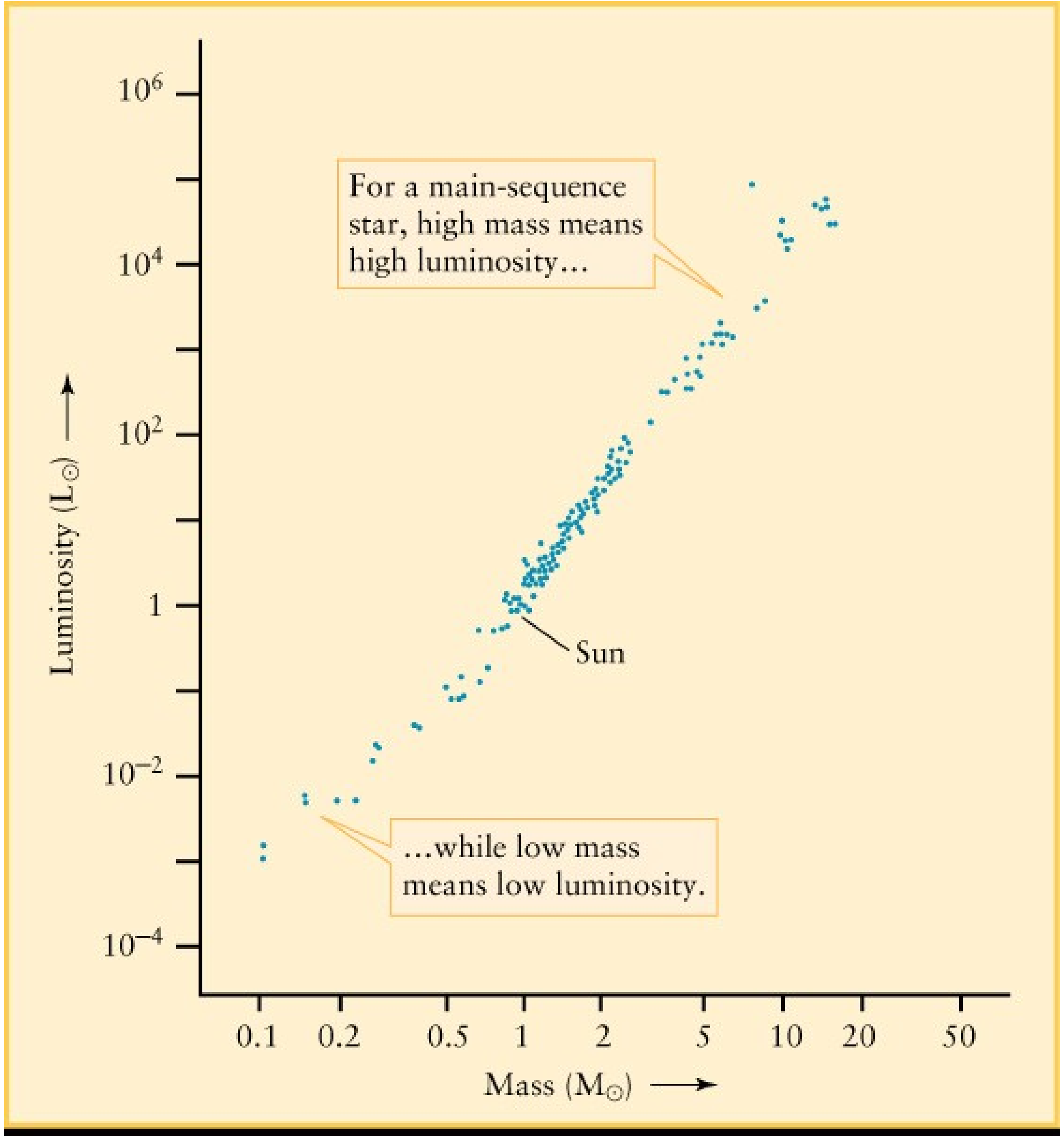


Figure 17-22
Stellar Masses

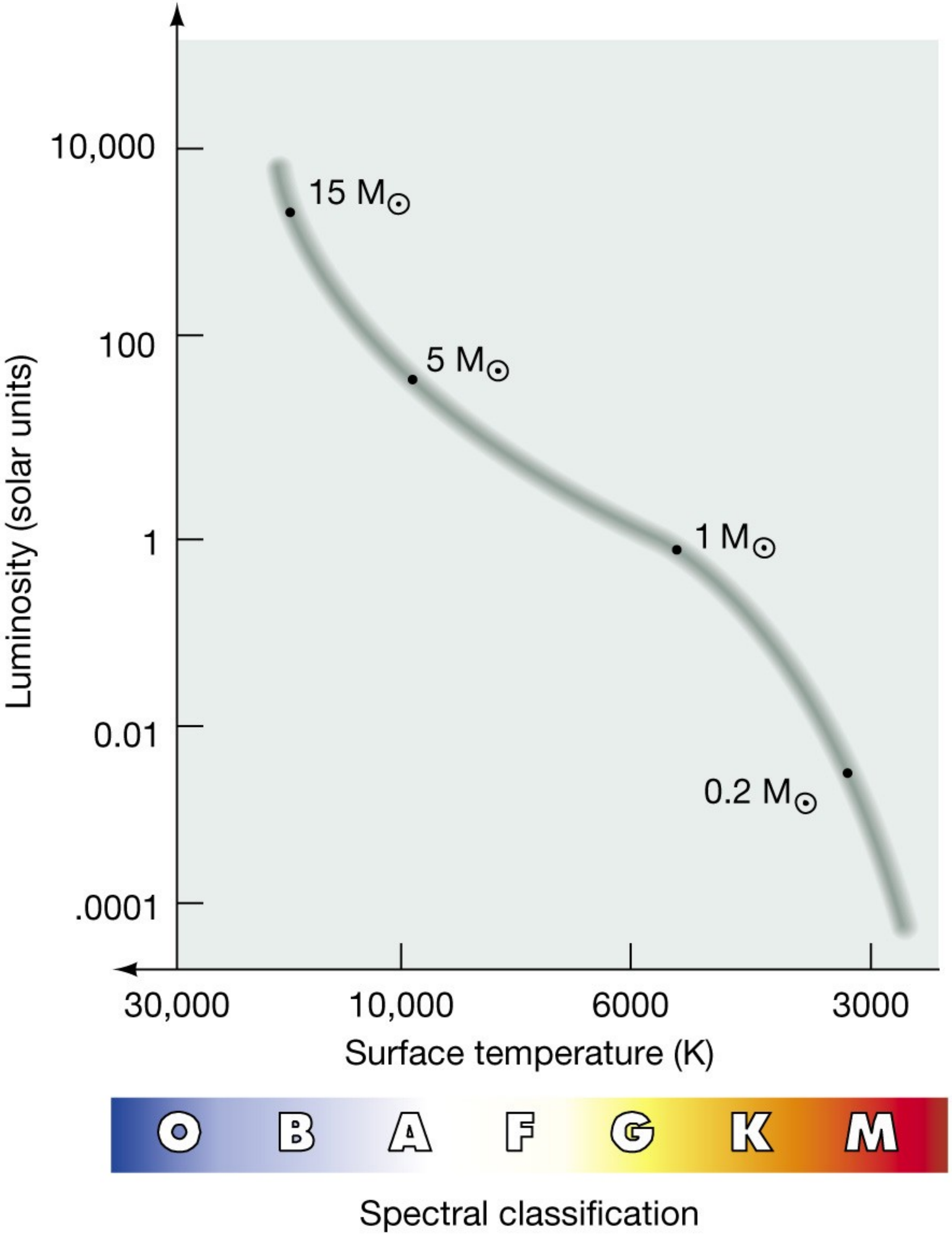


Figure 17-24
Stellar Radii and Luminosities

Only stars on the M-S are plotted here.

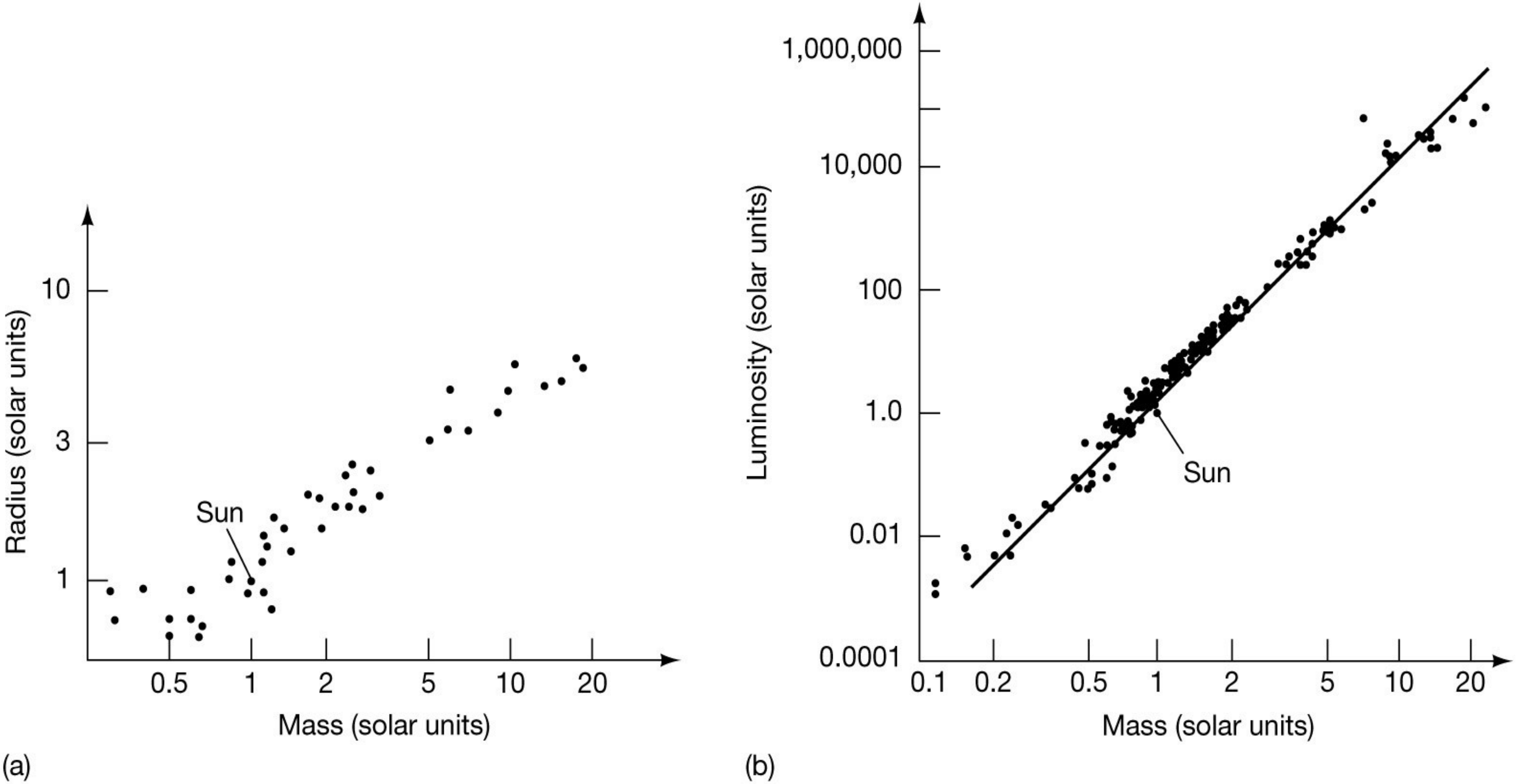
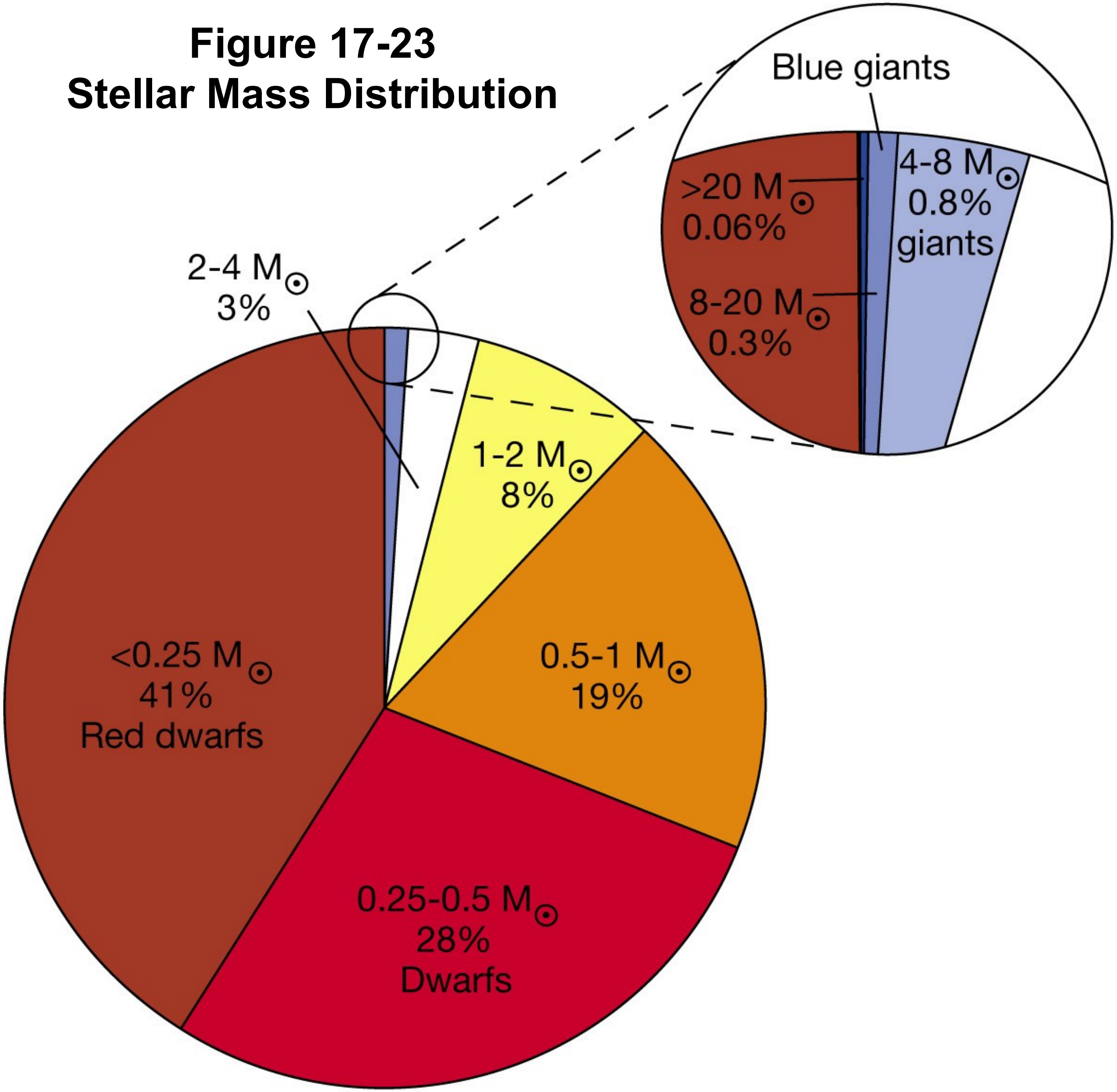


Figure 17-23
Stellar Mass Distribution



10. Spectroscopic parallax: a method of measuring distances to stars based on their spectrum.

a) Values for the Sun

NA. *(The distance to the sun is 10^{-5} LY)*

b) Range of values for other stars

The distance range over which spectroscopic parallax is most useful for determining distances is 1000 LY – 40,000 LY.

c) How it's measured

For single stars: Spectroscopy is used to identify the spectral type of a star, including its luminosity class. From this, one estimates the stars luminosity (L or M). The difference between the apparent brightness, m, and M gives a distance.

10. Spectroscopic parallax

c) How it's measured (cont.)

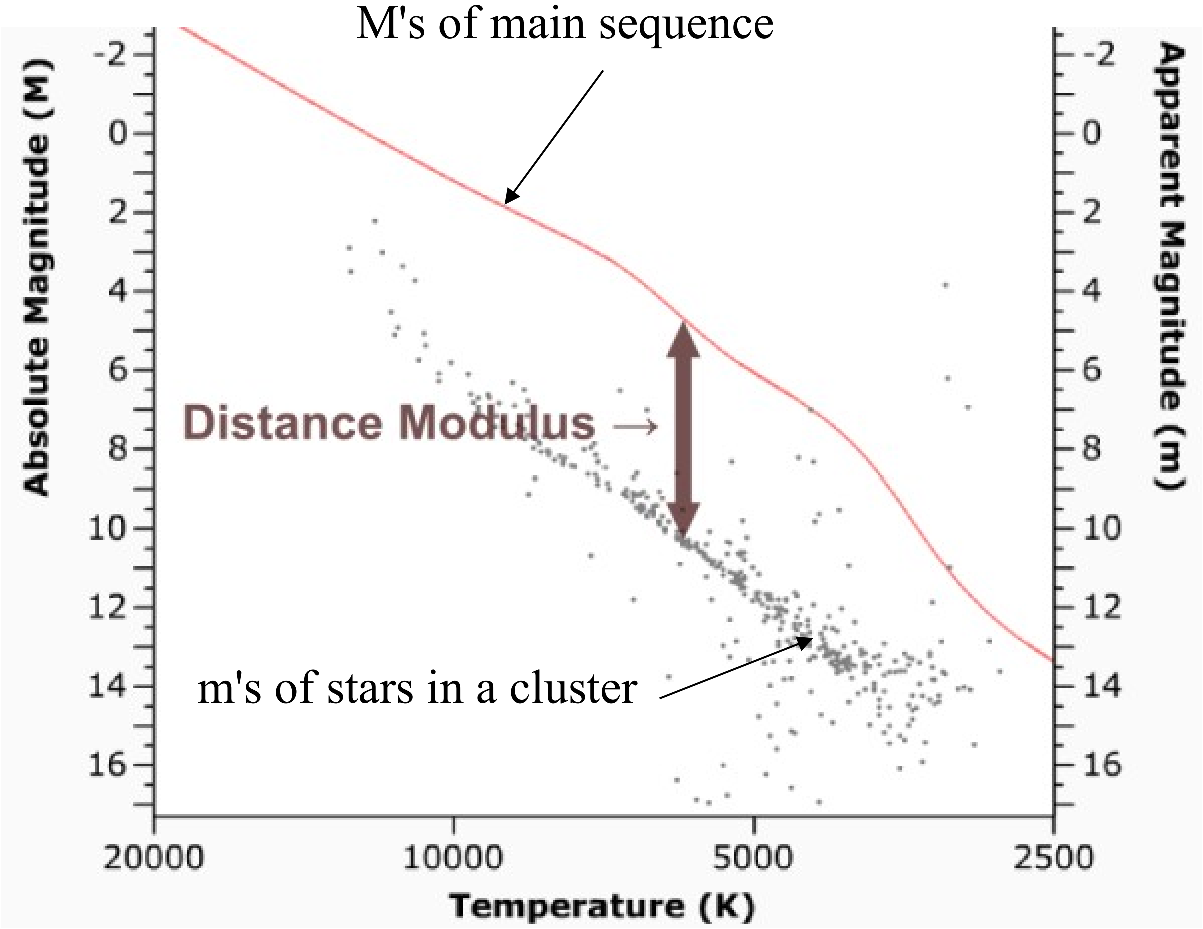
For a cluster of stars: two-color photometry can be done on a cluster of stars to obtain color index (B-V or B/V) and apparent brightness, *m*, for each star. A plot of *m* vs B-V will exhibit a Main Sequence just like a real H-R diagram (a plot of *M* vs B-V). The vertical offset of the cluster's main sequence from the main sequence on *M* vs B-V gives us (*m*-*M*) and thus a distance for the entire cluster. (This is called main-sequence fitting.)

d) Theory behind interpretation of measurement.

$m-M = 5 \log (D/10pc)$. Where D is the distance in pc.

10. Spectroscopic parallax

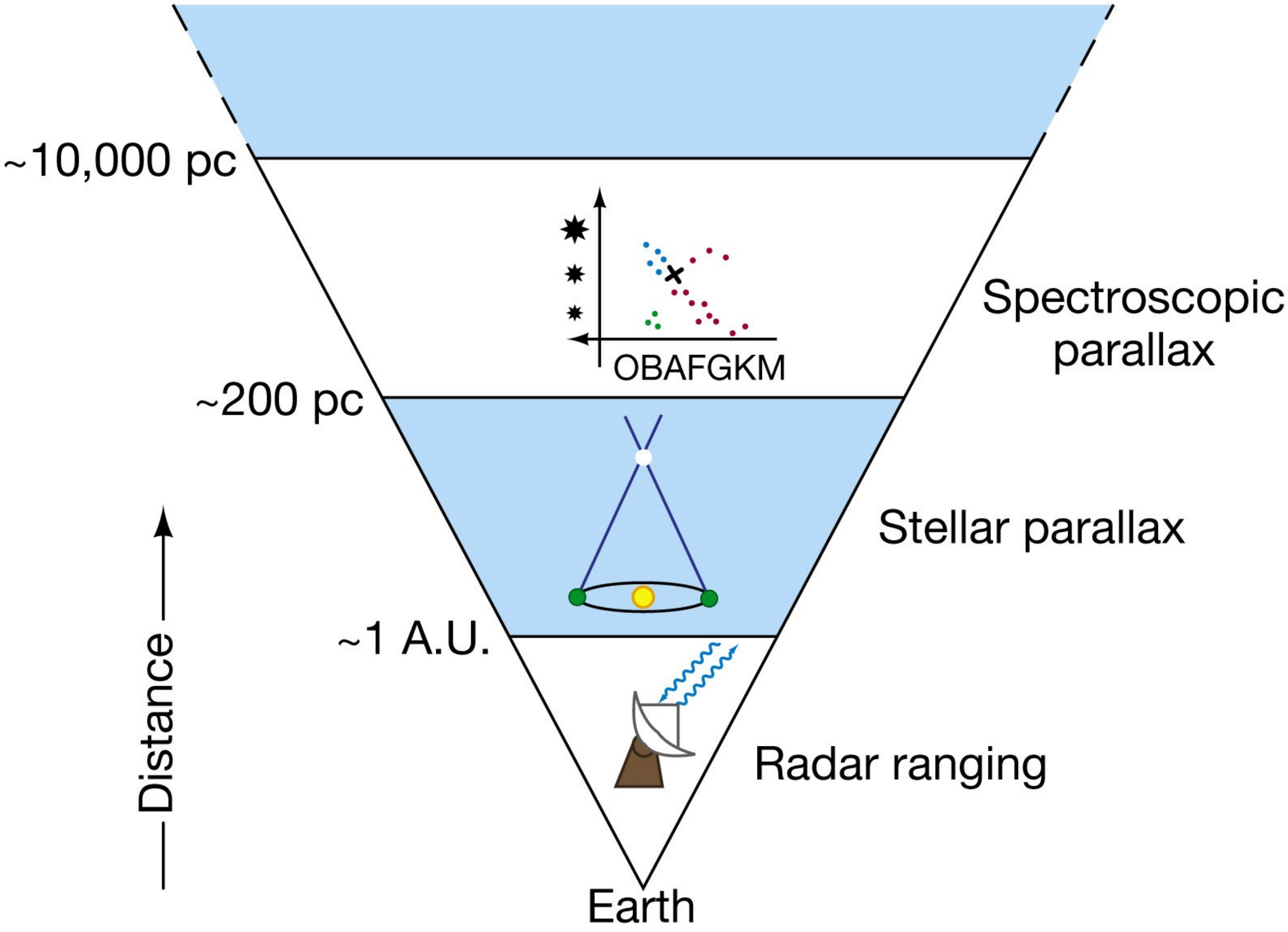
When applied to a whole cluster of stars (all at same distance) it is called "main sequence fitting".



M's of main sequence

m's of stars in a cluster

Figure 17-17
Stellar Distances



11. Radial & Tangential velocity, proper motion

a) Values for the Sun

Vr = 0 (on average), Vt ~ 30 km/s, μ~1,315,000 "/year, but these are really reflex motions caused by the motion of the Earth around the Sun.

(The motion of the Sun relative to our galaxy's center is about 200 km/s.)

b) Range of values for other stars

Speeds of stars relative to the Sun range from 0 to about 400 km/s.

c) How it's measured

For *Vr*: Use spectrograph to get a spectrum of the star. Measure the doppler shifting of absorption lines to get the radial velocity.

For *μ*: Take images of the star over many years. Measure how many arcseconds the star moves per year relative to background stars. (One must correct for parallax, which also makes a star "move").

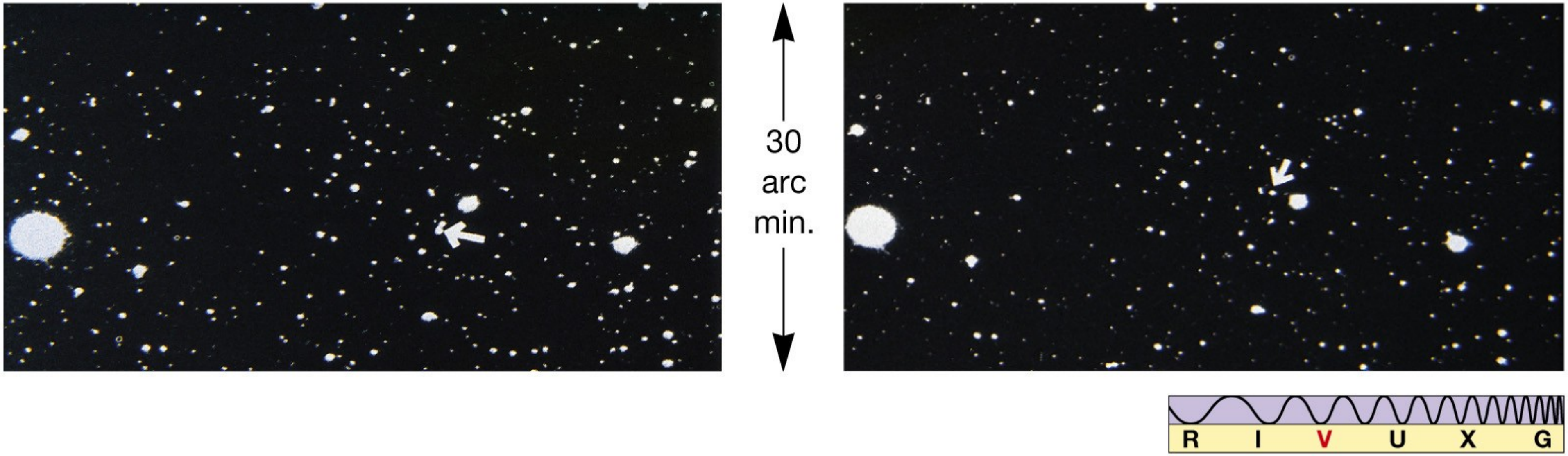
For *Vt*: V_t (km/s) = 4.74 μ d(pc). Need distance and proper mot.

d) Theory behind interpretation of measurement.

For *Vr*: the radial motion of the star causes a Doppler shift according to (observed wavelength – rest wavelength)/rest wavelength = v/c.

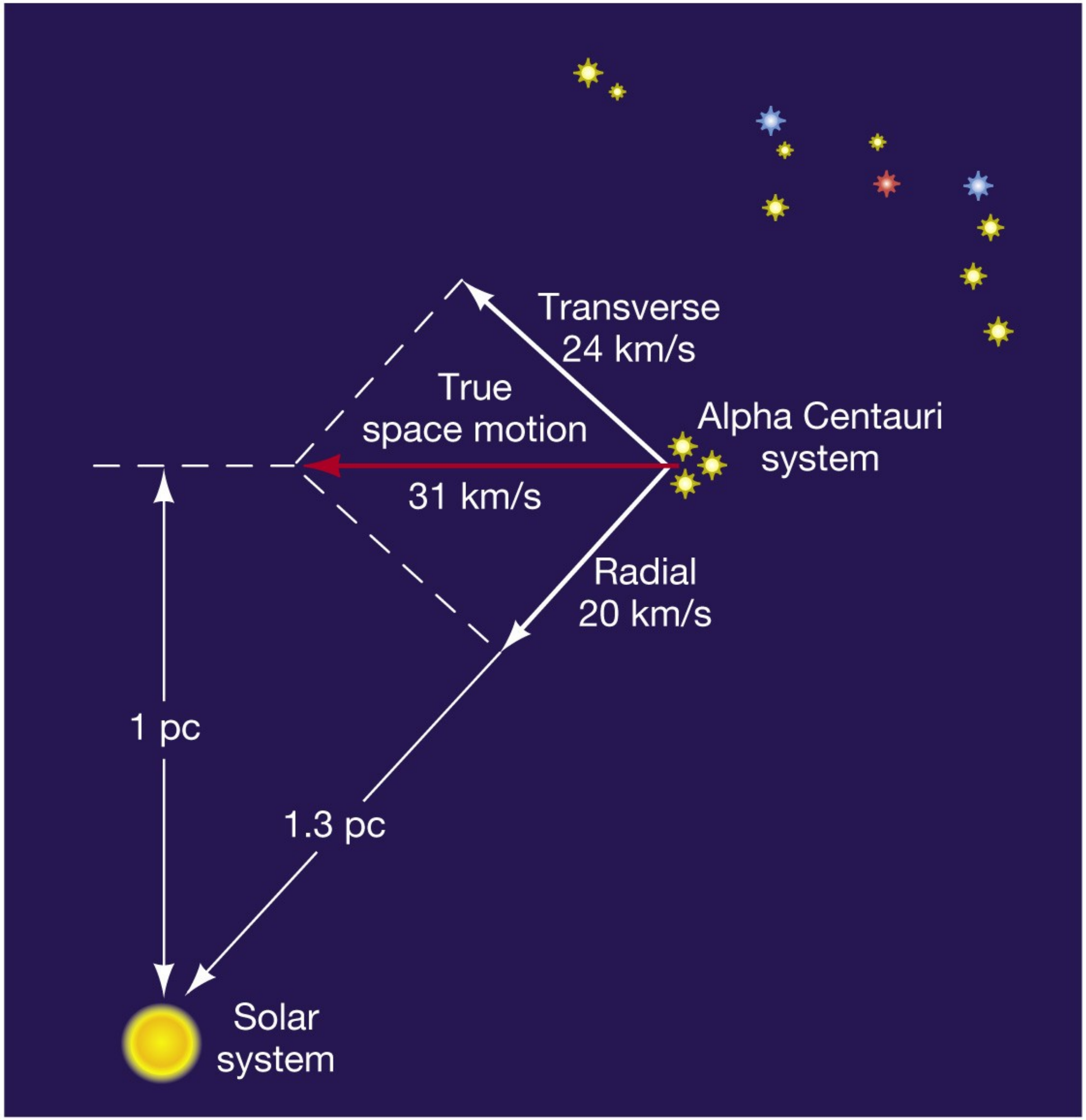
For *Vt*: simple geometry. AD = LD/D

Figure 17-3
Proper Motion



This figure shows a very high proper motion star.

Figure 17-4
Real Spatial Motion



12. Composition (*metallicity*)

a) Values for the Sun

Mostly Hydrogen (71% by mass, 91.2% by number)
Helium is next abundant (27.1% by mass, 8.7% by number)
All other elements are "metals" (1.9% by mass, 0.1% by number)

b) Range of values for other stars

The ratio of H/He is very similar. But metal content differs. Old stars have less metals and young stars have more metals.

c) How it's measured

Spectroscopy – look at absorption line strengths.

d) Theory behind interpretation of measurement.

At a given temp, the greater the line strength the greater the abundance. Atomic physics and radiative transfer tells us what line strength to expect.

13. Lifetime

a) Values for the Sun

10 billion years. $\tau_\odot = 10^{10}$ yrs

b) Range of values for other stars

About 300,000 yrs to 10^{11} yrs.

c) How it's measured

Measure the mass using binary stars, then lifetime is a function of mass.

d) Theory behind interpretation of measurement.

Lifetime, $\tau \sim$ Mass/Luminosity (“fuel” / “rate of burning fuel”).

We’ve discovered a mass-luminosity relationship: $L \sim M^4$.

Therefore, $\tau \sim M/M^4 \sim M^{-3}$. To change ~ to = we must use the Sun to find the coefficient: $\tau_\odot=10^{10}$ yrs, so $\tau = 10^{\square\square\square} M^{-3}$ years.

Actually, this applies best to stars with masses between 0.43 – 2.0 $M_\odot$.

13. Lifetime

a) Values for the Sun

10 billion years. $\tau_\odot = 10^{10}$ yrs

b) Range of values for other stars

300,000 yrs to 10^{11}

c) How it's measured

Measure the mass using binary stars, then lifetime is a function of mass.

d) Theory behind interpretation of measurement.

Lifetime ~ Mass/Luminosity