Python for Astronomy
Sessions Outline

Astronomy Online Reference
[OpenStax: Astronomy]

Python Online Reference
[Think Python]

JupyterLab Reference

P4A Course Goals

1. Learn some basics about Hertzsprung Russell diagrams
2. Use this topic as a mechanism to learn Python for Astronomy
3. Query astro satellite databases such as Kepler, Gaia
4. Analyze, Clean, and Plot Data
5. Create plots for Star Clusters to determine their age

Session 1

Agenda - 1st session

Session Logistics

- Walkthrough Course Website
- Slack - Pythonintro Channel in BRIEF Programs

Tools

- JupyterLab (BushAstroLab - Python Implementation)

Session Goals

- Setup JupyterLab
- Learn Basics
  - Images, Videos
  - Do some Astro Calculations

Session Logistics

Sessions each Thursday starting 7:00 PM for 5 sessions total

Each Session will use the same Google Meet with password

Recordings will be made and available a few days later

Sessions designed to last 1 hour with extension for 30 minutes as needed

Mostly hands-on each day with some Astronomy basics

Recent Observatories in Space

Observatory	Date Operation Began	Bands of the Spectrum	Notes	Website
James Webb Space Telescope (JWST)	2022	infrared (IR)	6.5-m mirror; images and spectra	webb.nasa.gov
Hubble Space Telescope (HST)	1990	visible, UV, IR	2.4-m mirror; images and spectra	hubblesite.org
Chandra X-Ray Observatory	1999	X-rays	X-ray images and spectra	chandra.si.edu
XMM-Newton	1999	X-rays	X-ray spectroscopy	cosmos.esa.int/web/xmm-newton
International Gamma-Ray Astrophysics Laboratory (INTEGRAL)	2002	X- and gamma-rays	higher resolution gamma-ray images	sci.esa.int/integral/
Spitzer Space Telescope	2003	IR	0.85-m telescope	spitzer.caltech.edu
Fermi Gamma-ray Space Telescope	2008	gamma-rays	first high-energy gamma-ray observations	fermi.gsfc.nasa.gov
Kepler	2009	visible-light	planet finder	kepler.nasa.gov
Wide-field Infrared Survey Explorer (WISE)	2009	IR	whole-sky map, asteroid searches	nasa.gov/mission_pages/WISE/main
Gaia	2013	visible-light	Precise map of the Milky Way	sci.esa.int/gaia/
Transiting Exoplanet Survey Satellite (TESS)	2018	visible-light	Planet finder	tess.mit.edu

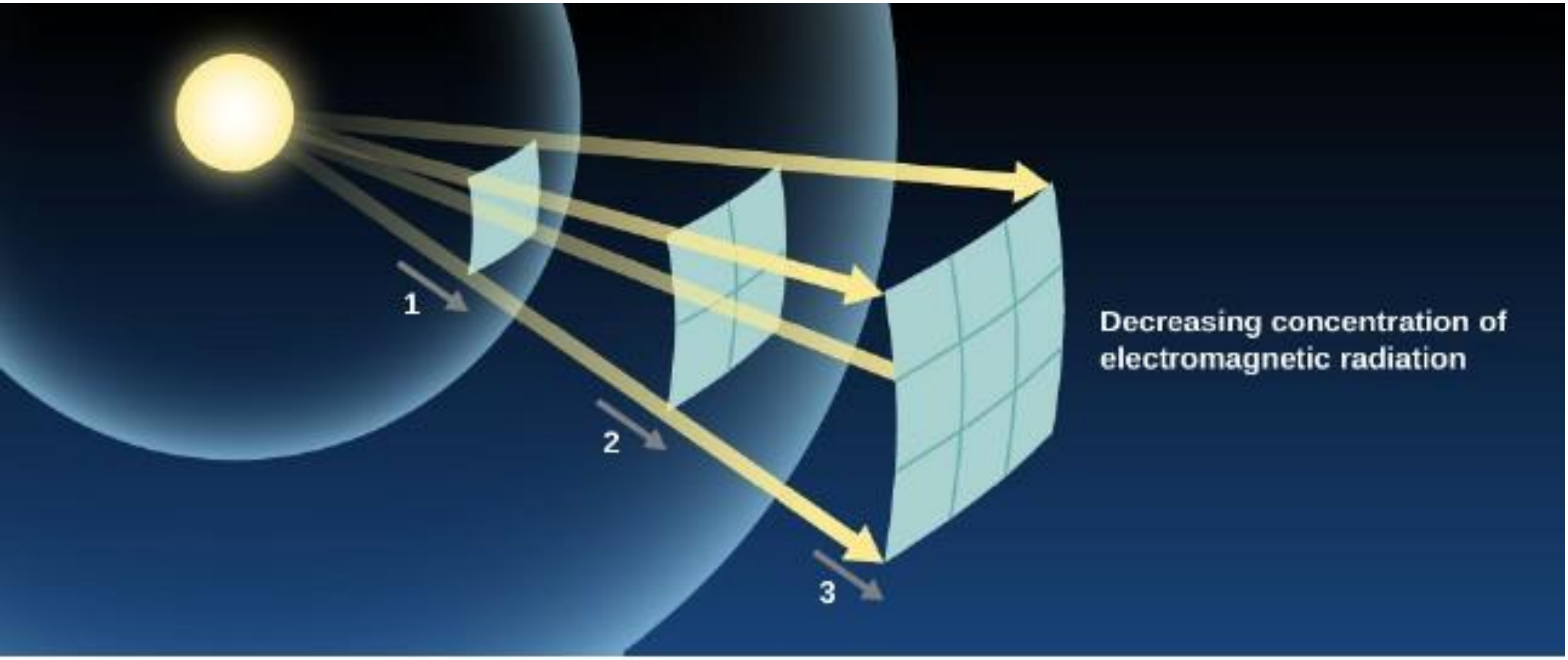


Figure 5.5 Inverse Square Law for Light. As light radiates away from its source, it spreads out in such a way that the energy per unit area (the amount of energy passing through one of the small squares) decreases as the square of the distance from its source.

Brightness decreases in proportion to the square of the distance
This is because the surface area of a sphere of radius ‘r’ is
Brightness ‘b’ is inversely proportional to Distance ‘r’
So, how much brighter is star2 than star1 if it is twice, ½ or 3 times the distance of star1?

Can you do this in Colab with this picture embedded?

EXAMPLE 5.2

The Inverse Square Law for Light

The intensity of a 120-W lightbulb observed from a distance 2 m away is 2.4 W/m^2. What would be the intensity if this distance was doubled?

Solution

If we move twice as far away, then the answer will change according to the inverse square of the distance, so the new intensity will be $(1/2)^2 = 1/4$ of the original intensity, or 0.6 W/m^2.

Check Your Learning

How many times brighter or fainter would a star appear if it were moved to:

a. twice its present distance?

b. ten times its present distance?

c. half its present distance?

Session 2

Homework

Eratosthenes was told that on the first day of summer at Syene, Egypt (near modern Aswan), sunlight struck the bottom of a vertical well at noon. This indicated that the Sun was directly over the well-meaning that Syene was on a direct line from the center of Earth to the Sun. At the corresponding time and date in Alexandria, Eratosthenes observed the shadow a column made and saw that the Sun was not directly overhead, but was slightly south of the zenith, so that its rays made an angle with the vertical equal to about 1/50of a circle (7°). Because the Sun's rays striking the two cities are parallel to one another, why would the two rays not make the same angle with Earth's surface? Eratosthenes reasoned that the curvature of the round Earth meant that straight up" was not the same in the two cities. And the measurement of the angle in Alexandria, he realized, allowed him to figure out the size of Earth. Alexandria, he saw, must be 1/50 of Earth's circumference north of Syene (**Figure 2.11**). Alexandria had been measured to be 5000 stadia north of Syene. (The *stadium* was a Greek unit of length, derived from the length of the racetrack in a stadium.) Eratosthenes thus found that Earth's circumference must be 50 • 5000, or 250,000 stadia.

Pompey's Pillar (column)

From Wikipedia, the free encyclopedia

Coordinalos: 31'10'56.98•N 29'53'47.23•E

"Pompey's pillar" redirects here. For other uses, see *Pompey's Pillar (disambiguation).*

Pompey's Pillar (Arabic.: ,µ1J.>=) is the name given to a Roman triumphal column in Alexandria, Egypt. Set up in honour of the Roman emperor Diocletian between 298-302 AD, the giant Corinthian column originally supponed a colossal porphyry statue of the emperor in armour.[1] It stands at the eastern side of the *temenos* of the Serapeum of Alexandria, beside the ruins of the temple of Serapis itself. The erroneous name and association with Pompey stems from historical misreading of the Greek dedicatory inscription on the base.[2]

Pompey's Pillar

Pompey's Pillar

Shown within Egypt

Location	Egypt Alexandria, Egypt
Coordinates	31"10'56.98.N 29'53'47.23.E
Type	Roman triumphal column
Diameter	c. 2.7-2.8 m (column shah)
Height	c. 33.85m (total original with 7 m statue) 26.85 m (present total)

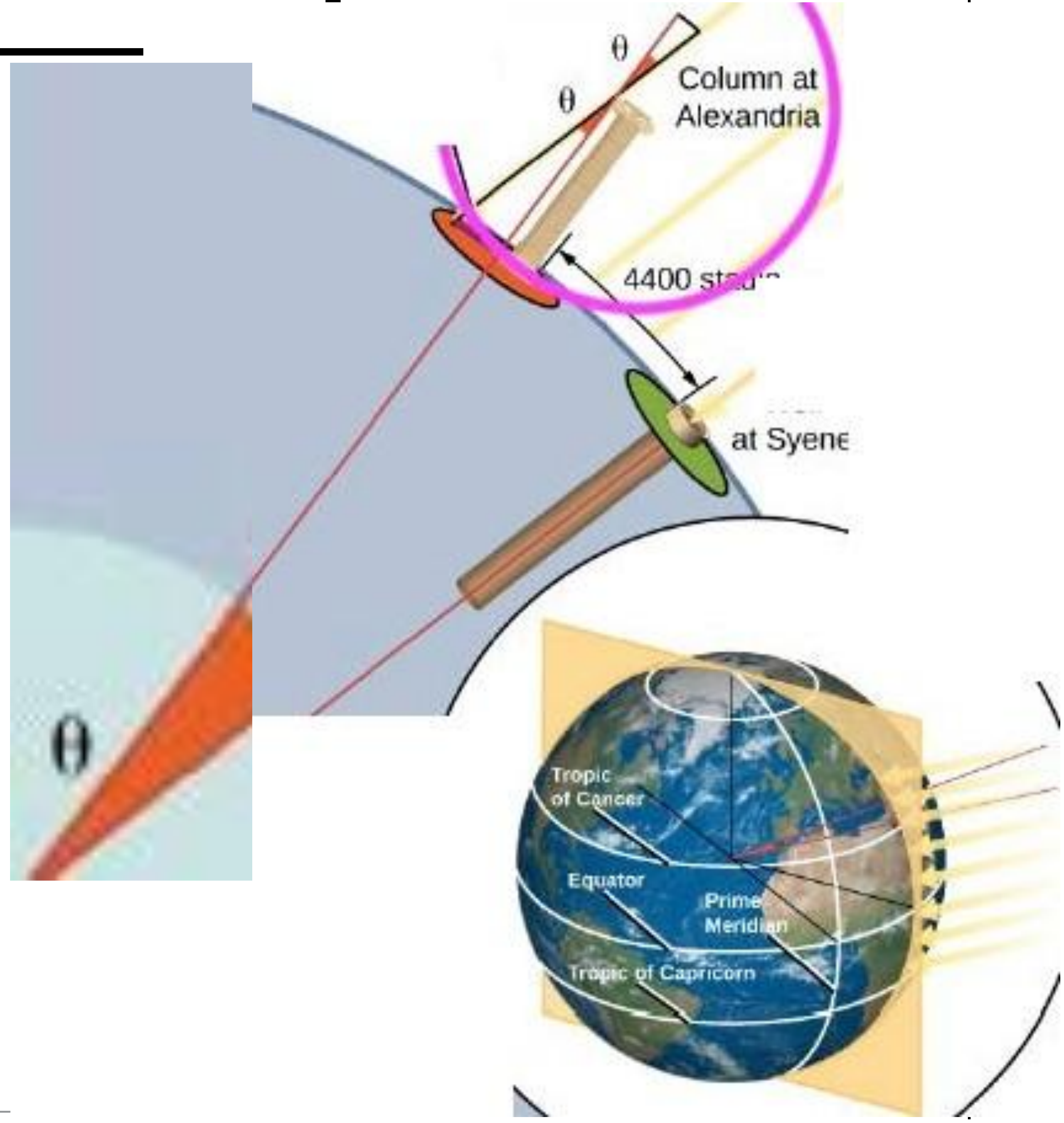
Contents (hide)

1 Construction
2 Ascents
3 See also
4 Notes
5 References
6 Sources

Construction [edit]

In 297 Diocletian, *Augustus* since 284, campaigned in Egypt to suppress the revolt of the usurper Domitius Domitianus. After a long siege, Diocletian captured Alexandria and executed Domilianus's successor Aurelius Achilleus in 298. In 302 the emperor returned to the city and inaugurated a state grain supply.[2] The dedication of the column monument and its statue of Diocletian, describes Diocletian as *po/iouchos* (Ancient Greek: noA1ooxov AAe avl>pe(ac;, romanized: *poliouchon Alexandreias,* lit.'city-guardian-god ACC of A!exandria'J.[3][4] In the founh century AD this designation also applied to Serapis, the malecounterpan of Isis in the pantheon instituted by the Hellenistic rulers of Egypt, the Ptolemies.[5][6] The sanctuary complex dedicated to Serapis in which the column was originally erected, the Serapeum, was built under King Ptolemy 111 Euergetes in the third century BC and probably rebuilt in the era of the second century AD emperor Hadrian after it sustained damage in the Kites Wars; in the later founh century AD it was considered by Ammianus Marcellinus a marvel rivalled only by Rome's sanctuary to Jupiter *Optimus Maximus* on the Capitoline Hill, the Capitolium.[7]

The monument stands some 26.85 m (88.1 ft) high, including its base and capital, and originally would have supponed a statue some 7 m (23 ft) tall.[2][8][1][1] The only known monolithic column in Roman Egypt (i.e., not composed of drums),[10] it is one of the largest ancient monoliths and one of the largest monolithic columns ever



1 Stadia = 180 m

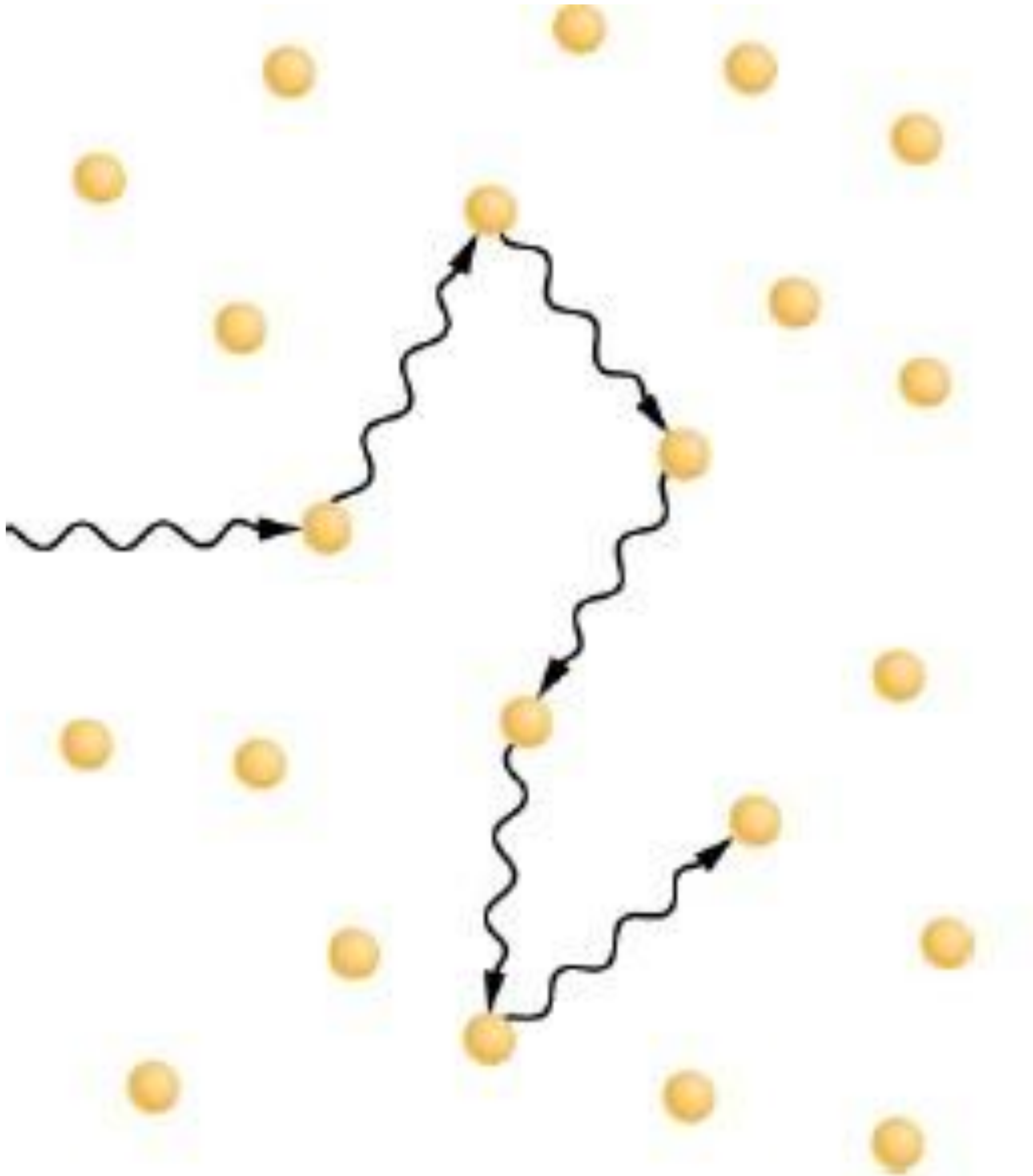
Shadow of Alexandria Column measures (1/50)th of a circle

Using the information presented here and using high school Maths, you can determine the Circumference & Diameter of Earth!

Can you do it in Google Colab with above picture (download here) embedded?

Session 3

Electromagnetic Radiation
Stellar Properties
Hertzsprung Russell Diagram



Photons absorbed and re-emitted on
the way to the surface of the Sun!

Figure 16.13 Photons Deep in the Sun. A photon moving through the dense gases in the solar interior travels only a short distance before it interacts with one of the surrounding atoms. The resulting photon usually has a lower energy after each interaction and may then travel in any random direction.

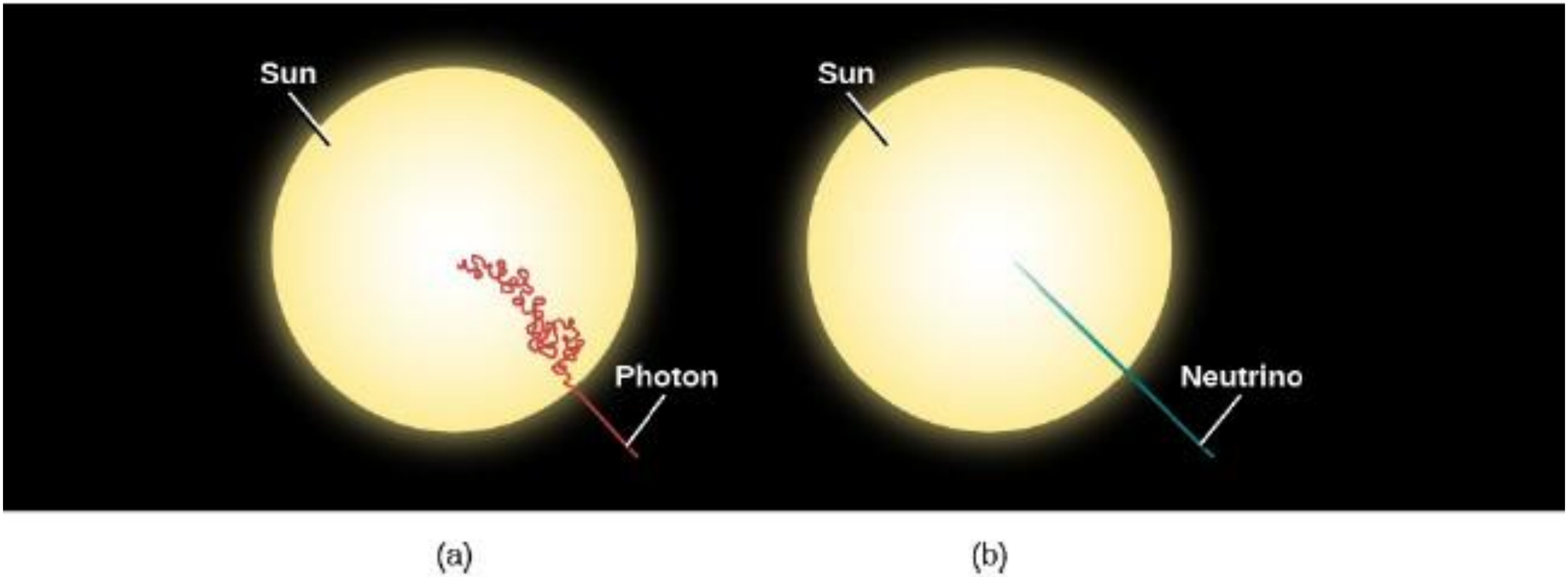
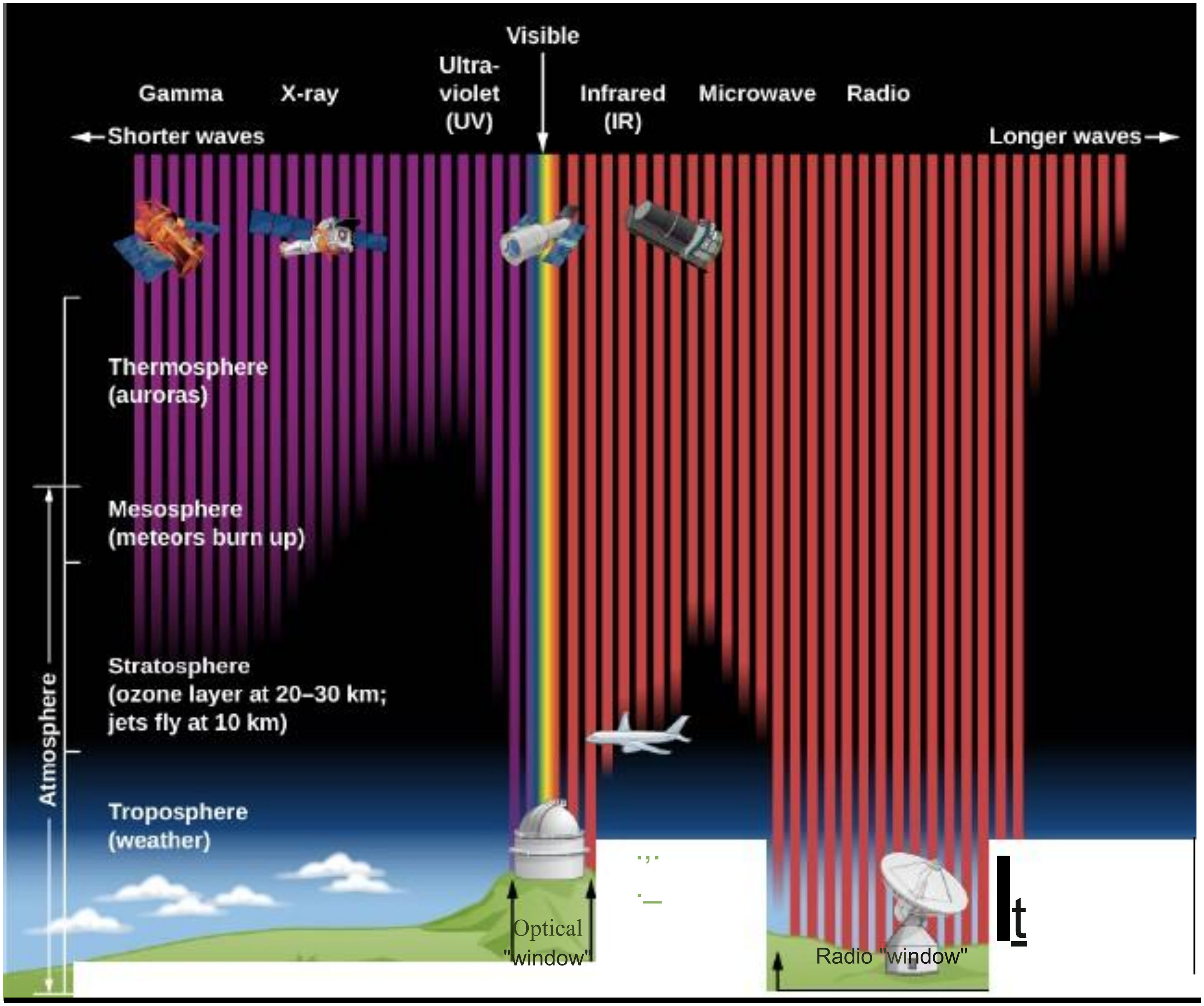


Figure 16.14 Photon and Neutrino Paths in the Sun. (a) Because photons generated by fusion reactions in the solar interior travel only a short distance before being absorbed or scattered by atoms and sent off in random directions, estimates are that it takes between 100,000 and 1,000,000 years for energy to make its way from the center of the Sun to its surface. (b) In contrast, neutrinos do not interact with matter but traverse straight through the Sun at the speed of light, reaching the surface in only a little more than 2 seconds.

Light might take up to 1,000,000 years to reach the surface of the Sun from its center!

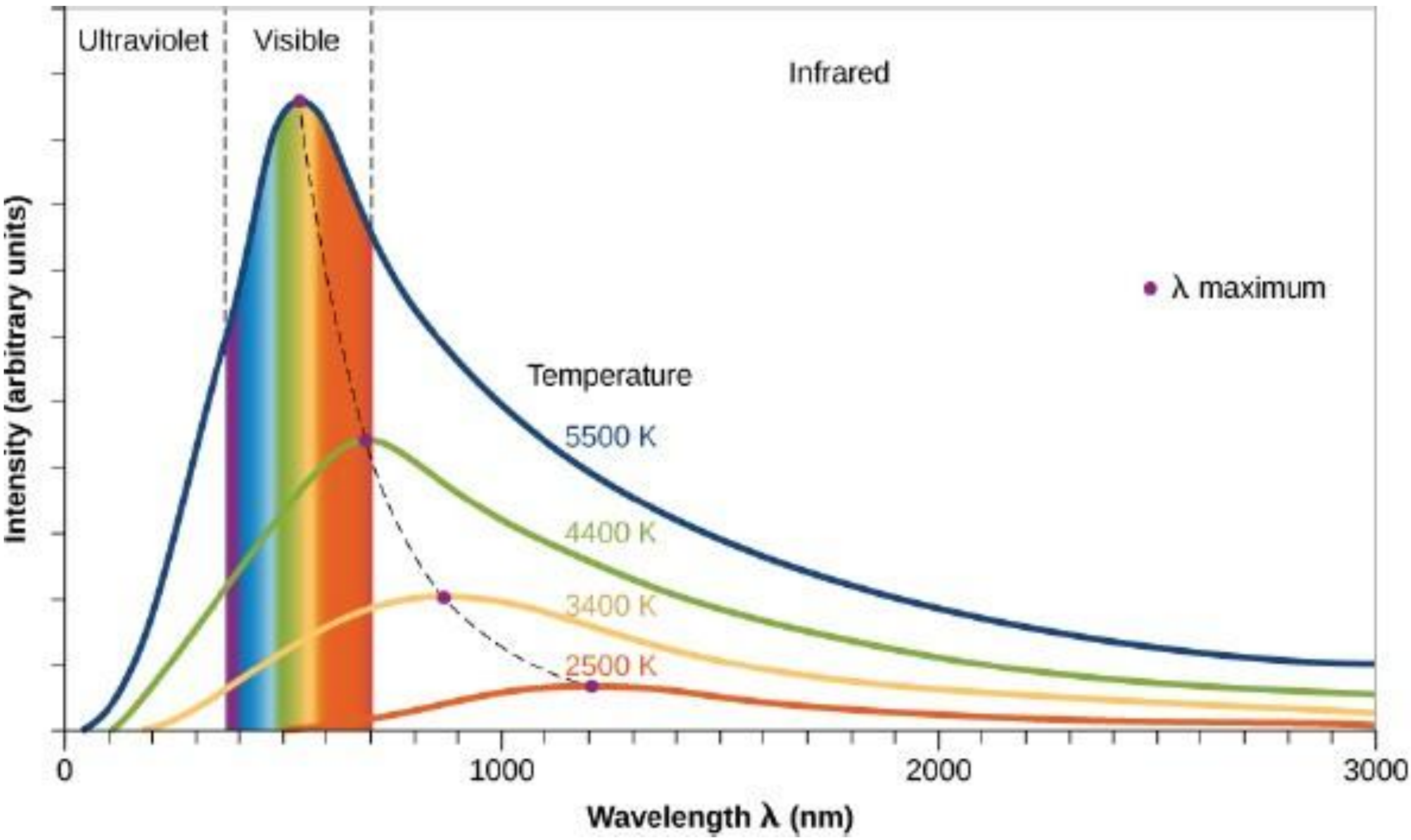
Can you do the calculation in colab as to how long it will take to reach Earth from the surface of the Sun? Embed pictures above!



Visible
Gamma
X-ray
Ultra-
violet
(UV)
Infrared
(IR)
Microwave
Radio
Shorter waves
Longer waves
Thermosphere
(auroras)
Mesosphere
(meteors burn up)
Stratosphere
(ozone layer at 20–30 km;
jets fly at 10 km)
Troposphere
(weather)
Atmosphere
Optical
"window"
Radio "window"

Types of Electromagnetic Radiation

Type of Radiation	Wavelength Range (nm)	Radiated by Objects at This Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^8 K	Produced in nuclear reactions; require very high-energy processes
X-rays	0.01–20	10^6–10^8 K	Gas in clusters of galaxies, supernova remnants, solar corona
Ultraviolet	20–400	10^4–10^6 K	Supernova remnants, very hot stars
Visible	400–700	10^3–10^4 K	Stars
Infrared	10^3–10^6	10–10^3 K	Cool clouds of dust and gas, planets, moons
Microwave	10^6–10^9	Less than 10 K	Active galaxies, pulsars, cosmic background radiation
Radio	More than 10^9	Less than 10 K	Supernova remnants, pulsars, cold gas


Ultraviolet
Visible
Infrared
λ maximum
Temperature
5500 K
4400 K
3400 K
2500 K
Intensity (arbitrary units)
0
1000
2000
3000
Wavelength λ (nm)

Star Properties

Mass & Luminosity (Magnitude)

Stars are born with a wide variety of ***mass***. The most massive stars are 100 times more massive than the Sun while the least massive ones are only 0.08 times the mass of the Sun. Most stars spend about 90% of their lifetimes shining due to nuclear fusion that goes on in their cores, but after awhile they evolve and begin to die. How long they live and what they evolve to become when they die depends on their mass. In fact, the mass of a star also determines its most important properties: its luminosity, temperature and radius.

A star's **luminosity**, which is how much energy is emitted per second from the star, is measured in Watts or in solar luminosities ($L_{\odot}$) where $1L_{\odot} = 3.85 \times 10^{26}$ Watt. We determine a star's luminosity by measuring its distance and its apparent brightness, which we call its apparent magnitude. Knowing those two, we can calculate its absolute magnitude, which is how bright the star would be if it were 10 parsecs away from us, and its luminosity relative to the Sun.

Temperature & Radius

A star's **temperature** is the temperature of the gas on the surface of the star. We measure temperature on the Kelvin scale, in which 0 K means that an object has absolutely zero energy. Note that the temperature of the surface of a star is much lower than the temperature in the interior of the star where nuclear reactions happen. For example, the Sun's surface temperature is approximately 6,000 K, but the temperature at the center of the Sun is 15,000,000 K! That is why nuclear reactions only happen in the interiors of stars.

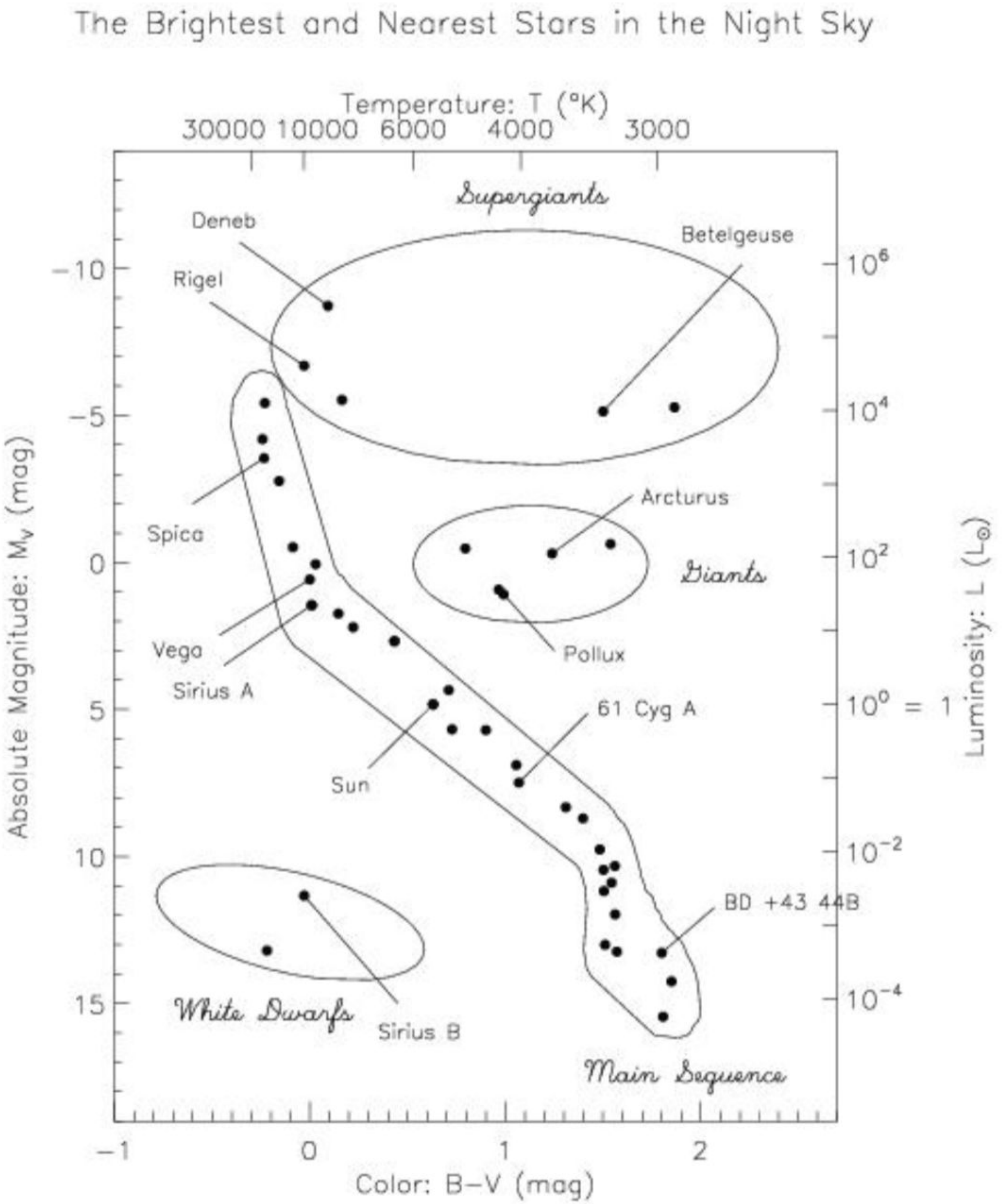
A star's ***radius*** is simply half the star's diameter. Stars are simply large balls of gas held together by gravity, and they are approximately spherical in shape. Radii of stars can be measured in meters, but because stars are so very large that its much more convenient to measure stellar radii in units of the Sun's radius, where 1 R☉ = 6.96 x 10^8 m.

Stefan's law:

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

Temperature of a Star is related to its color!

Hertzsprung Russell Diagram: Mass, Radius, Luminosity, Temperature, Color, Distance, Lifetimes



Star Magnitudes

how do you measure brightness?

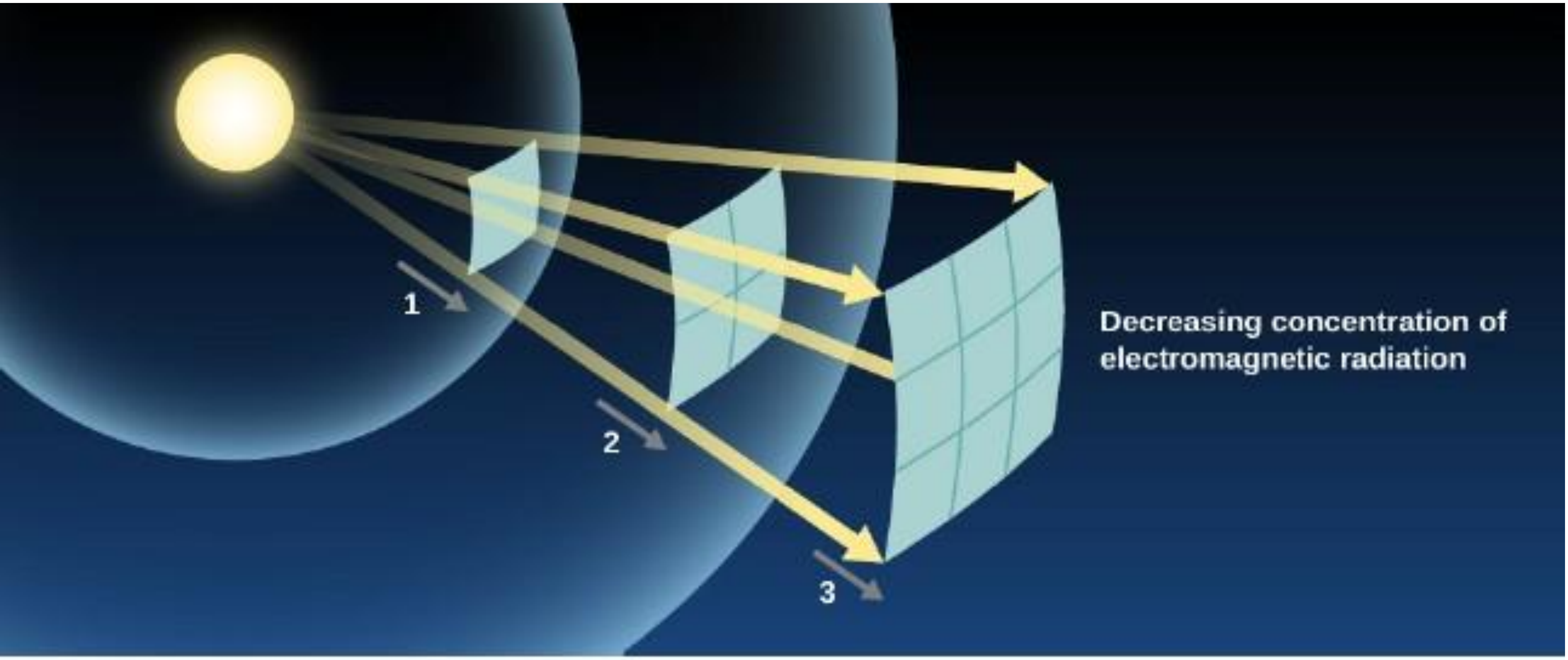


Figure 5.5 Inverse Square Law for Light. As light radiates away from its source, it spreads out in such a way that the energy per unit area (the amount of energy passing through one of the small squares) decreases as the square of the distance from its source.

Brightness decreases in proportion to the square of the distance
This is because the surface area of a sphere of radius ‘r’ is
Brightness ‘b’ is inversely proportional to Distance ‘r’
So, how much brighter is star2 than star1 if it is twice, ½ or 3 times the distance of star1?

Can you do this in Colab with this picture embedded?

Hipparchus Magnitude Scale

Hipparchus did not have a telescope or any instrument that could measure apparent brightness accurately, so he simply made estimates with his eyes. He sorted the stars into six brightness categories, each of which he called a **magnitude**. He referred to the brightest stars in his catalog as first-magnitudes stars, whereas those so faint he could barely see them were sixth-magnitude stars. During the nineteenth century, astronomers attempted to make the scale more precise by establishing exactly how much the apparent brightness of a sixth-magnitude star differs from that of a first-magnitude star. Measurements showed that we receive about 100 times more light from a first-magnitude star than from a sixth-magnitude star. Based on this measurement, astronomers then defined an accurate magnitude system in which a difference of five magnitudes corresponds exactly to a brightness ratio of 100:1. In addition, the magnitudes of stars are decimalized; for example, a star isn't just a "second-magnitude star," it has a magnitude of 2.0 (or 2.1, 2.3, and so forth). So what number is it that, when multiplied together five times, gives you this factor of 100? Play on your calculator and see if you can get it. The answer turns out to be about 2.5, which is the fifth root of 100. This means that a magnitude 1.0 star and a magnitude 2.0 star differ in brightness by a factor of about 2.5. Likewise, we receive about 2.5 times as much light from a magnitude 2.0 star as from a magnitude 3.0 star. What about the difference between a magnitude 1.0 star and a magnitude 3.0 star? Since the difference is 2.5 times for each "step" of magnitude, the total difference in brightness is $2.5 \times 2.5 = 6.25$ times.

Magnitude	1	2	3	4	5	6
Brightness	1					100
Multiplication Factor	1	??	??	??	??	??

Mag 1 Star is 100 times as bright as Mag 6 Star

What same number multiplied 5 times gives you 100 ??

EXAMPLE 5.2

The Inverse Square Law for Light

The intensity of a 120-W lightbulb observed from a distance 2 m away is 2.4 W/m^2. What would be the intensity if this distance was doubled?

Solution

If we move twice as far away, then the answer will change according to the inverse square of the distance, so the new intensity will be $(1/2)^2 = 1/4$ of the original intensity, or 0.6 W/m^2.

Check Your Learning

How many times brighter or fainter would a star appear if it were moved to:

a. twice its present distance?

b. ten times its present distance?

c. half its present distance?

Apparent vs Absolute Magnitude

An object's absolute magnitude is defined to be equal to the apparent magnitude that the object would have if it were viewed from a distance of exactly 10 parsecs (32.6 light-years)

1 2 3 4 5 6 ← mag scale

| 1 | 2 | 3 | 4 | 5 |

5 intervals for a 100 factor change in brightness

Ratio of brightness $= \left(\sqrt[5]{100}\right)^{\text{Difference in magnitude}}$

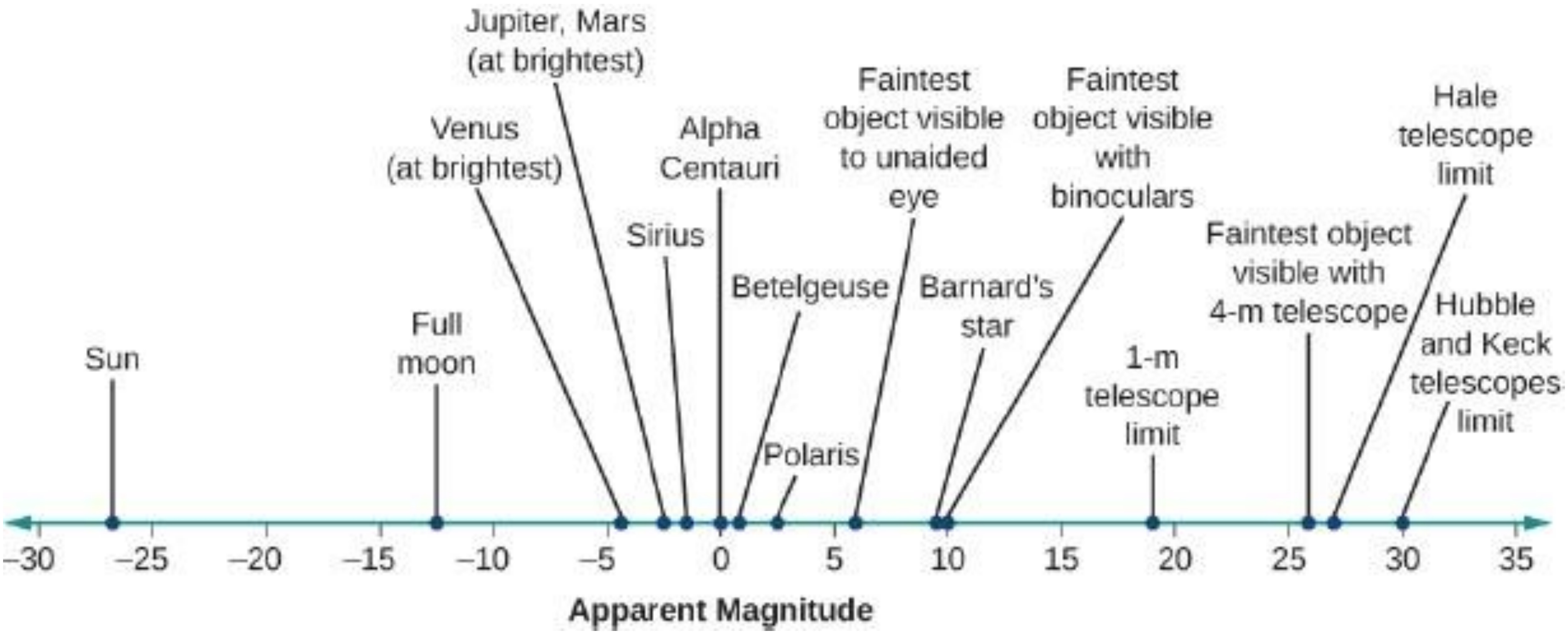
$$\frac{b_2}{b_1} = (100)^{\frac{m_1 - m_2}{5}}$$

$$\log\left(\frac{b_2}{b_1}\right) = \frac{m_1 - m_2}{\cancel{5}\ 2.5}\ \cancel{\log 100}^{\,2}$$

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

Mag diff

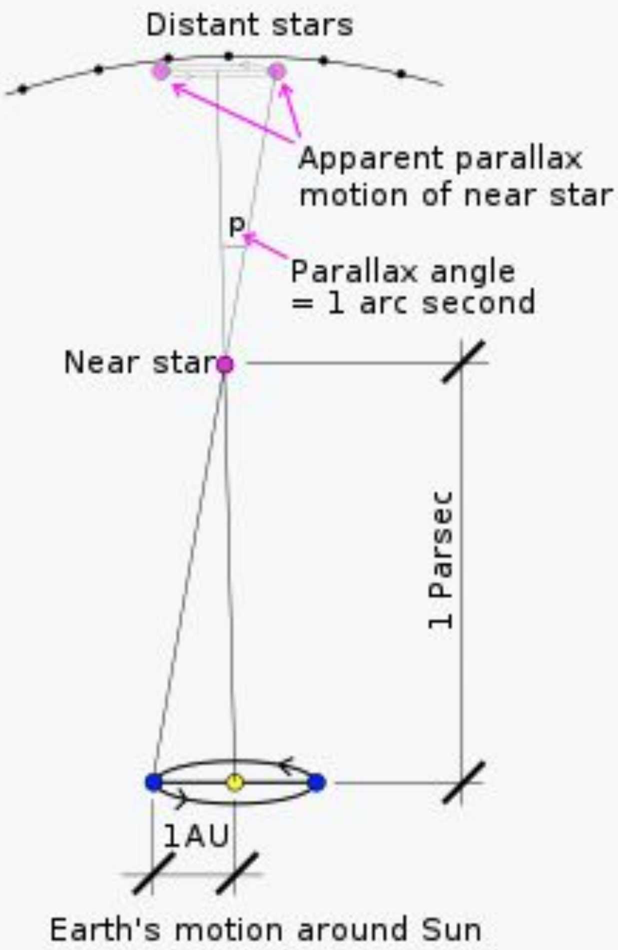
Lum. Ratio



Sun
Full moon
Venus (at brightest)
Jupiter, Mars (at brightest)
Sirius
Alpha Centauri
Betelgeuse
Polaris
Faintest object visible to unaided eye
Barnard's star
Faintest object visible with binoculars
1-m telescope limit
Faintest object visible with 4-m telescope
Hale telescope limit
Hubble and Keck telescopes limit
–30
–25
–20
–15
–10
–5
0
5
10
15
20
25
30
35
Apparent Magnitude

Parallax Angle (pa) and Distance in Parsec (pc)

Parsec



A parsec is the distance from the Sun to an astronomical object that has a parallax angle of one arcsecond (not to scale)

General information

Unit system	astronomical units
Unit of	length/distance
Symbol	pc

Conversions

1 pc *in ...*	*... is equal to ...*
metric (SI) units	3.0857×10^{16} m ~31 petametres
imperial & US units	1.9174×10^{13} mi
astronomical units	$2.062\,65 \times 10^{5}$ au 3.261 56 ly

How do you measure stellar distance?

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

Mag diff

Lum. Ratio

$$m_{10} - m_d = 2.5 \log\left(\frac{b_d}{b_{10}}\right) = 2.5 \log\left(\frac{d}{10}\right)^2$$

$$= 2.5 \times 2 \log\left(\frac{d}{10}\right)$$

$$= 5 \log\left(\frac{d}{10}\right)$$

EXAMPLE 17.1

The Magnitude Equation

Even scientists can't calculate fifth roots in their heads, so astronomers have summarized the above discussion in an equation to help calculate the difference in brightness for stars with different magnitudes. If m1 and m2 are the magnitudes of two stars, then we can calculate the ratio of their

brightness using this equation:

$$m_1 - m_2 = 2.5 \log\left(\frac{b_2}{b_1}\right) \quad \text{or} \quad \frac{b_2}{b_1} = 2.5^{m_1 - m_2}$$

Here is another way to write this equation:

$$\frac{b_2}{b_1} = \left(100^{0.2}\right)^{m_1 - m_2}$$

Check Your Learning

It is a common misconception that Polaris (magnitude 2.0) is the brightest star in the sky, but, as we saw, that distinction actually belongs to Sirius (magnitude -1.5). How does Sirius' apparent brightness

compare to that of Polaris?

Answer:

$$\frac{b_{\text{Sirius}}}{b_{\text{Polaris}}} = \left(100^{0.2}\right)^{2.0 - (-1.5)} = \left(100^{0.2}\right)^{3.5} = 100^{0.7} = 25$$

(Hint: If you only have a basic calculator, you may wonder how to take 100 to the 0.7th power. But this is something you can ask Google to do. Google now accepts mathematical questions and will answer them. So try it for yourself. Ask Google, "What is 100 to the 0.7th power?")

Our calculation shows that Sirius' apparent brightness is 25 times greater than Polaris' apparent brightness.

compare to that of Polaris?

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Our calculation shows that Sirius' apparent brightness is 25 times greater than Polaris' apparent brightness.

Relationship between Apparent Magnitude, Absolute Magnitude and Distance

Apparent Magnitude

Apparent magnitude m of a star is a number that tells how bright that star appears at its great distance from Earth. The scale is "backwards" and logarithmic. Larger magnitudes correspond to fainter stars. Note that brightness is another way to say the *flux of light*, in Watts per square meter, coming towards us.

On this magnitude scale, a brightness ratio of 100 is set to correspond exactly to a magnitude difference of 5. As magnitude is a logarithmic scale, one can always transform a brightness ratio B_2/B_1 into the equivalent magnitude difference m_2-m_1 by the formula:

$m_2-m_1 = -2.50 \log(B_2/B_1)$.

You can check that for brightness ratio $B_2/B_1=100$, we have $\log(B_2/B_1) = \log(100) = \log(10^2) = 2$, and then $m_2-m_1=-5$, the basic definition of this scale (brighter is more negative m). One then has the following magnitudes and their corresponding relative brightnesses:

magnitude m	0	1	2	3	4	5	6	7	8	9	10
relative brightness ratios	1	2.5	6.3	16	40	100	250	630	1600	4000	10,000

(Note that the lower row of numbers is just $(2.512)^m$.)

Absolute Magnitude

Absolute magnitude M_v is the apparent magnitude the star would have if it were placed at a distance of 10 parsecs from the Earth. Doing this to a star (it is a little difficult), will either make it appear brighter or fainter. From the *inverse square law for light*, the ratio of its brightness at 10 pc to its brightness at its known distance d (in parsecs) is

$B_{10}/B_d=(d/10)^2$.

Then, like the formula above, we say that its absolute magnitude is

$M_v = m - 2.5 \log[(d/10)^2]$.

Stars farther than 10 pc have M_v more negative than m, that is why there is a minus sign in the formula. If you use this formula, make sure you put the star's distance d in *parsecs* (1 pc = 3.26 ly = 206265 AU).

Distance Determination

The above relation can also be used to determine the distance to a star if you know both its apparent magnitude and absolute magnitude. This would be the case, for example, when one uses Cepheid or other variable stars for distance determination. Turning the formula inside out:

$d = (10\ \text{pc}) \times 10^{(m-M_v)/5}$

For example, for a Cepheid variable with $M_v = -4$, and m = 18, the distance is

$d = (10\ \text{pc}) \times 10^{[18-(-4)]/5} = 2.51 \times 10^5$ pc.

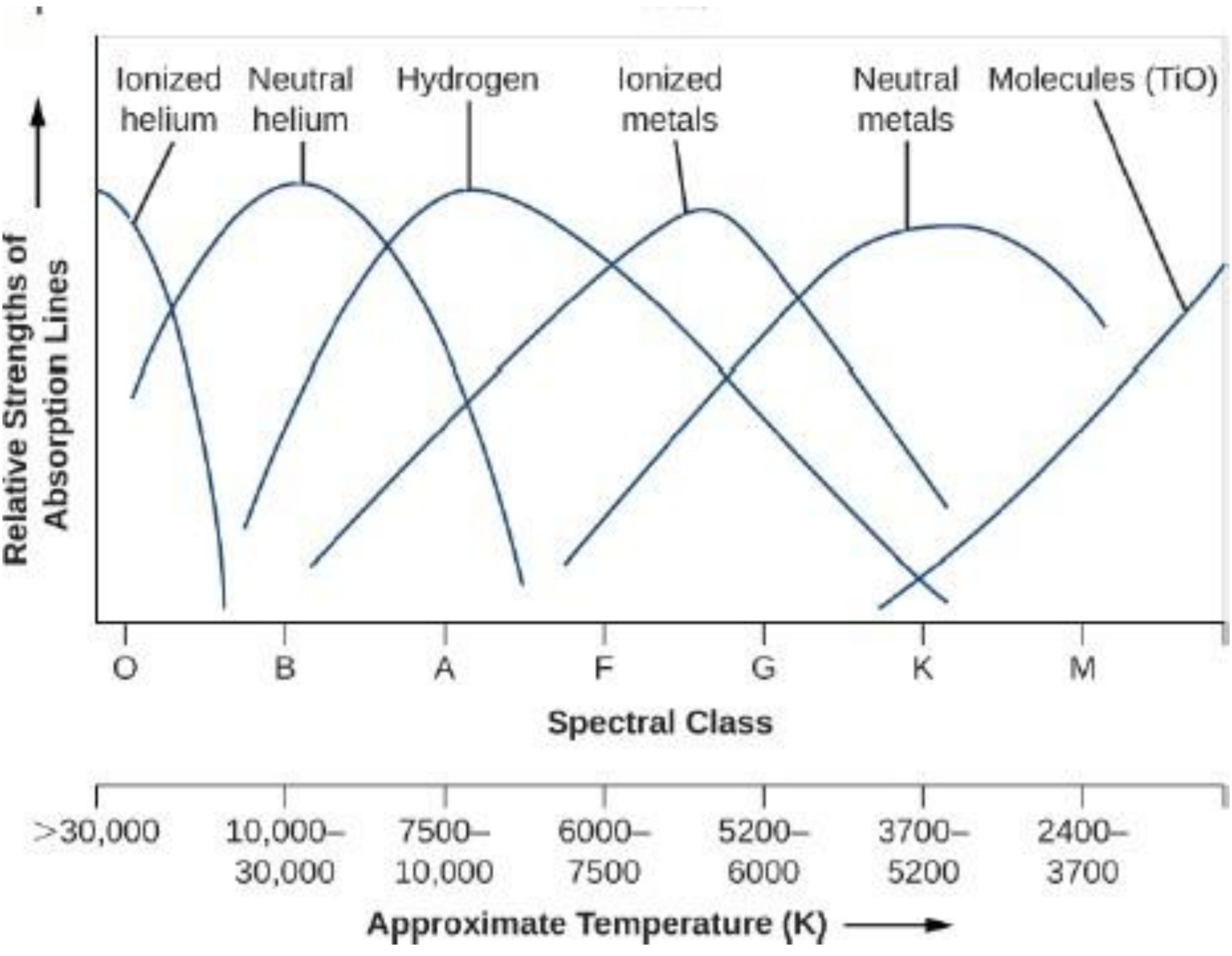
Session 4
Reading the HRD
Stellar Lifetimes
Star Colors
Stellar Distances

Taken from APOD. Credit and Copyright: Stefan Seip

Example Star Colors and Corresponding Approximate Temperatures

Star Color	Approximate Temperature	Example
Blue	25,000 K	Spica
White	10,000 K	Vega
Yellow	6000 K	Sun
Orange	4000 K	Aldebaran
Red	3000 K	Betelgeuse

Example Star Colors and Corresponding Approximate Temperatures



Ionized helium
Neutral helium
Hydrogen
Ionized metals
Neutral metals
Molecules (TiO)
Relative Strengths of Absorption Lines
O
B
A
F
G
K
M
Spectral Class
>30,000
10,000–30,000
7500–10,000
6000–7500
5200–6000
3700–5200
2400–3700
Approximate Temperature (K)

Spectral Classes for Stars

Spectral Class	Color	Approximate Temperature (K)	Principal Features	Examples
0	Blue	> 30,000	Neutral and ionized helium lines, weak hydrogen lines	10 Lacertae
B	Blue-white	10,000-30,000	Neutral helium lines, strong hydrogen lines	Rigel, Spica
A	White	7500-10,000	Strongest hydrogen lines, weak ionized calcium lines, weak ionized metal (e.g., iron, magnesium) lines	Sirius, Vega
F	Yellow-white	6000-7500	Strong hydrogen lines, strongionized cakium lines, weak sodium lines, many ionized metal lines	Canopus, Procyon
G	Yellow	5200-6000	Weaker hydrogen lines, strongionized calcium lines, strong sodium lines, many lines of ionized and neutral metals	Sun, Capella
K	Orange	3700-5200	Very weak hydrogen lines, strong ionized calcium lines, strong sodium lines, many lines of neutral metals	Arcturus, Aldebaran
M	Red	2400-3700	Strong lines of neutral metals and molecular bands of titanium oxide dominate	Betelgeuse, Antares
y	Infrared[1,1]	<700	Ammonia lines	WISE 1828+26 50
L	Red	1300-2400	Metal hydride lines, alkali metal lines (e.g., sodium, potassium, rubidium)	Teide 1
T	Magenta	700-1300	Methane lines	Gliese 2298

Stars within 21 Light-Years of the Sun

Spectral Type	Number of Stars
A	2
F	1
G	7
K	17
M	94
White dwarfs	8
Brown dwarfs	33

the *Hertzsprung–Russell diagram*, abbreviated **H–R diagram.** It is one of the most important and widely used diagrams in astronomy, with applications that extend far beyond the purposes for which it was originally developed more than a century ago.

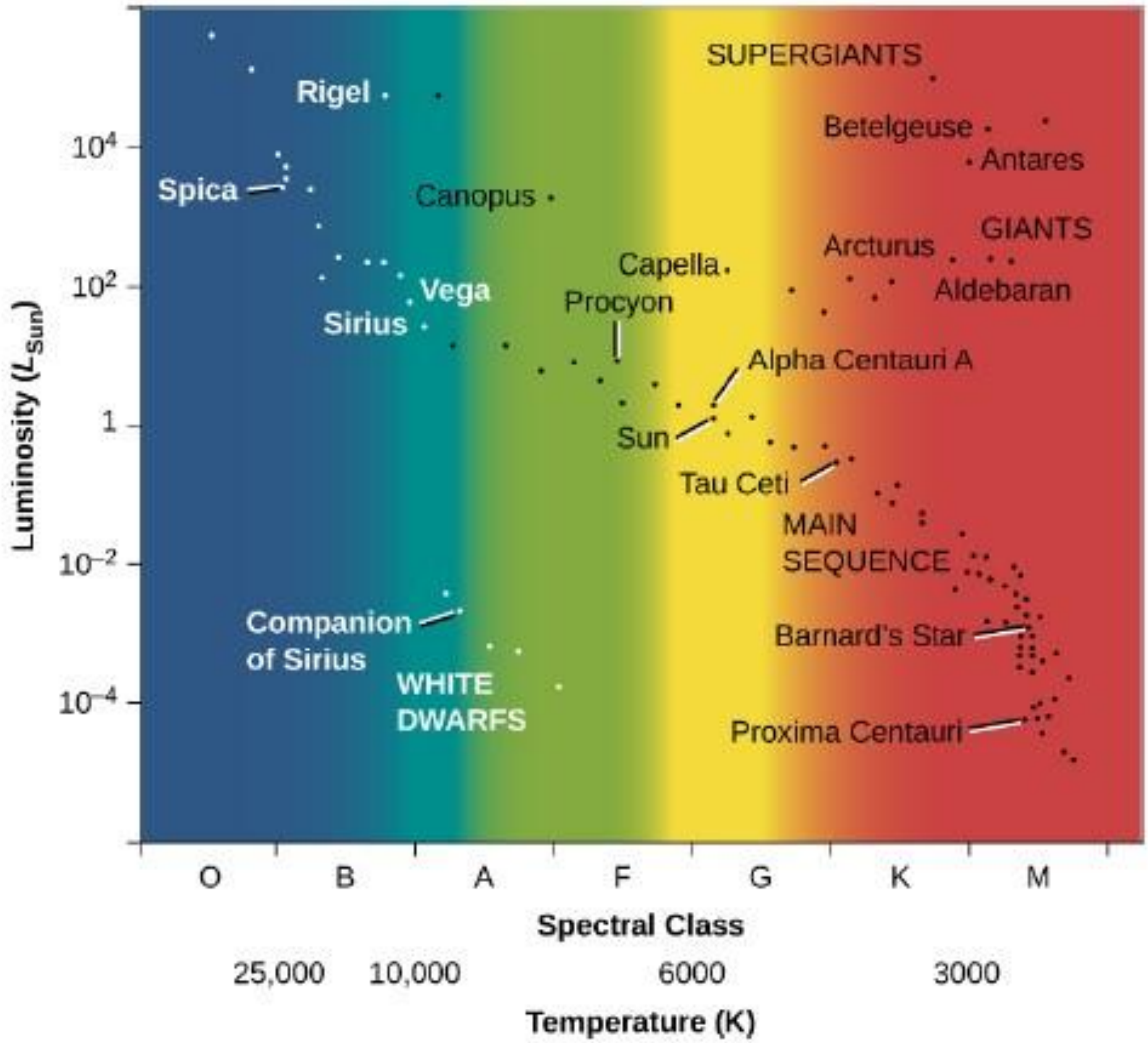


Figure 18.14 H–R Diagram for a Selected Sample of Stars. In such diagrams, luminosity is plotted along the vertical axis. Along the horizontal axis, we can plot either temperature or spectral type (also sometimes called spectral class). Several of the brightest stars are identified by name. Most stars fall on the main sequence.

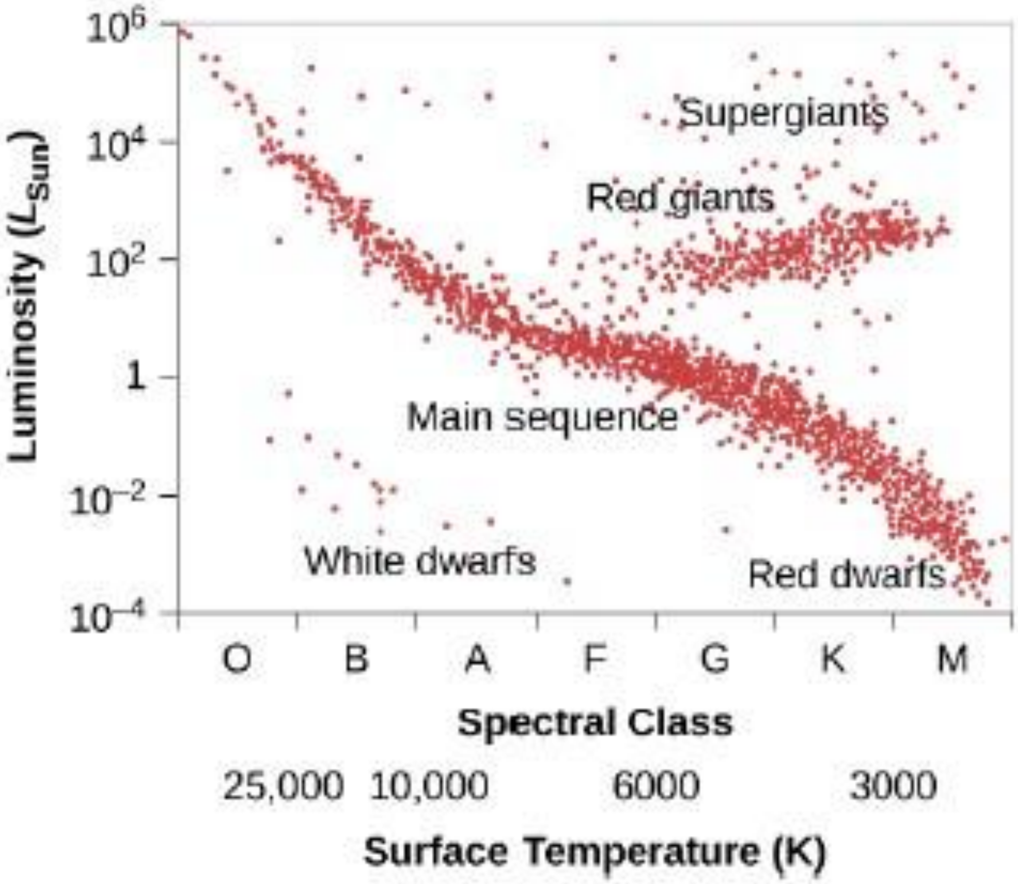
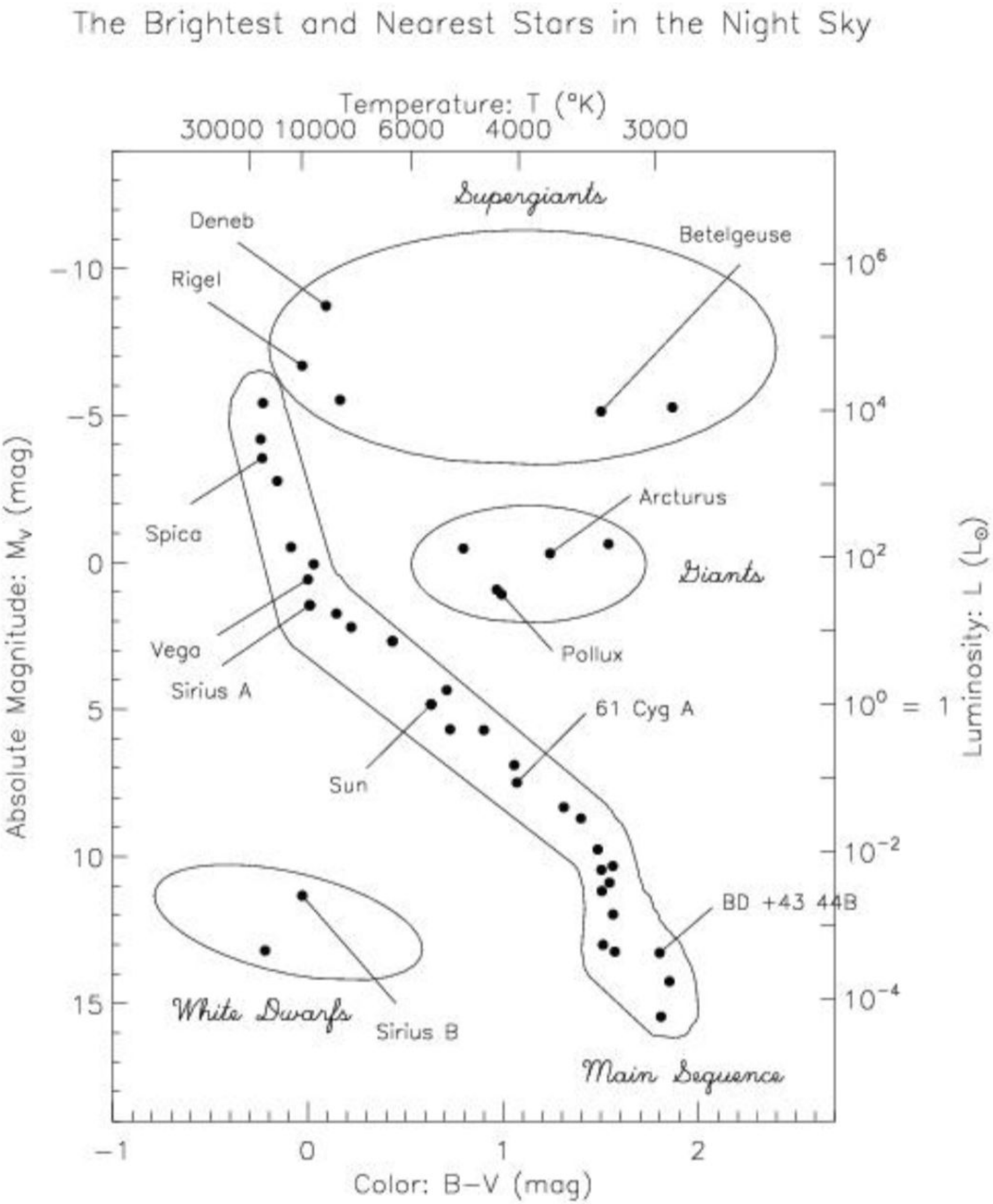


Figure 18.15 Schematic H–R Diagram for Many Stars. Ninety percent of all stars on such a diagram fall along a narrow band called the main sequence. A minority of stars are found in the upper right; they are both cool (and hence red) and bright, and must be giants. Some stars fall in the lower left of the diagram; they are both hot and dim, and must be white dwarfs.

Hertzsprung Russell Diagram: Mass, Radius, Luminosity, Temperature, Color, Distance, Lifetimes



Characteristics of Main-Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Temperature	Radius (Sun = 1)
O5	40	7×10^5	40,000 K	18
B0	16	2.7×10^5	28,000 K	7
A0	3.3	55	10,000 K	2.5
F0	1.7	5	7500 K	1.4
G0	1.1	1.4	6000 K	1.1
K0	0.8	0.35	5000 K	0.8
M0	0.4	0.05	3500 K	0.6

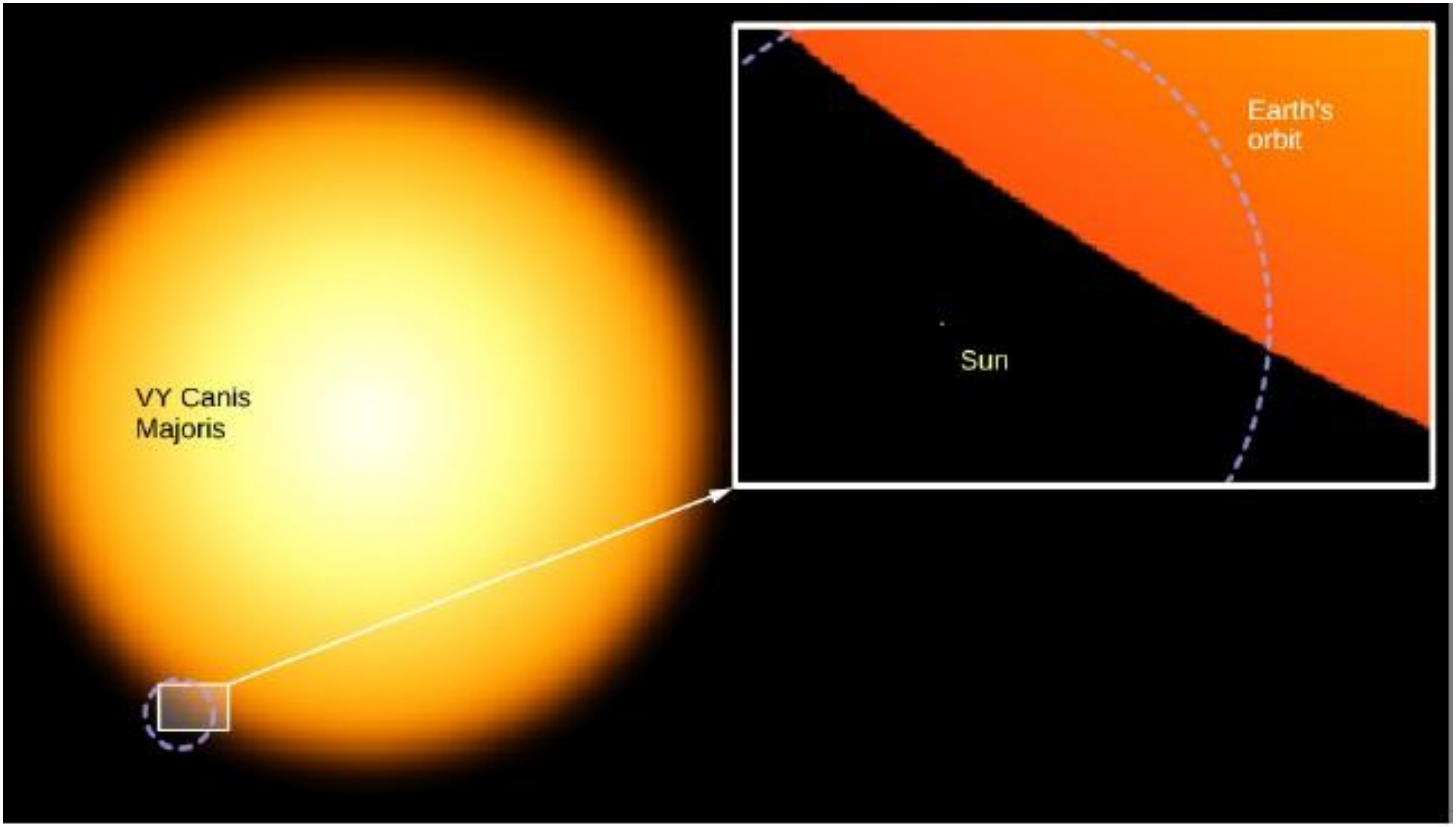
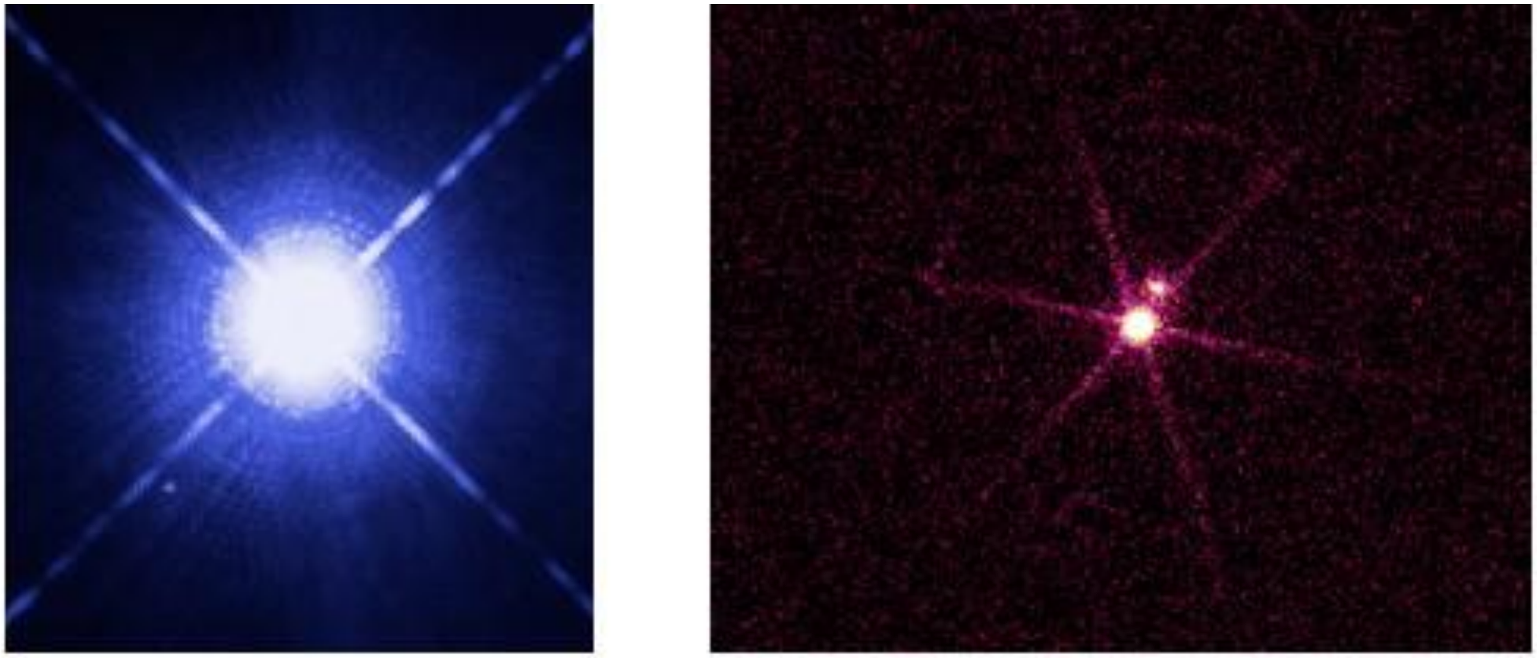


Figure 18.16 The Sun and a Supergiant. Here you see how small the Sun looks in comparison to one of the largest known stars: VY Canis Majoris, a supergiant.



(a) (b)

Figure 18.17 Two Views of Sirius and Its White Dwarf Companion. (a) The (visible light) image, taken with the Hubble Space Telescope, shows bright Sirius A, and, below it and off to its left, faint Sirius B. (b) This image of the Sirius star system was taken with the Chandra X-Ray Telescope. Now, the bright object is the white dwarf companion, Sirius B. Sirius A is the faint object above it; what we are seeing from Sirius is probably not actually X-ray radiation but rather ultraviolet light that has leaked into the detector. Note that the ultraviolet intensities of these two objects are completely reversed from the situation in visible light because Sirius B is hotter and emits more higher-frequency radiation. (credit a: modification of work by NASA, H.E. Bond and E. Nelan (Space Telescope Science Institute), M. Barstow and M. Burleigh (University of Leicester) and J.B. Holberg (University of Arizona); credit b: modification of work by NASA/SAO/CXC)

The Nearest Stars

No known star (other than the Sun) is within 1 light-year or even 1 parsec of Earth. The stellar neighbors nearest the Sun are three stars in the constellation of Centaurus. To the unaided eye, the brightest of these three stars is Alpha Centauri, which is only 30° from the south celestial pole and hence not visible from the mainland United States. Alpha Centauri itself is a binary star—two stars in mutual revolution—too close together to be distinguished without a telescope. These two stars are 4.4 light-years from us. Nearby is a third faint star, known as Proxima Centauri. Proxima, with a distance of 4.3 light-years, is slightly closer to us than the other two stars. If Proxima Centauri is part of a triple star system with the binary Alpha Centauri, as seems likely, then its orbital period may be longer than 500,000 years.

Proxima Centauri is an example of the most common type of star, and our most common type of stellar neighbor (as we saw in Stars: A Celestial Census.) Low-mass red M dwarfs make up about 70% of all stars and dominate the census of stars within 10 parsecs (33 light-years) of the Sun. For example, a recent survey of the solar neighborhood counted 357 stars and brown dwarfs within 10 parsecs, and 248 of these are red dwarfs. Yet, if you wanted to see an M dwarf with your naked eye, you would be out of luck. These stars only produce a fraction of the Sun's light, and nearly all of them require a telescope to be detected.

The nearest star visible without a telescope from most of the United States is the brightest appearing of all the stars, Sirius, which has a distance of a little more than 8 light-years. It too is a binary system, composed of a faint white dwarf orbiting a bluish-white, main-sequence star. It is an interesting coincidence of numbers that light reaches us from the Sun in about 8 minutes and from the next brightest star in the sky in about 8 years.

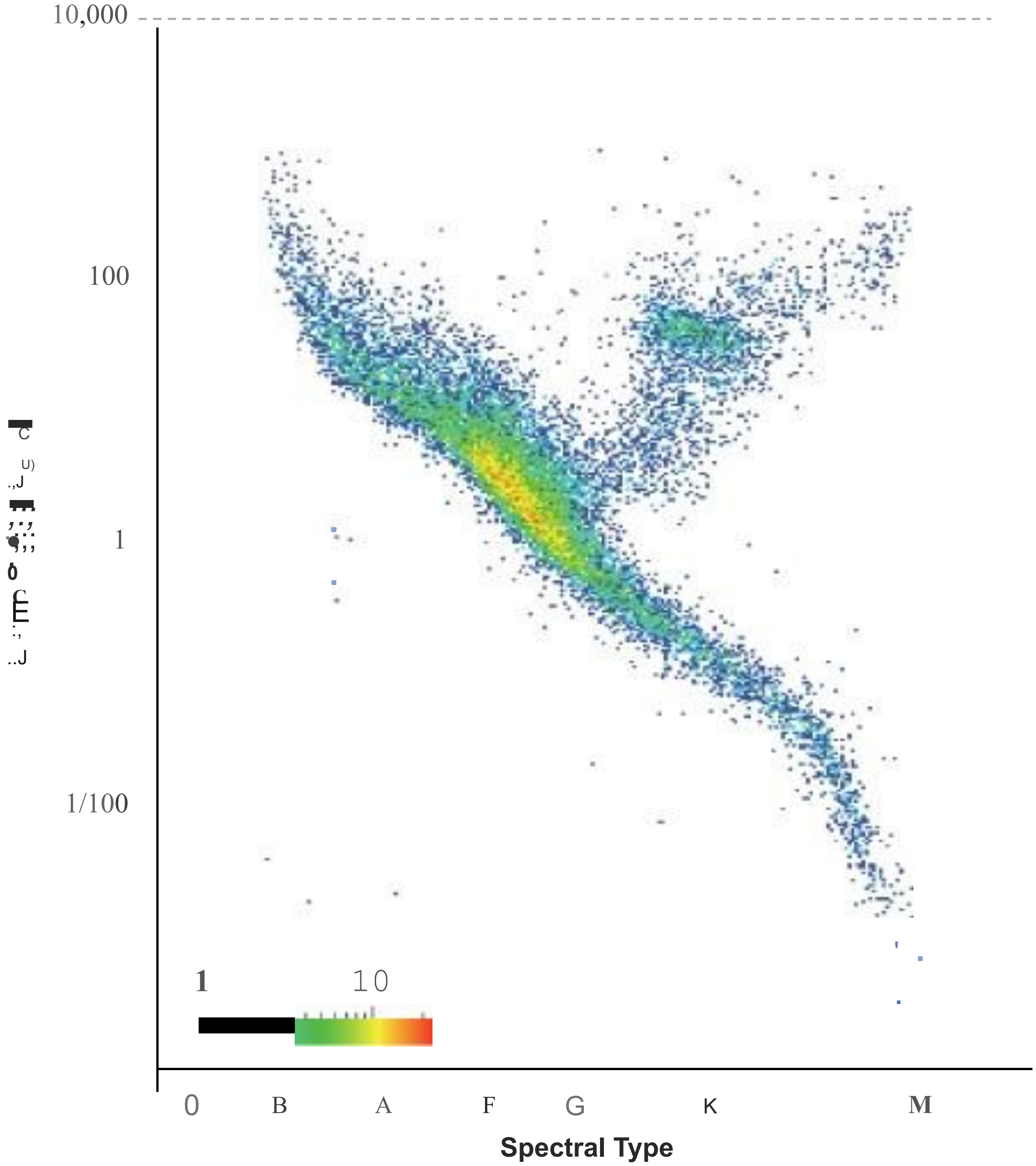


Figure 19.8 H-R Diagramof Stars Measured by Galaand Hipparcos. This pk>< indudes16,631starsfor whichthe parallaxeshavean accuracy of1°"'orbetter. Thecolorsindicate the numbersof starsat each point of the diagram with red corresponding to the largest number and blue to the lowest.Luminosity is ploc:tedalong the verticalaxis,withluminosity increasing upward.An infrared coloris plottedas *a*proxy for temperature. with temperature decreasing to the right.Mostof the datapointsare distributed along the diagonal running fromthetople corner(high luminosity, hightemperature} to the bottomright(low temperature, low luminosity}. Theseare mainsequence stars. Thelarge clumpor datapointsabovethe main sequence on the rightsideof the diagram is composedof red giantstars.(credit: modification or work by theEuropean SpaceAgency)

The mostwidely used system of star dassification divides stars of a given spectral class into six categories called luminosity classes. These luminosity classes are denoted by Roman numbers as follows:

Ia: Brightest supergiants
Ib: Less luminous supergiants II:

Bright giants

III: Giants
IV: Subgiants (intermediate between giants and main-sequence stars) V:

Main-sequence stars

The full spectral specification of a star includes its luminosity class. For example, a main-sequence star with spectral class F3 is wrinen as F3 V. The specification for an M2 giant is M2 III. Figure 19.15 illustrates the approximate position of stars of various luminosity classes on the H-R diagram. The dashed portions of the

lines represent regions with very few or no stars.

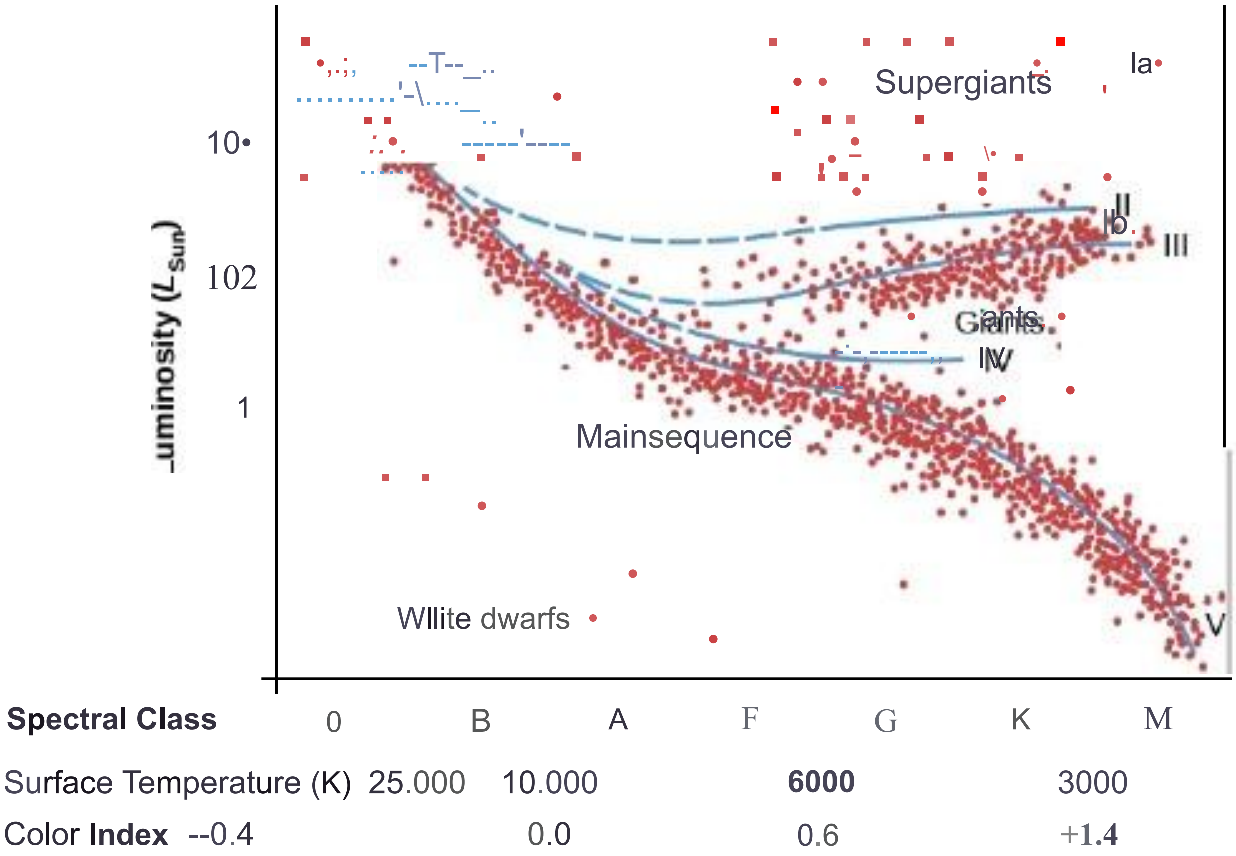


Figure 19.15 Luminosity Classes. Starsof the sametemperature (or spectralclass} can fallinto different fuminositydasseson the Herttsprung•Russell diagram. By studyingdetails of the spectrum for eachstar,astronomerscan determine which luminosity classthey fallin (whether theyaremain-sequence stars,giantstars. or supergiant stars).

Distance Range of Celestial Measurement Methods

Method	Distance Range
Trigonometric parallax	4–30,000 light-years when the Gaia mission is complete
RR Lyrae stars	Out to 300,000 light-years
H–R diagram and spectroscopic distances	Out to 1,200,000 light-years
Cepheid stars	Out to 60,000,000 light-years

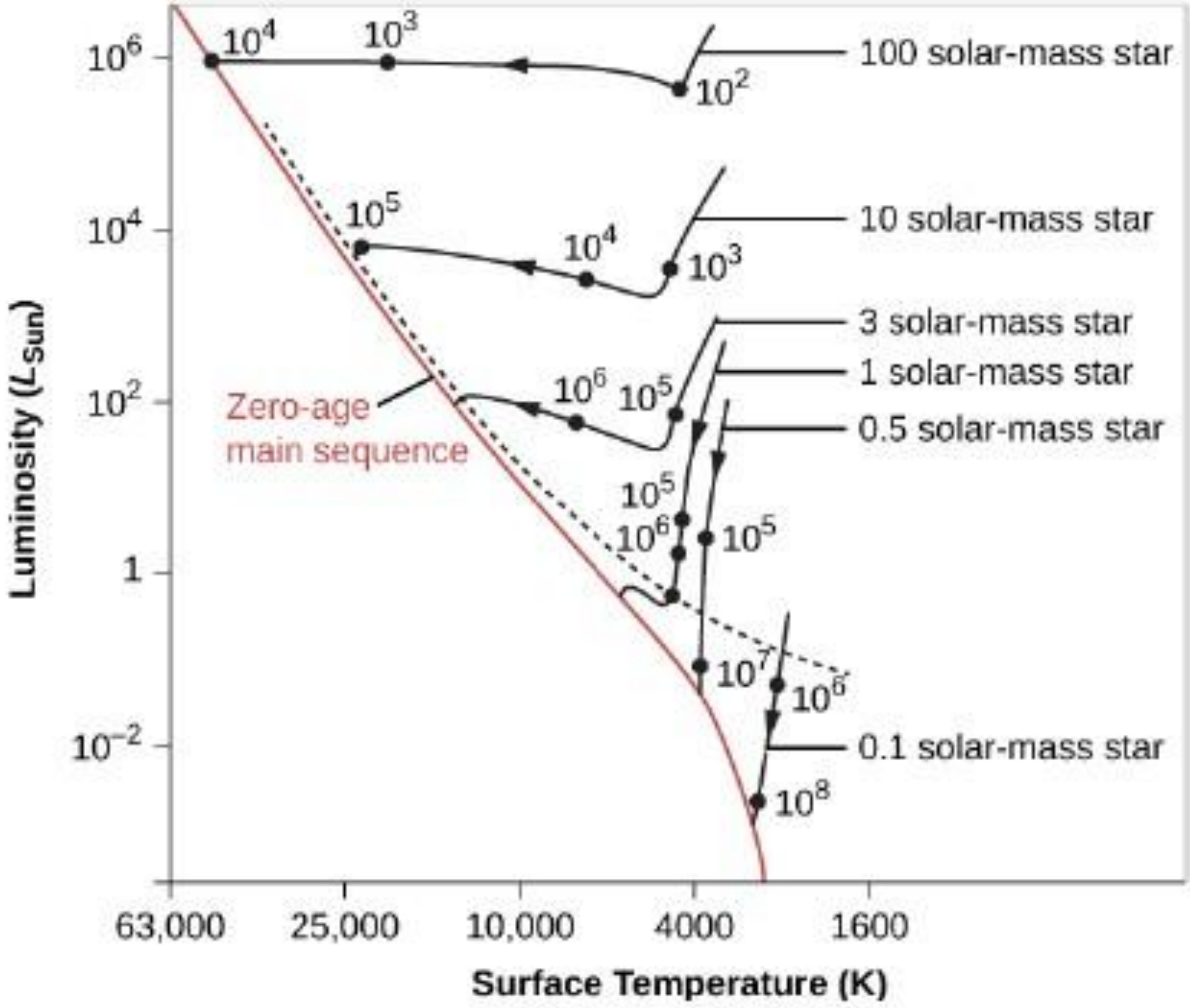


Figure 21.12 Evolutionary Tracks for Contracting Protostars. Tracks are plotted on the H–R diagram to show how stars of different masses change during the early parts of their lives. The number next to each dark point on a track is the rough number of years it takes an embryo star to reach that stage (the numbers are the result of computer models and are therefore not well known). Note that the surface temperature (K) on the horizontal axis increases toward the left. You can see that the more mass a star has, the shorter time it takes to go through each stage. Stars above the dashed line are typically still surrounded by infalling material and are hidden by it.

Lifetimes of Main-Sequence Stars

Spectral Type	Surface Temperature (K)	Mass (Mass of Sun = 1)	Lifetime on Main Sequence (years)
A0	9600	3.3	500 million
F0	7350	1.7	2.7 billion
G0	6050	1.1	9 billion
K0	5240	0.8	14 billion
M0	3750	0.4	200 billion

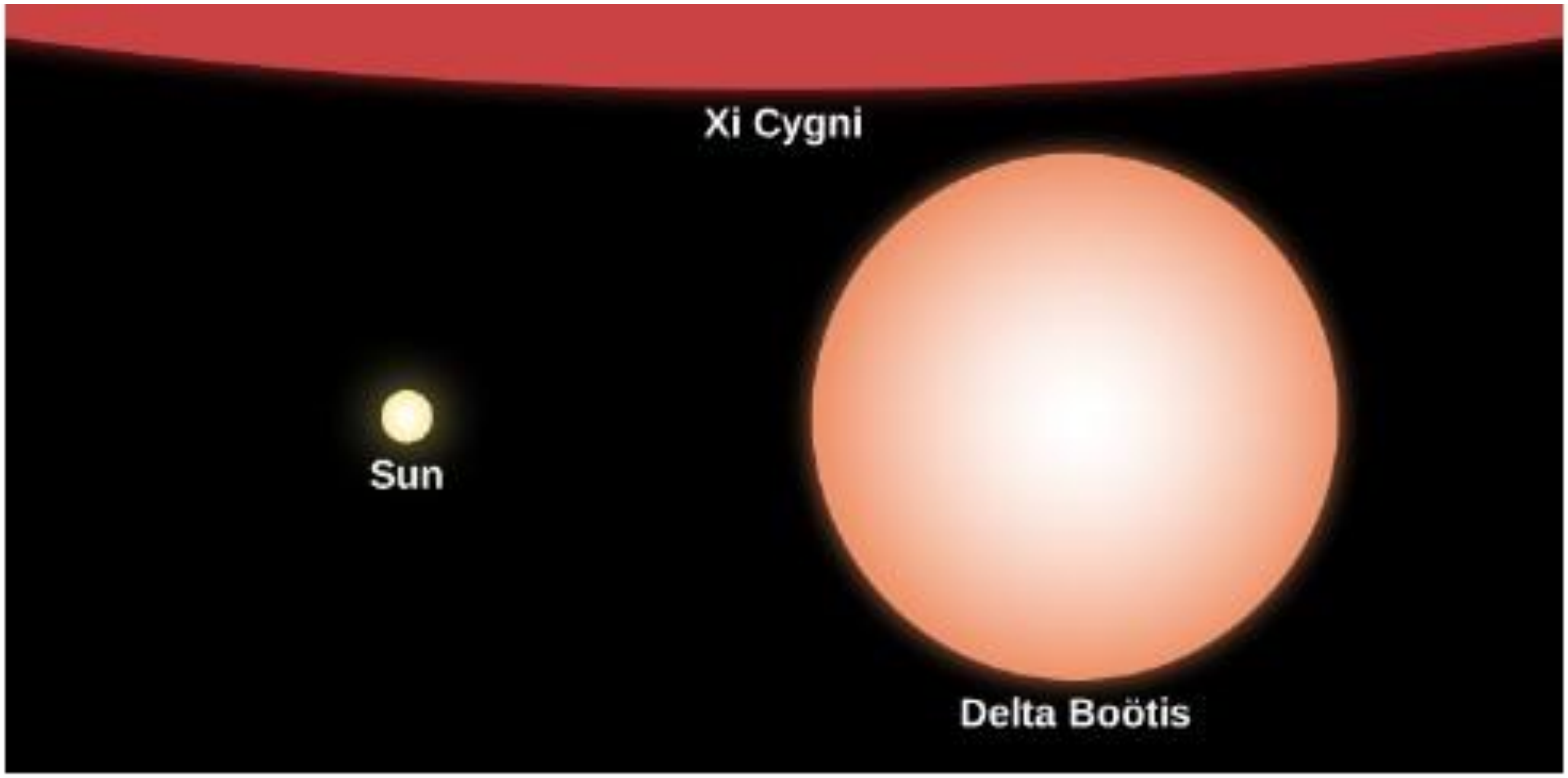


Figure 22.3 Relative Sizes of Stars. This image compares the size of the Sun to that of Delta Boötis, a giant star, and Xi Cygni, a supergiant. Note that Xi Cygni is so large in comparison to the other two stars that only a small portion of it is visible at the top of the frame.

Comparing a Supergiant with the Sun

Property	Sun	Betelgeuse
Mass (2×10^{33} g)	1	16
Radius (km)	700,000	500,000,000
Surface temperature (K)	5,800	3,600
Core temperature (K)	15,000,000	160,000,000
Luminosity (4×10^{26} W)	1	46,000
Average density (g/cm^3)	1.4	1.3×10^{-7}
Age (millions of years)	4,500	10

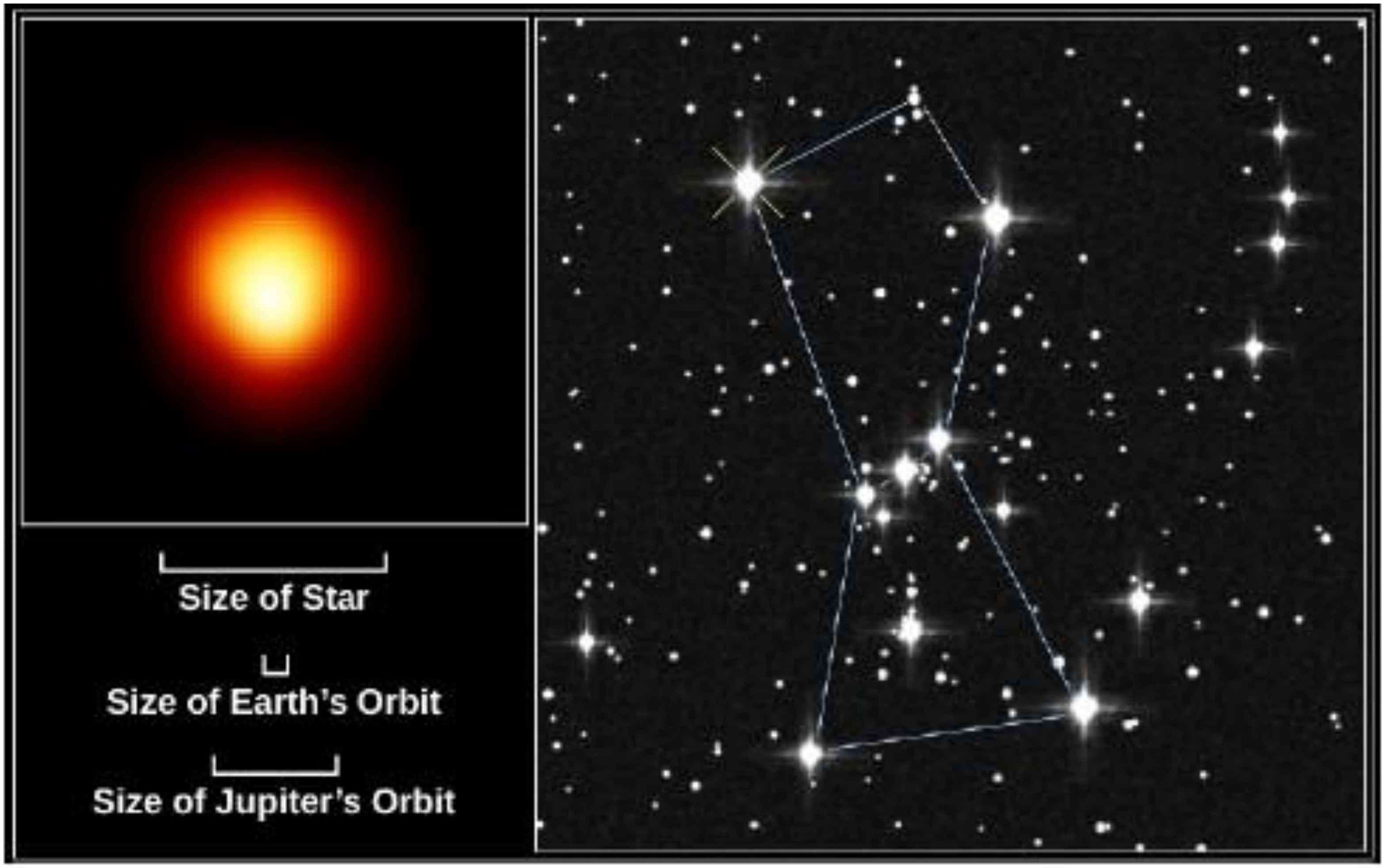


Figure 22.4 Betelgeuse. Betelgeuse is in the constellation Orion, the hunter; in the right image, it is marked with a yellow "X" near the top left. In the left image, we see it in ultraviolet with the Hubble Space Telescope, in the first direct image ever made of the surface of another star. As shown by the scale at the bottom, Betelgeuse has an extended atmosphere so large that, if it were at the center of our solar system, it would stretch past the orbit of Jupiter. (credit: Modification of work by Andrea Dupree (Harvard-Smithsonian CfA), Ronald Gilliland (STScI), NASA and ESA)

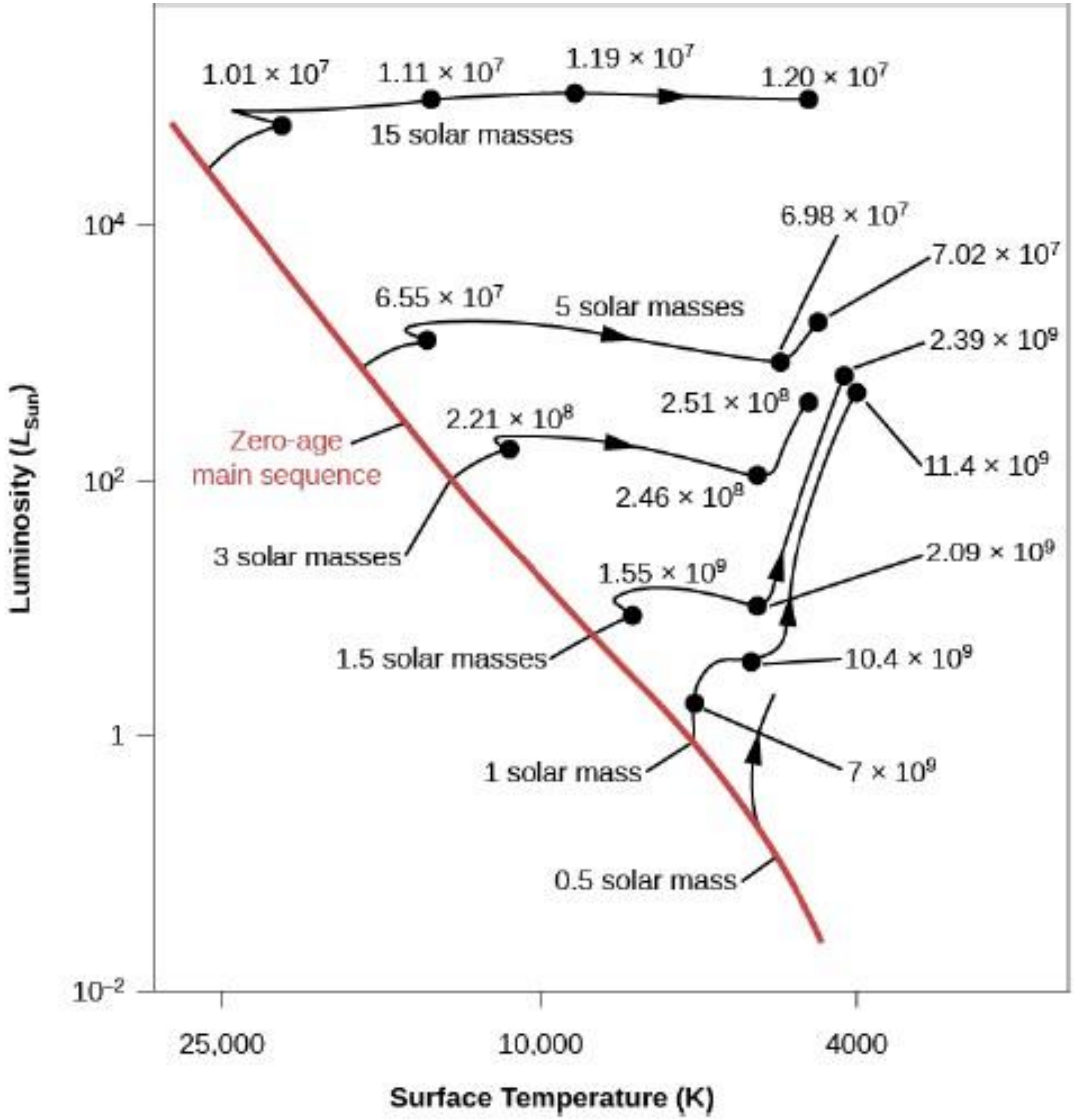


Figure 22.5 Evolutionary Tracks of Stars of Different Masses. The solid black lines show the predicted evolution from the main sequence through the red giant or supergiant stage on the H–R diagram. Each track is labeled with the mass of the star it is describing. The numbers show how many years each star takes to become a giant. The red line is the zero-age main sequence. While theorists debate the exact number of years shown here, our main point should be clear. The more massive the star, the shorter time it takes for each stage in its life.

Characteristics of Star Clusters

Characteristic	Globular Clusters	Open Clusters	Associations
Number in the Galaxy	150	Thousands	Thousands
Location in the Galaxy	Halo and central bulge	Disk (and spiral arms)	Spiral arms
Diameter (in light-years)	50–450	<30	100–500
Mass M_{Sun}	10^4–10^6	10^2–10^3	10^2–10^3
Number of stars	10^4–10^6	50–1000	10^2–10^4
Color of brightest stars	Red	Red or blue	Blue
Luminosity of cluster (L_{Sun})	10^4–10^6	10^2–10^6	10^4–10^7
Typical ages	Billions of years	A few hundred million years to, in the case of unusually large clusters, more than a billion years	Up to about 10^7 years

Session 5

Mining the
Hertzsprung Russell Diagram
Star Clusters

H–R Diagrams of Young Clusters

What does theory predict for the H–R diagram of a cluster whose stars have recently condensed from an interstellar cloud? Remember that at every stage of evolution, massive stars evolve more quickly than their lower-mass counterparts. After a few million years ("recently" for astronomers), the most massive stars should have completed their contraction phase and be on the main sequence, while the less massive ones should be off to the right, still on their way to the main sequence. These ideas are illustrated in Figure 22.8, which shows the H–R diagram calculated by R. Kippenhahn and his associates at Munich University for a hypothetical cluster with an age of 3 million years.

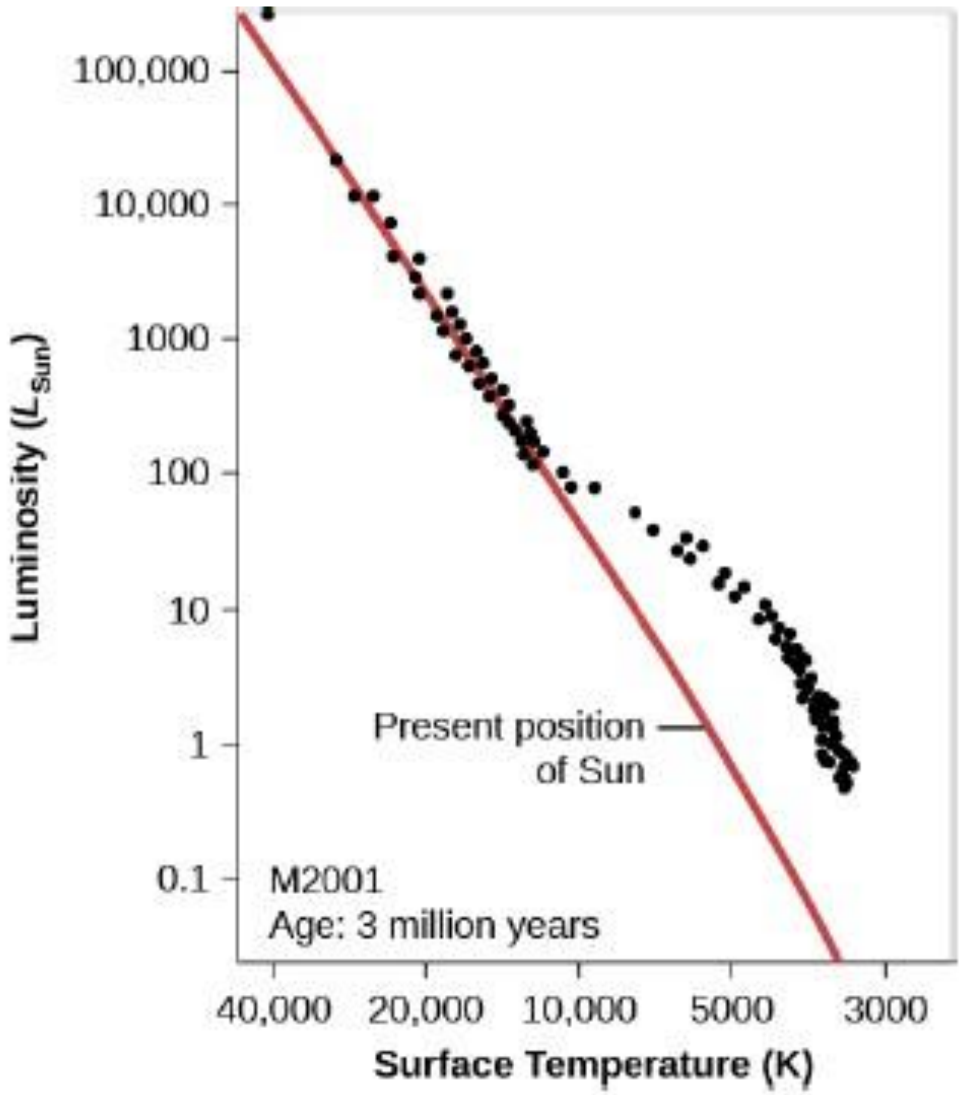


Figure 22.8 Young Cluster H–R Diagram. We see an H–R diagram for a hypothetical young cluster with an age of 3 million years. Note that the high-mass (high-luminosity) stars have already arrived at the main-sequence stage of their lives, while the lower-mass (lower-luminosity) stars are still contracting toward the zero-age main sequence (the red line) and are not yet hot enough to derive all of their energy from the fusion of hydrogen.

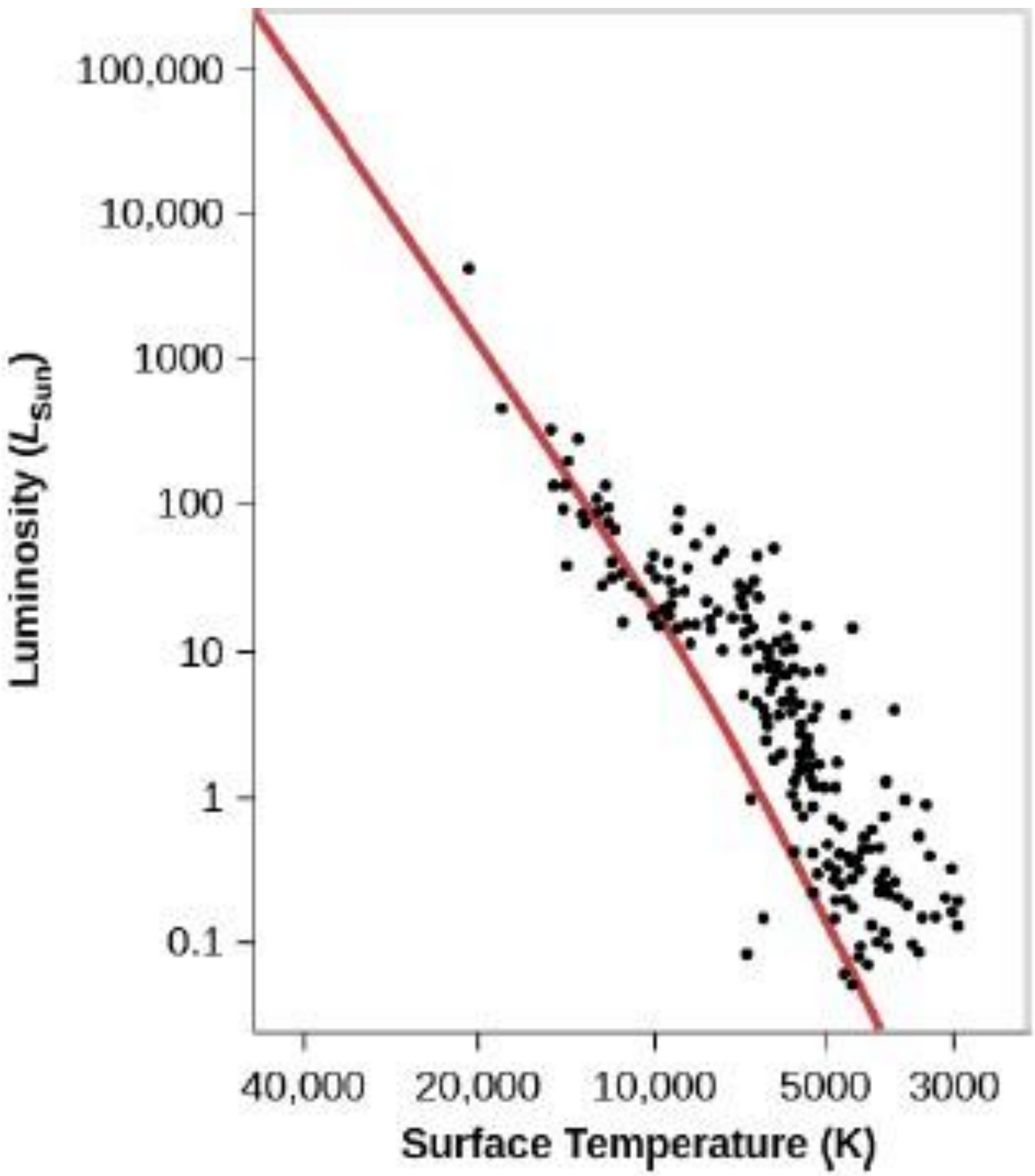
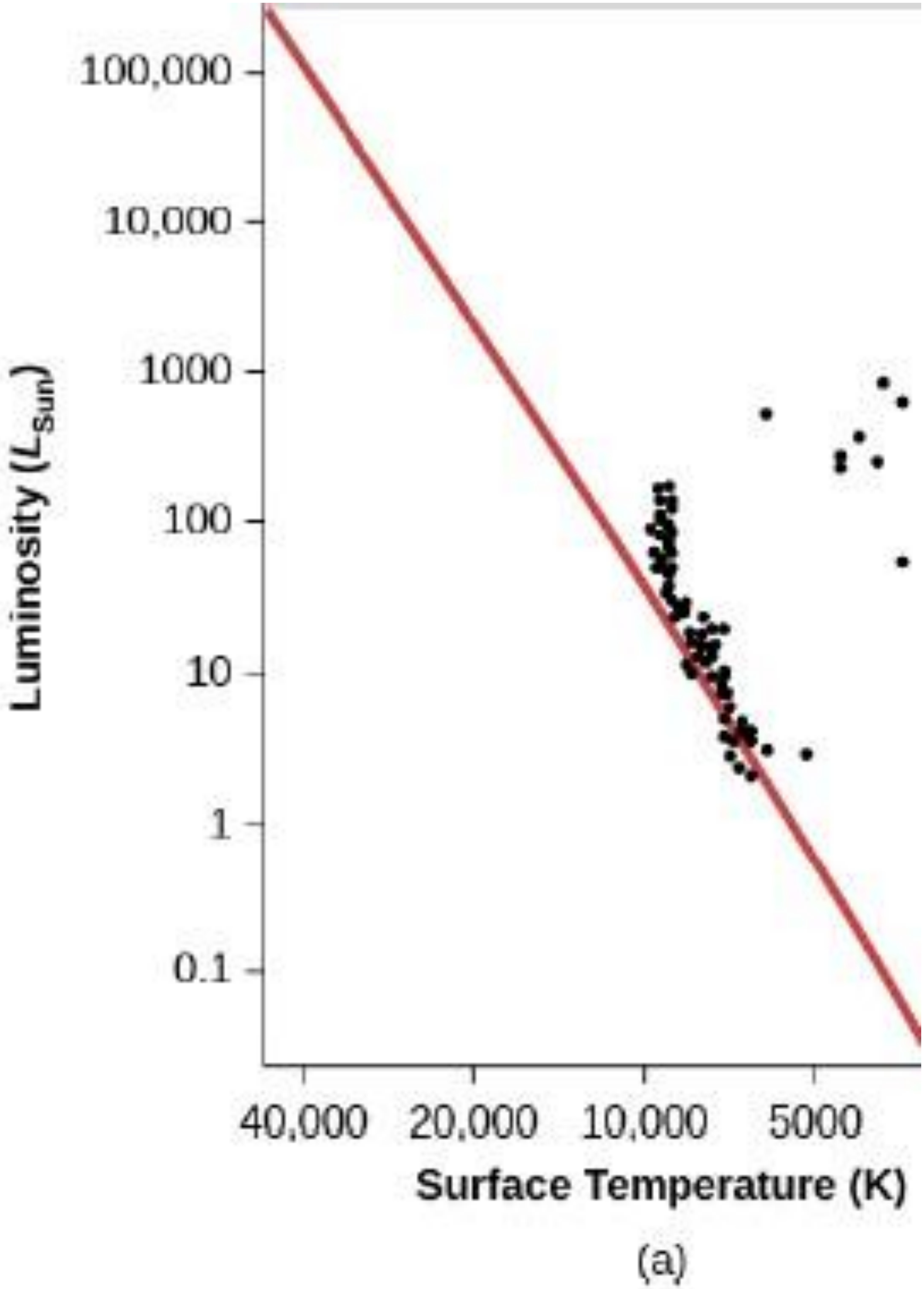


Figure 22.10 NGC 2264 H–R Diagram. Compare this H–R diagram to that in Figure 22.8; although the points scatter a bit more here, the theoretical and observational diagrams are remarkably, and satisfyingly, similar.



gure 22.12 Cluster M41. (a) Cluster M41 is older than NGC 2264
rs are no longer close to the zero-age main sequence (red line)

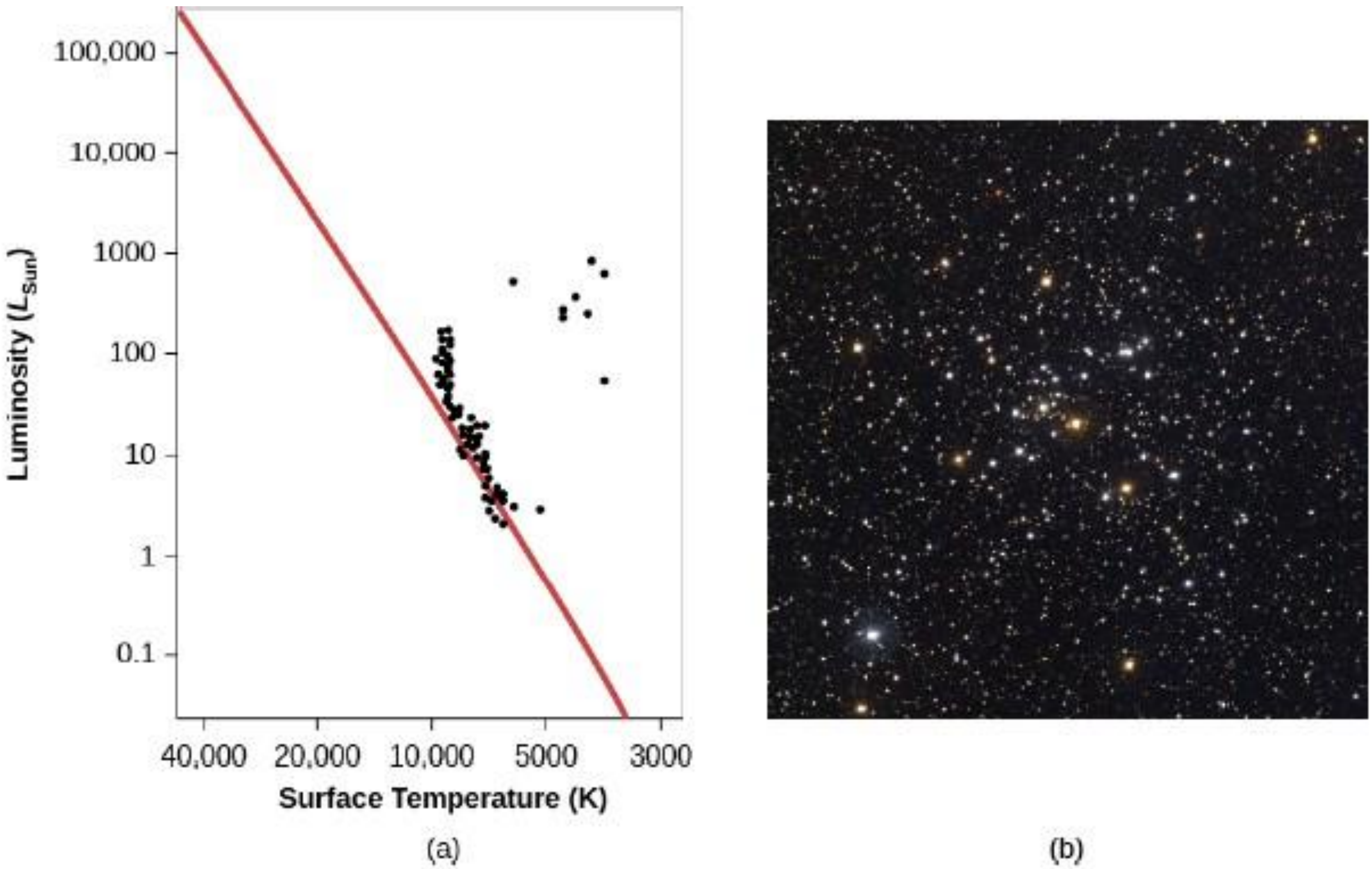


Figure 22.12 Cluster M41. (a) Cluster M41 is older than NGC 2264 (see **Figure 22.10**) and contains several red giants. Some of its more massive stars are no longer close to the zero-age main sequence (red line). (b) This ground-based photograph shows the open cluster M41. Note that it contains several orange-color stars. These are stars that have exhausted hydrogen in their centers, and have swelled up to become red giants. (credit b: modification of work by NOAO/AURA/NSF)

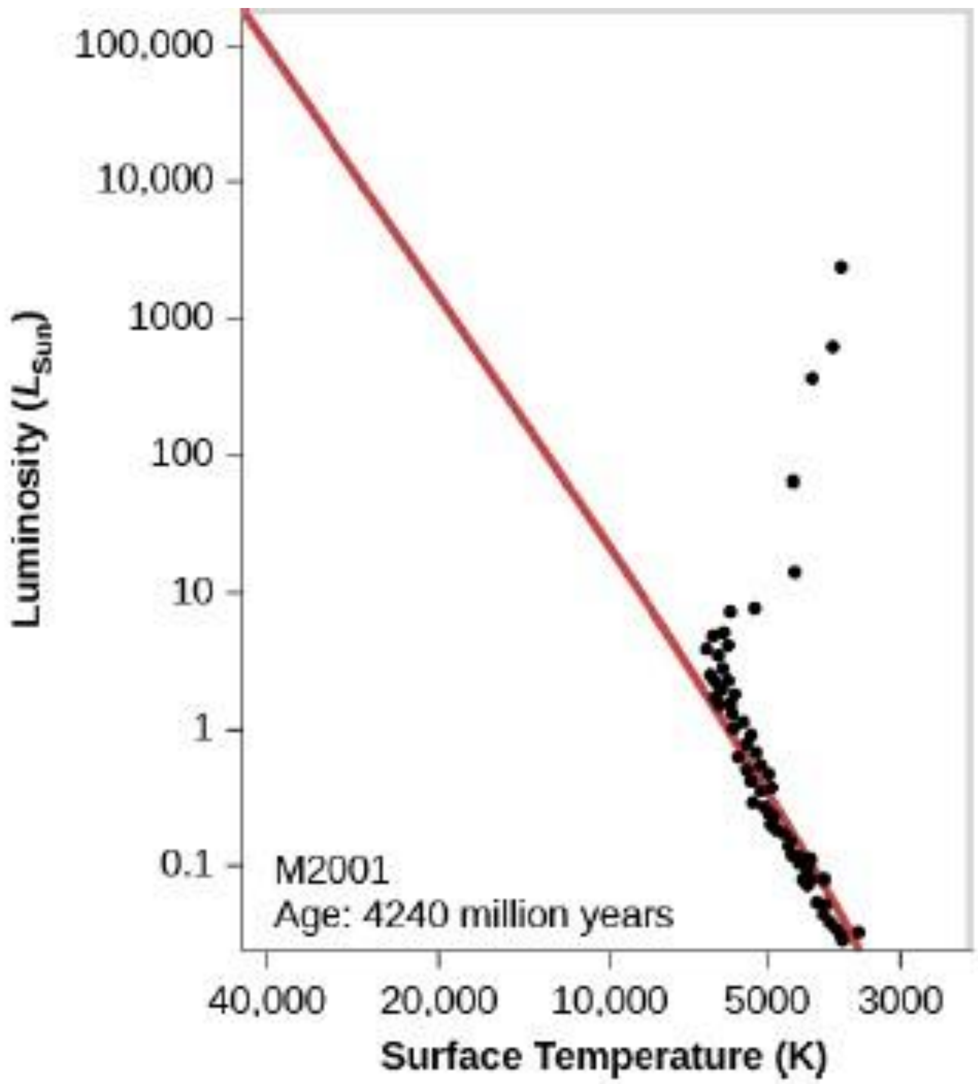


Figure 22.13 H–R Diagram for an Older Cluster. We see the H–R diagram for a hypothetical older cluster at an age of 4.24 billion years. Note that most of the stars on the upper part of the main sequence have turned off toward the red-giant region. And the most massive stars in the cluster have already died and are no longer on the diagram.

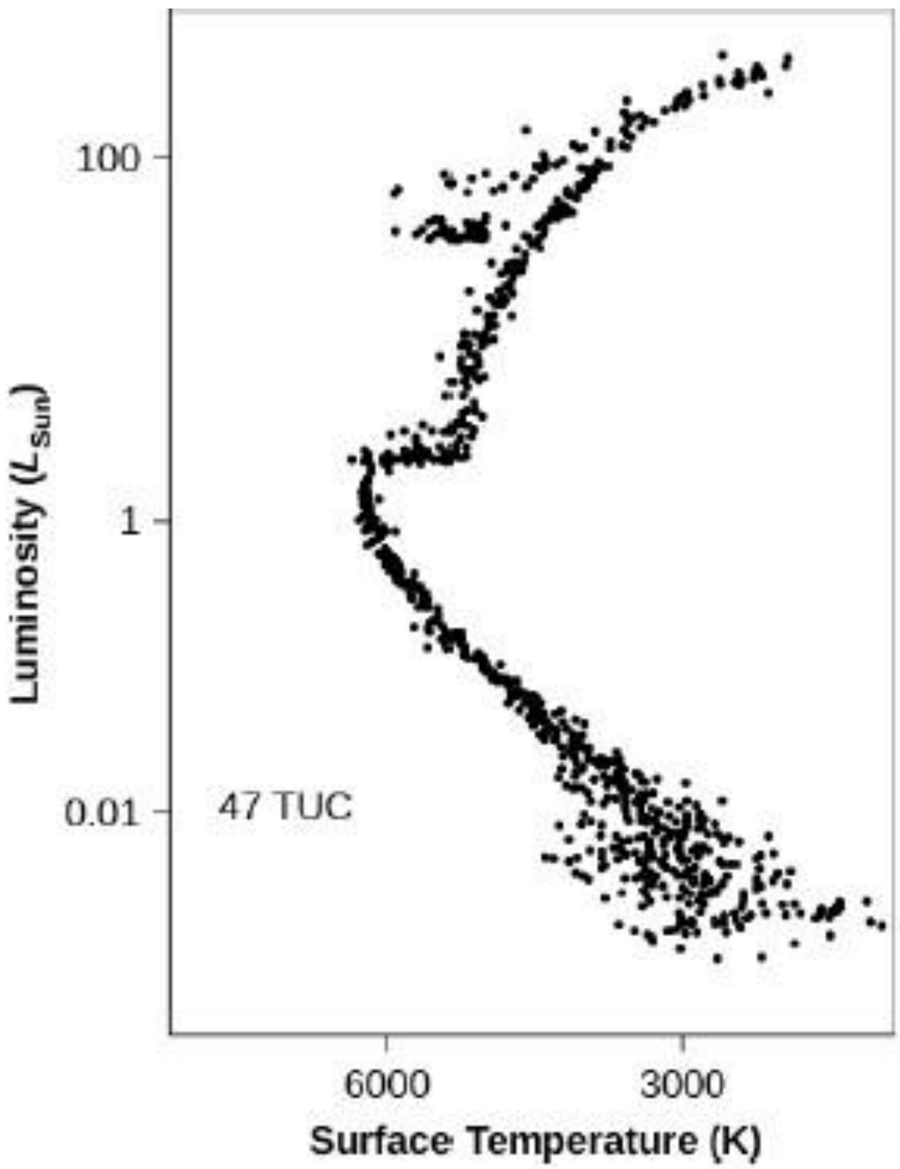


Figure 22.14 Cluster 47 Tucanae. This H–R diagram is for the globular cluster 47. Note that the scale of luminosity differs from that of the other H–R diagrams in this chapter. We are only focusing on the lower portion of the main sequence, the only part where stars still remain in this old cluster.

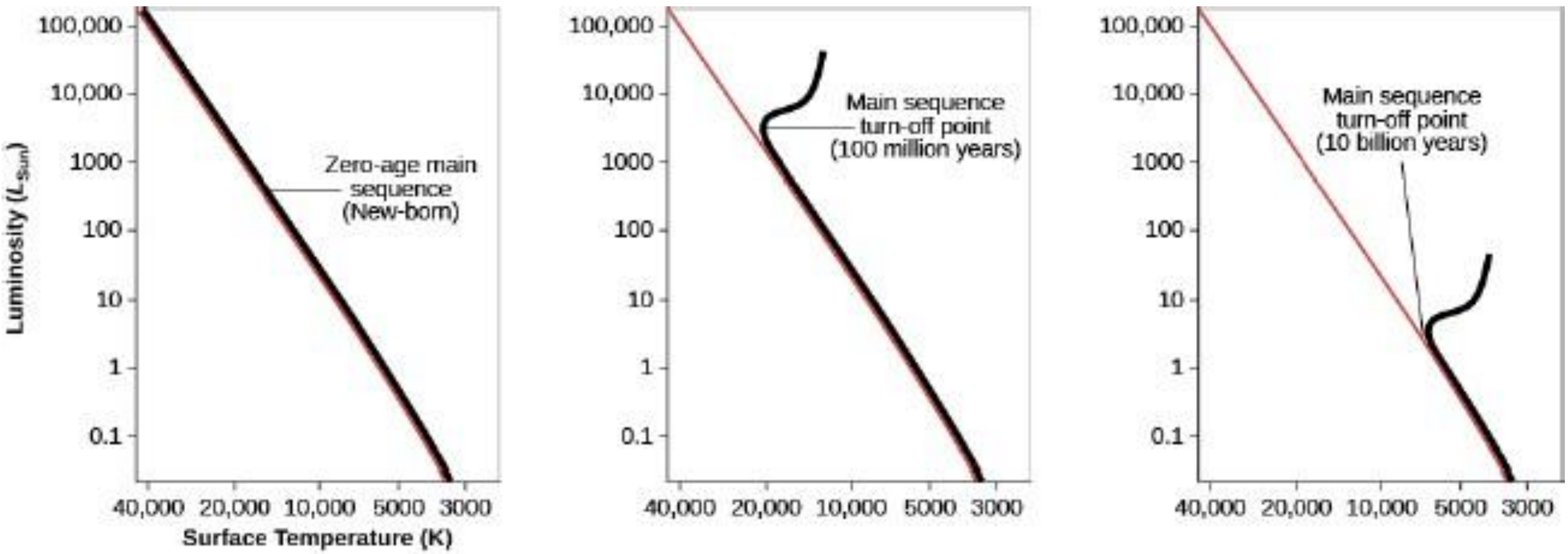


Figure 22.15 H–R Diagrams for Clusters of Different Ages. This sketch shows how the turn-off point from the main sequence gets lower as we make H–R diagrams for clusters that are older and older.

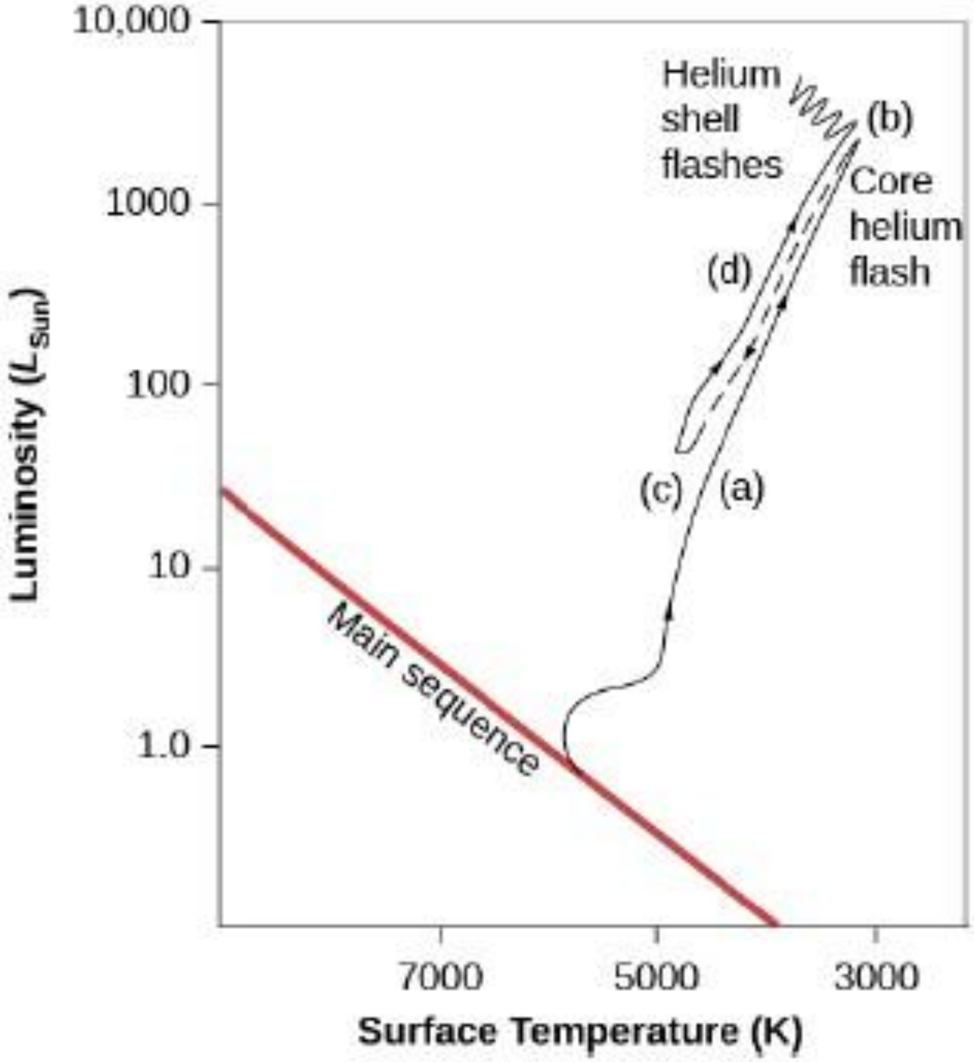


Figure 22.16 Evolution of a Star Like the Sun on an H–R Diagram. Each stage in the star's life is labeled. (a) The star evolves from the main sequence to be a red giant, decreasing in surface temperature and increasing in luminosity. (b) A helium flash occurs, leading to a readjustment of the star's internal structure and to (c) a brief period of stability during which helium is fused to carbon and oxygen in the core (in the process the star becomes hotter and less luminous than it was as a red giant). (d) After the central helium is exhausted, the star becomes a giant again and moves to higher luminosity and lower temperature. By this time, however, the star has exhausted its inner resources and will soon begin to die. Where the evolutionary track becomes a dashed line, the changes are so rapid that they are difficult to model.

The Evolution of a Star with the Sun's Mass

Stage	Time in This Stage (years)	Surface Temperature (K)	Luminosity (L_{Sun})	Diameter (Sun = 1)
Main sequence	11 billion	6000	1	1
Becomes red giant	1.3 billion	3100 at minimum	2300 at maximum	165
Helium fusion	100 million	4800	50	10
Giant again	20 million	3100	5200	180

The Ultimate Fate of Stars and Substellar Objects with Different Masses

Initial Mass (Mass of Sun = 1)[1]	Final State at the End of Its Life
< 0.01	Planet
0.01 to 0.08	Brown dwarf
0.08 to 0.25	White dwarf made mostly of helium
0.25 to 8	White dwarf made mostly of carbon and oxygen
8 to 10	White dwarf made of oxygen, neon, and magnesium
10 to 40	Supernova explosion that leaves a neutron star
> 40	Supernova explosion that leaves a black hole

Table 23.1

EXAMPLE 23.1

Extreme Gravity

In this section, you were introduced to some very dense objects. How would those objects' gravity affect you? Recall that the force of gravity, F, between two bodies is calculated as

$$F = \frac{GM_1M_2}{R^2}$$

where G is the gravitational constant, 6.67×10^{-11} Nm^2/kg^2, M_1 and M_2 are the masses of the two bodies, and R is their separation. Also, from Newton's second law,

$$F = M \times a$$

where a is the acceleration of a body with mass M.

So let's consider the situation of a mass—say, you—standing on a body, such as Earth or a white dwarf (where we assume you will be wearing a heat-proof space suit). You are M_1 and the body you are standing on is M_2. The distance between you and the center of gravity of the body on which you stand is its radius, R. The force exerted on you is

$$F = M_1 \times a = \mathrm{GM}_1 M_2 \big/ R^2$$

Solving for a, the acceleration of gravity on that world, we get

$$g = \frac{(G \times M)}{R^2}$$

Note that we have replaced the general symbol for acceleration, *a*, with the symbol scientists use for the acceleration of gravity, *g*.

Say that a particular white dwarf has the mass of the Sun (2×10^{30} kg) but the radius of Earth (6.4×10^6 m). What is the acceleration of gravity at the surface of the white dwarf?

Solution

The acceleration of gravity at the surface of the white dwarf is

$$g(\text{white dwarf}) = \frac{(G \times M_{\text{Sun}})}{{R_{\text{Earth}}}^2} = \frac{\left(6.67 \times 10^{-11}\ \text{m}^2/\text{kg s}^2 \times 2 \times 10^{30}\ \text{kg}\right)}{\left(6.4 \times 10^6\ \text{m}\right)^2} = 3.26 \times 10^6\ \text{m/s}^2$$

Compare this to *g* on the surface of Earth, which is $9.8\ \text{m/s}^2$.

Check Your Learning

What is the acceleration of gravity at the surface if the white dwarf has the twice the mass of the Sun and is only half the radius of Earth?

Answer:

$$g(\text{white dwarf}) = \frac{(G \times 2M_{\text{Sun}})}{(0.5R_{\text{Earth}})^2} = \frac{\left(6.67 \times 10^{-11}\ \text{m}^2/\text{kg s}^2 \times 4 \times 10^{30}\ \text{kg}\right)}{\left(3.2 \times 10^6\right)^2} = 2.61 \times 10^7\ \text{m/s}^2$$