Astronomy 17: Analyzing Starlight

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Thinking Ahead

To understand the stars, we must first determine their basic properties, such as what their temperatures are, how much material they contain (their masses), and how much energy they produce.

We learn a star by decoding the messages contained in the light and radiation that reaches Earth. So what questions should we ask, and how do we find the answers?

Figure 17.1 Star Colors. This long time exposure shows the colors of the stars. The circular motion of the stars across the image is provided by Earth’s rotation. The various colors of the stars are caused by their different temperatures.

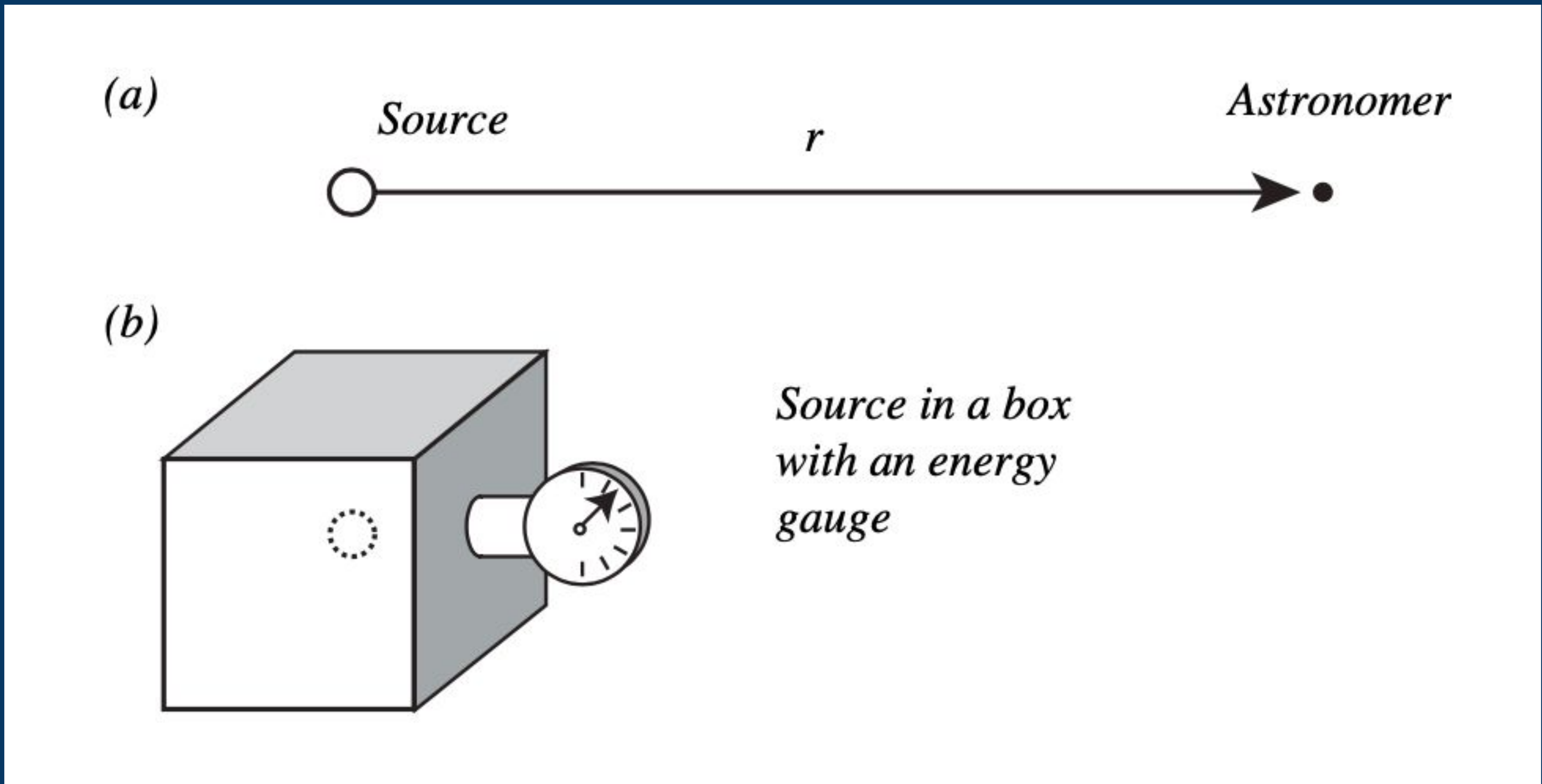
(credit: modification of work by ESO/A.Santerne)

17.1 The Brightness of Stars

LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Explain the difference between luminosity and apparent brightness
- Understand how astronomers specify brightness with magnitudes



Luminosity

luminosity—the total amount of energy at all wavelengths that it emits per second.

$$L_{\odot} = \text{Luminosity of the Sun} = 3.825 \times 10^{26}\ \text{W}$$

For example, the luminosity of Sirius is about 25 times that of the Sun. We use the symbol L_{Sun} (or $L_{\odot}$) to denote the Sun's luminosity; hence, that of Sirius can be written as 25 L_{Sun}.

The astronomer, however, cannot measure luminosity in this way. The star is too distant from the source to put it in a box, even in the unlikely case we has a big enough box.

Apparent Brightness

Apparent brightness: the amount of a star's energy that reaches a given area (say, one square meter) each second here on Earth.

Apparent brightness, F, is defined as the total energy per unit time per unit area that arrives from the source:

$$F = \frac{E}{tA}$$

F is usually known as the **flux** or the **flux density** in the astronomical literature. In the physics literature, the same quantity is usually called the **irradiance** (or, in studies restricted to visual light, the **illuminance**.) To make matters not only complex but also confusing, what astronomers call luminosity, ***L***, physicists call the **radiant flux**.

F will have units of power per unit area, or Wm^{-2}.

For example, the average flux from the Sun at the top of the Earth's atmosphere (the apparent brightness of the Sun) is about **1370 Wm^{-2}**, a quantity known as the **solar constant**.

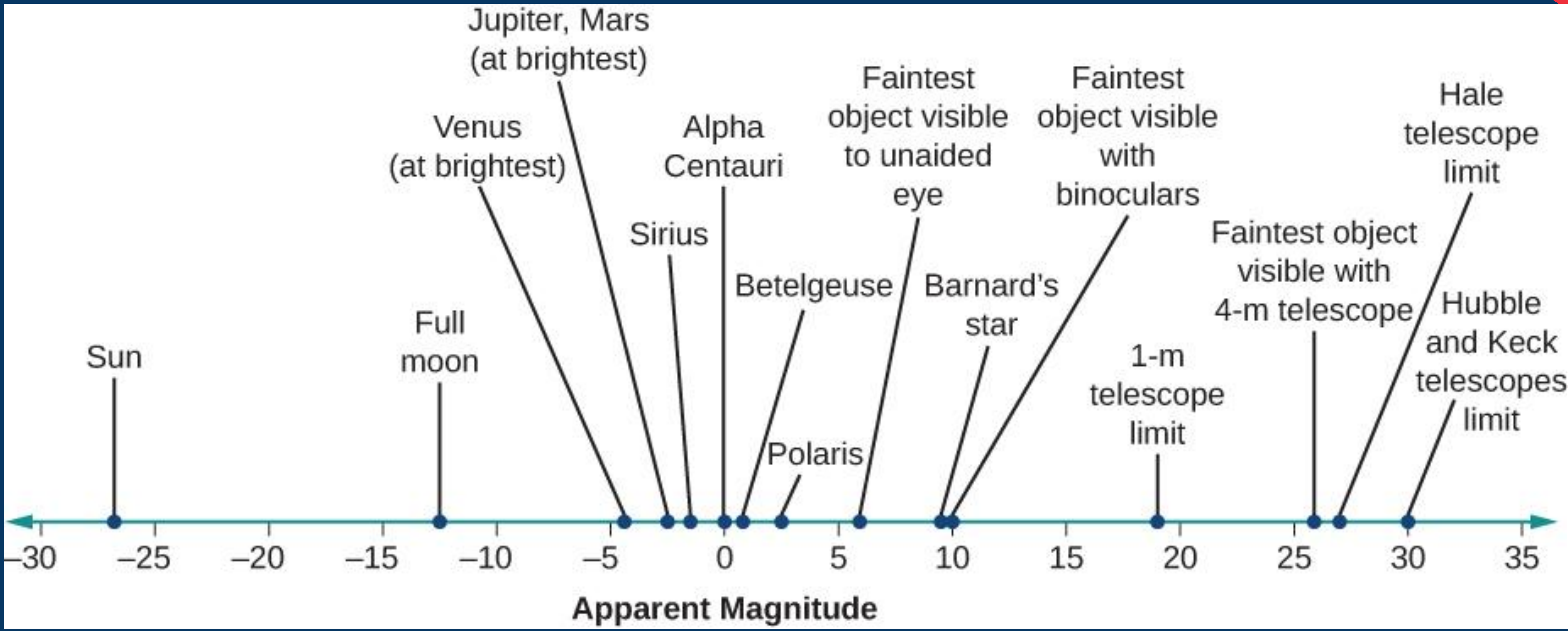
The Magnitude Scale

The process of measuring the apparent brightness of stars is called **photometry** (from the Greek *photo* meaning “light” and –*metry* meaning “to measure”).

Astronomical photometry began with **Hipparchus**. Around 150 B.C.E. He prepared a catalog of nearly 1000 stars that included not only their positions but also estimates of their apparent brightnesses.

He sorted the stars into six brightness categories, each of which he called a **magnitude**.

- the brightest stars in his catalog is the **first-magnitudes** stars,
- those so faint he could barely see them were **sixth-magnitude** stars.



The Magnitude Scale

William Pogson (c. AD 1856) discovered that Hipparchus's classes were in fact approximately a geometric progression in F.

Pogson proposed regularizing the system so that **a magnitude difference of 5 corresponds to a brightness ratio of 100:1**.

Smaller (more negative) magnitudes mean brighter objects

The Magnitude Equation

The relationship between apparent magnitude, m, and brightness, ***F***, is:

$$m = -2.5\, log_{10}(F)$$

If ***m1*** and ***m2*** are the magnitudes of two stars, then we can calculate the ratio of their brightness (b_2/b_1) using this equation:

$$m_1 - m_2 = 2.5\, log(\frac{b_2}{b_1})$$

or:

$$\frac{b_2}{b_1} = 2.5^{m_1 - m_2}$$

Here is another way to write this equation:

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

EXAMPLE 17.1 The Magnitude Equation

Imagine that an astronomer has discovered something special about a dim star (magnitude 8.5), and she wants to tell her students how much dimmer the star is than Sirius. Star 1 in the equation will be our dim star and star 2 will be Sirius.

EXAMPLE 17.1 The Magnitude Equation

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Solution:

Sirius has a magnitude of −1.5. In that case:

$$\frac{b_2}{b_1} = (100^{0.2})^{8.5-(-1.5)} = (100^{0.2})^{10}$$

$$= 100^2 = 100 \times 100 = 10,000$$

EXAMPLE 17.1 The Magnitude Equation

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?

EXAMPLE 17.1 The Magnitude Equation

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?

Solution:

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

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

Absolute magnitudes

The magnitude system can also be used to express the luminosity of a source.

The **absolute magnitude** of a source is defined to be the apparent magnitude (either bolometric or band-pass) that the source would have if it were at the standard distance of 10 parsecs in empty space (1 parsec = 3.086×10^{21} meters).

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

$$m - M = 5\,log(r) - 5$$

where ***M*** is the absolute magnitude and ***r*** is the actual distance to the source in parsecs.

17.2 Colors of Stars

LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Compare the relative temperatures of stars based on their colors
- Understand how astronomers use color indexes to measure the temperatures of stars

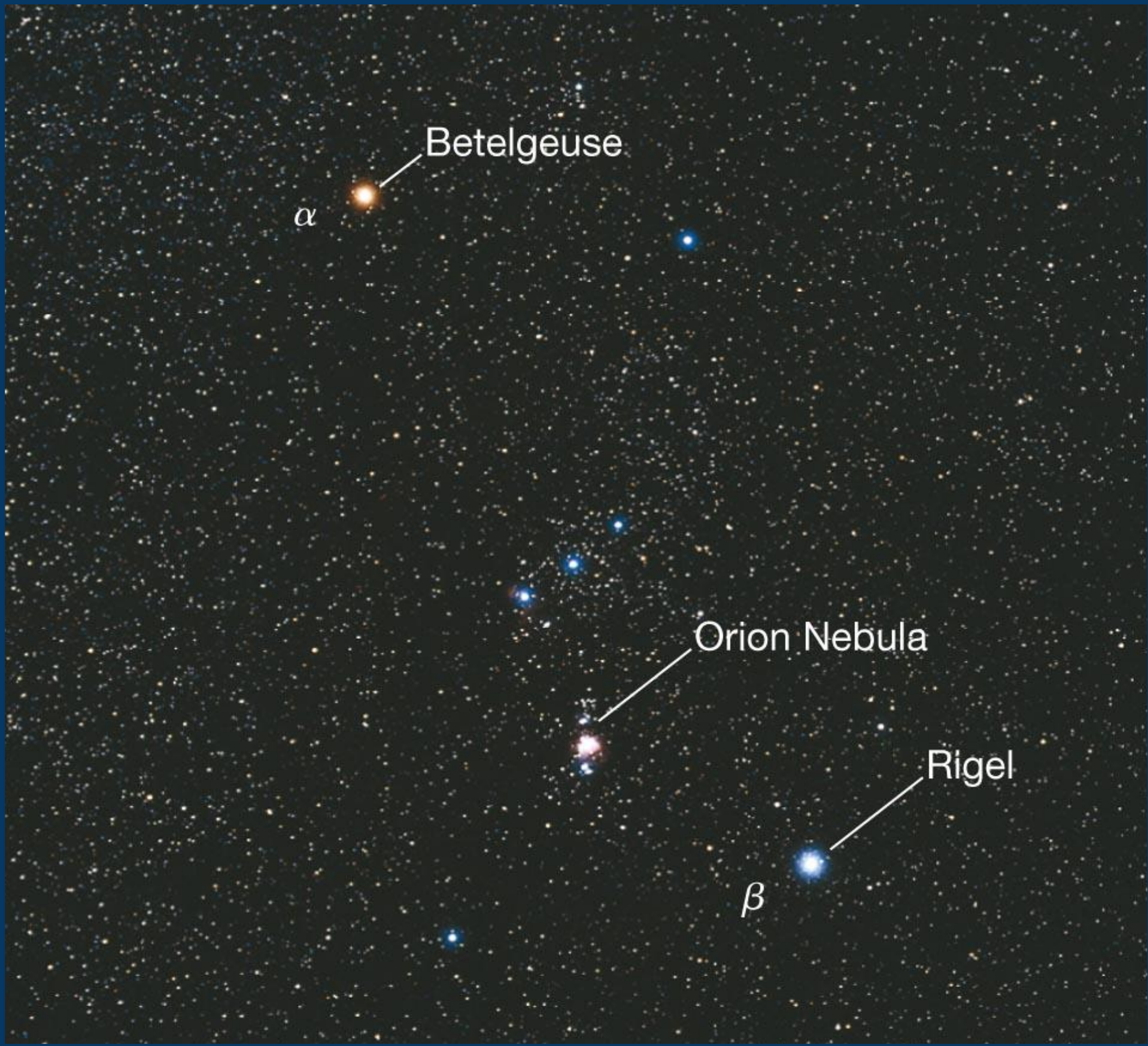
Colors of Stars

Figure 17.3 Sagittarius Star Cloud. This image, which was taken by the Hubble Space Telescope, shows stars in the direction toward the center of the Milky Way Galaxy. The bright stars glitter like colored jewels on a black velvet background. The color of a star indicates its temperature. Blue-white stars are much hotter than the Sun, whereas red stars are cooler. On average, the stars in this field are at a distance of about 25,000 light-years (which means it takes light 25,000 years to traverse the distance from them to us) and the width of the field is about 13.3 light-years.
(credit: Hubble Heritage Team (AURA/STScI/NASA))

Color and Temperature

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



Betelgeuse and Rigel

Our understanding of Blackbody Radiation explains why star's color is related to surface temperature.

Colors of Betelgeuse and Rigel in Orion are clearly red and blue

B (blue) and V (visual) filters admit different amounts of light for different temperatures

Activity 17.1: Blackbody spectrum

Go to this interactive simulation from the University of Colorado to see the color of a star changing as the temperature is changed.

https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html

Please make a short presentation (5’) introducing this interactive simulation.

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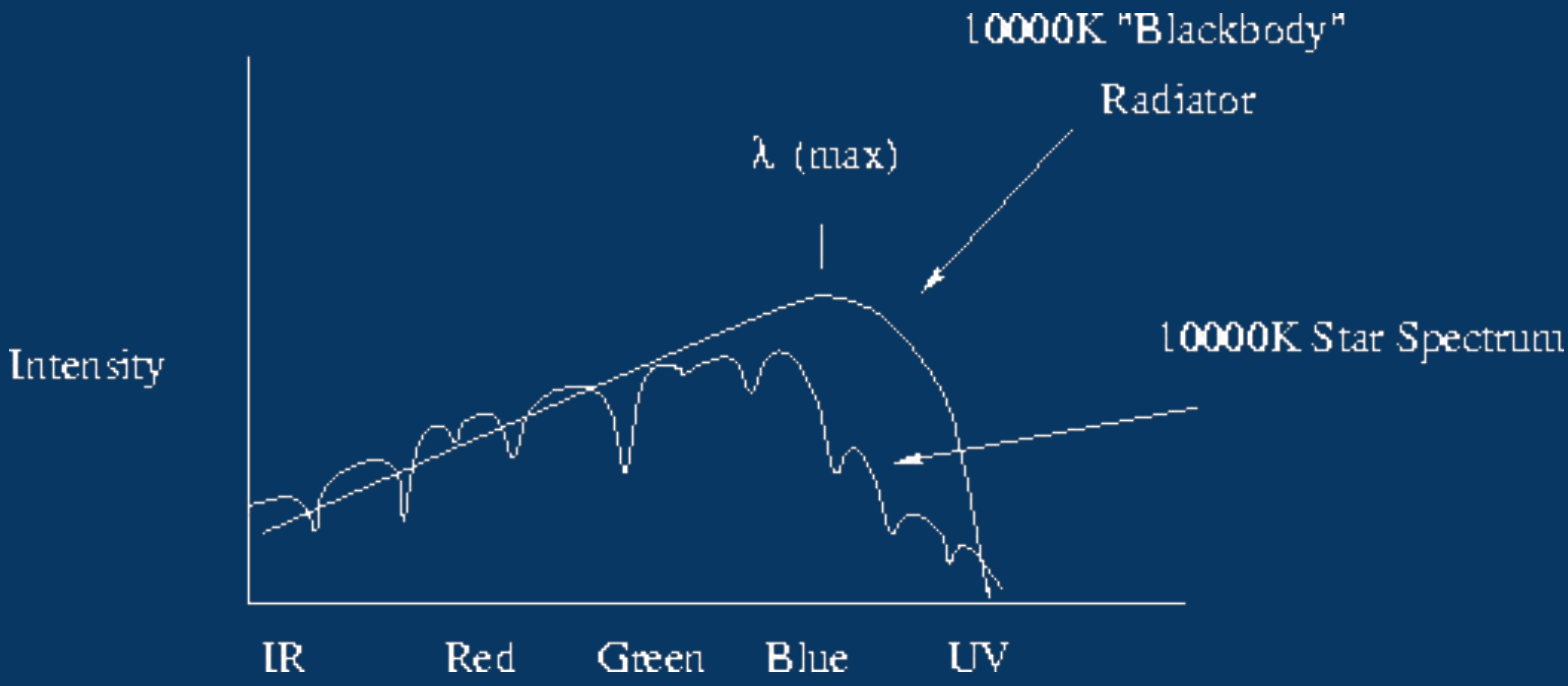
https://www.ucolick.org/~bolte/AY4_00/week4/star_vs_bb.gif

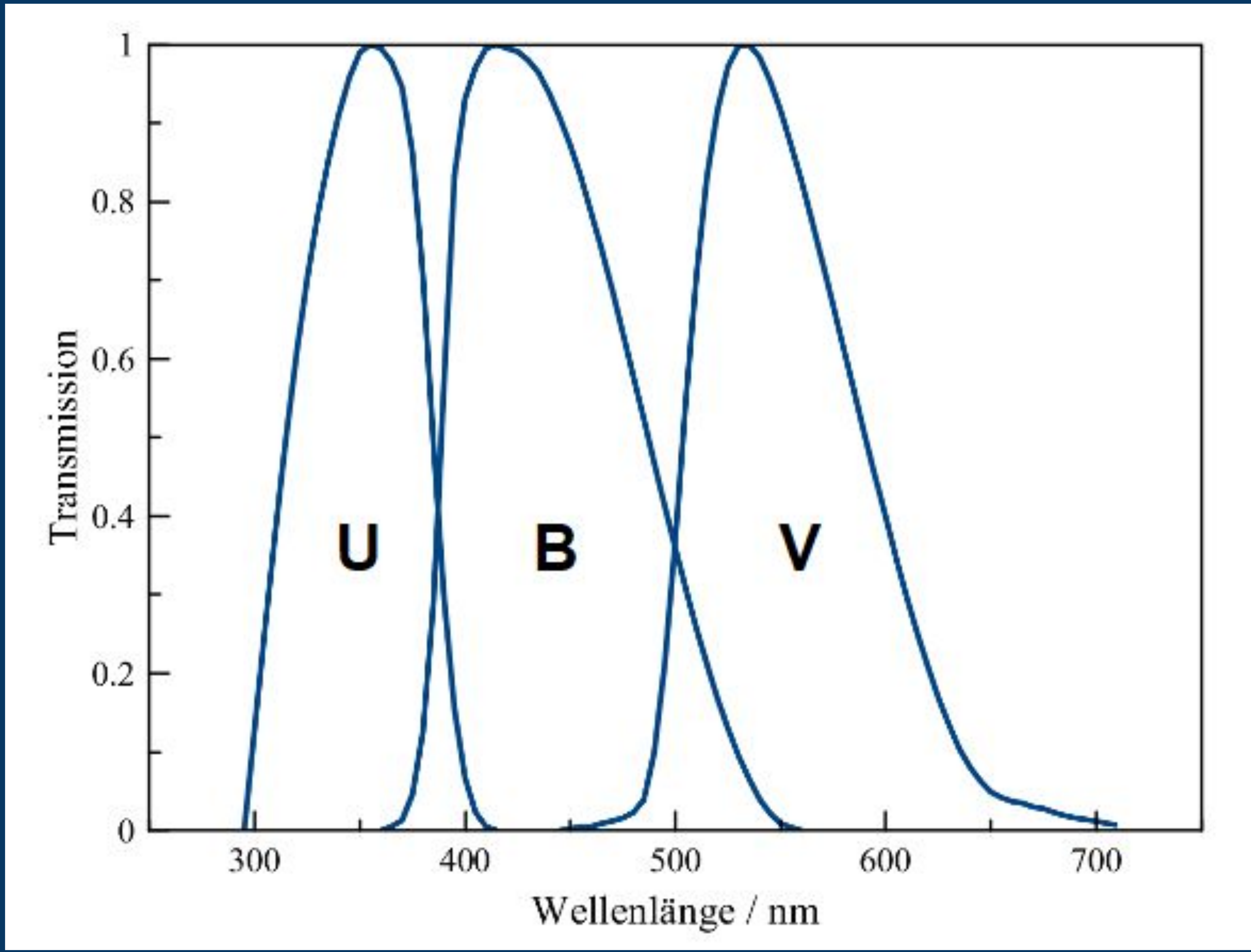


STELLAR SURFACE TEMPERATURES

Disperse the light from a star ("take a spectrum"), find the wavelength at which you have the most radiation, then apply Wien's Law.

Wien's Law lets us quantify the color-temperature relationship but Wien's Law gives temperatures for objects with Planck-like spectra.

Stars don't quite have Planck spectra because of the absorption lines, flux redistribution and other complications like that.

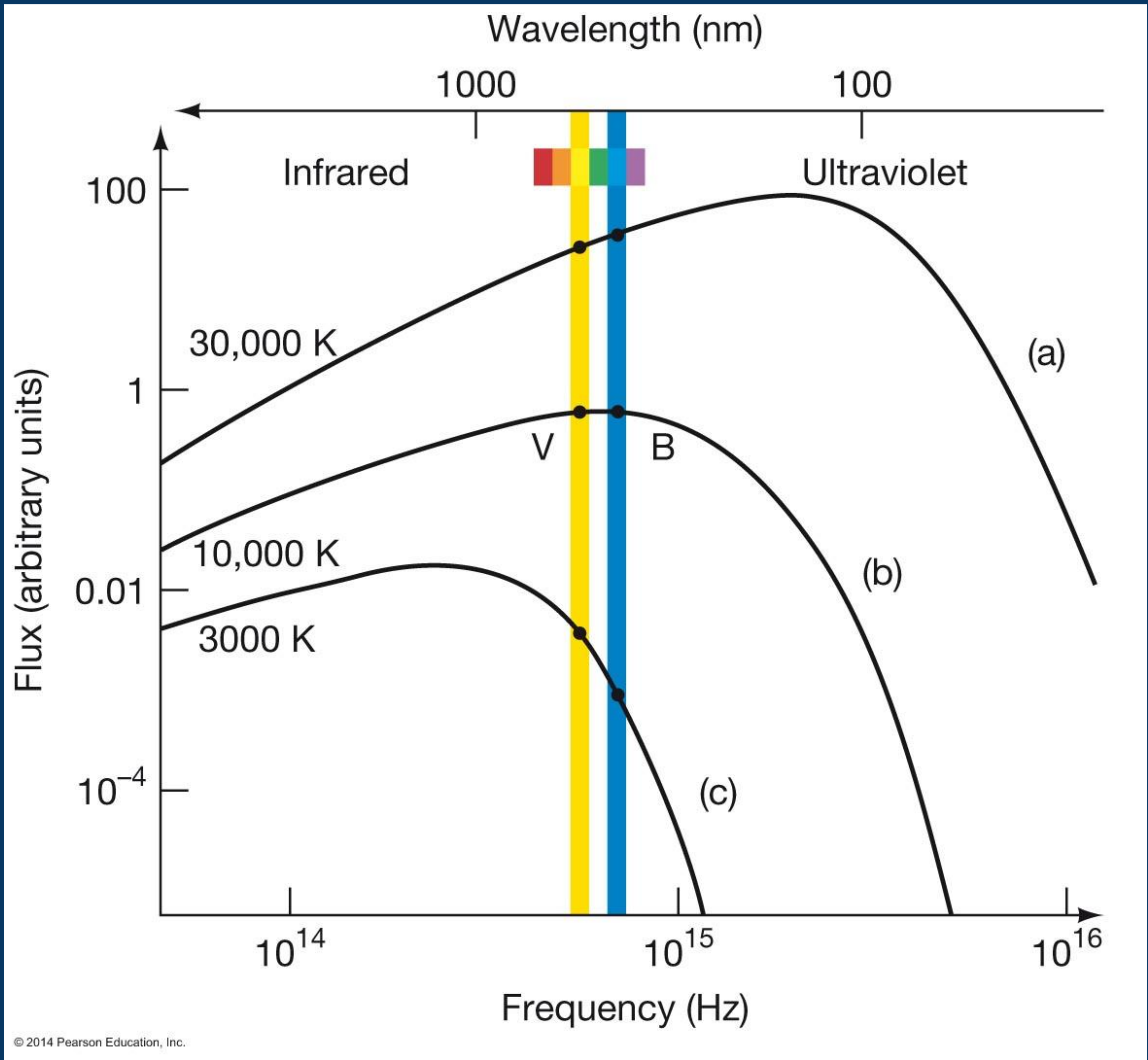


Color Indices

astronomers normally measure a star’s apparent brightness through filters.

The filters are named: U (ultraviolet), B (blue), and V (visual, for yellow). These filters transmit light near the wavelengths of 360 nanometers (nm), 420 nm, and 540 nm, respectively.

The difference between any two of these magnitudes—say, between the blue and the visual magnitudes (***B–V***)—is called a **color index**.



STELLAR SURFACE TEMPERATURES

Measure colors: The basic idea - for Planck spectra (from solid objects), the ratio of the light in two different color filters unambiguously gives the temperature of the objects.

The color index, relating the B and V intensities, is defined in two ways:

- ratio of B to V (B/V)
- difference between B and V (B-V)

Ratio of B to V (B/V)

In principle, the temperature of a star can be calculated directly from the B−V index, and there are several formulae to make this connection.

A good approximation can be obtained by considering stars as black bodies, using Ballesteros' formula:

$$T = 4600K\left(\frac{1}{0.92(B-V)+1.7}+\frac{1}{0.92(B-V)+0.62}\right)$$

- F. J. Ballesteros 2012 EPL 97 34008 https://iopscience.iop.org/article/10.1209/0295-5075/97/34008

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

Ratio of B to V (B/V)

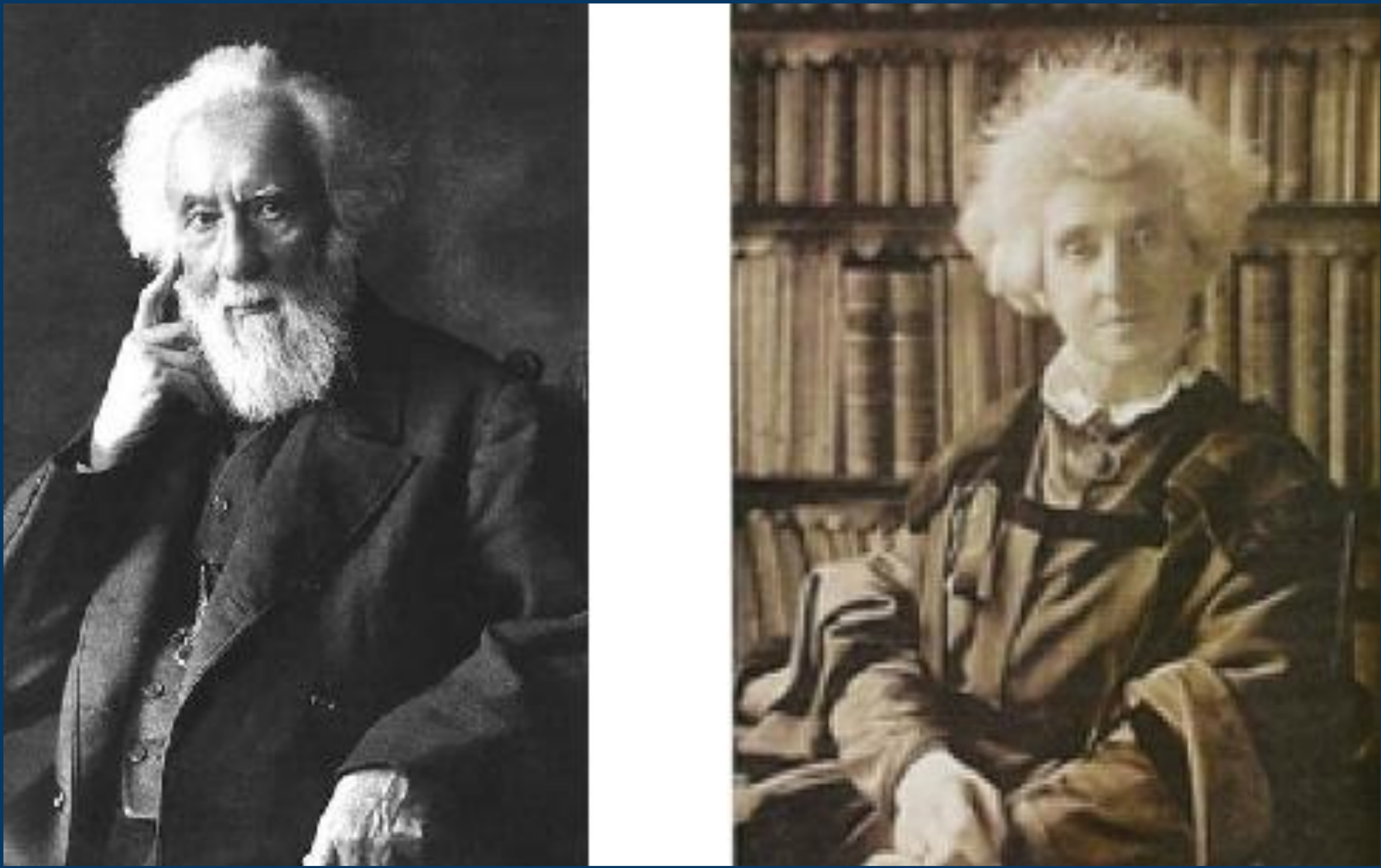
In the UBV system, the zeroth magnitudes fluxes are defined for a bright nearby star with a temperature of 10,000 K [Vega]. Thus B-V = 0 corresponds to a temperature of 10,000 K, while a star with the temperature of the Sun (5,770 K) has a B-V color of 0.65.

17.3 The Spectra of Stars

LEARNING OBJECTIVES

By the end of this section, you will be able to:

- Describe how astronomers use spectral classes to characterize stars
- Explain the difference between a star and a brown dwarf



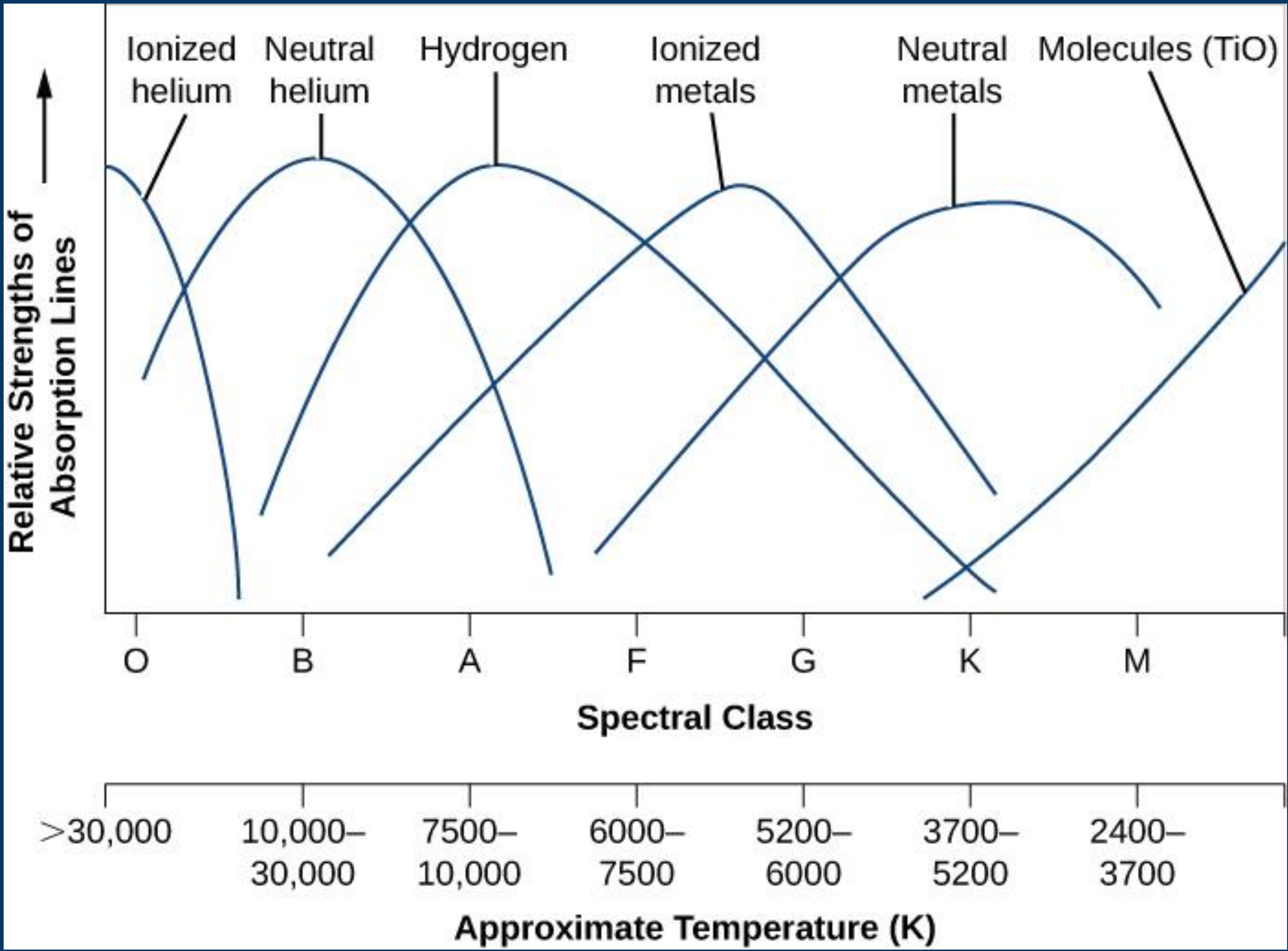
William Huggins (1824–1910) and Margaret Huggins (1848–1915)

William and Margaret Huggins were the first to identify the lines in the spectrum of a star other than the Sun; they also took the first spectrogram, or photograph of a stellar spectrum.

Star color	Approximate Temperature	Example
Blue	25,000 K	Spica
Blue - White	22,000 K	Bellatrix
Blue - White	12,000 K	Rigel
White	10,000 K	Vega
Yellow	6,000 K	Sun
Orange	4,000K	Aldebaran
Red	3,000K	Betelgeuse

Formation of Stellar Spectra

The primary reason that stellar spectra look different is because the stars have different temperatures. Most stars have nearly the same composition as the Sun, with only a few exceptions.



Absorption Lines in Stars of Different Temperatures

This graph shows the strengths of absorption lines of different chemical species (atoms, ions, molecules) as we move from hot (left) to cool (right) stars. The sequence of spectral types is also shown.

Activity 17.1: Spectrum Explorer

Use the Spectrum Explorer to see how each element's absorption lines change with temperature.

https://foothillastrosims.github.io/SpectrumExplorer/

Please make a short presentation (5') introducing this interactive simulation.

Assigned to:

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)

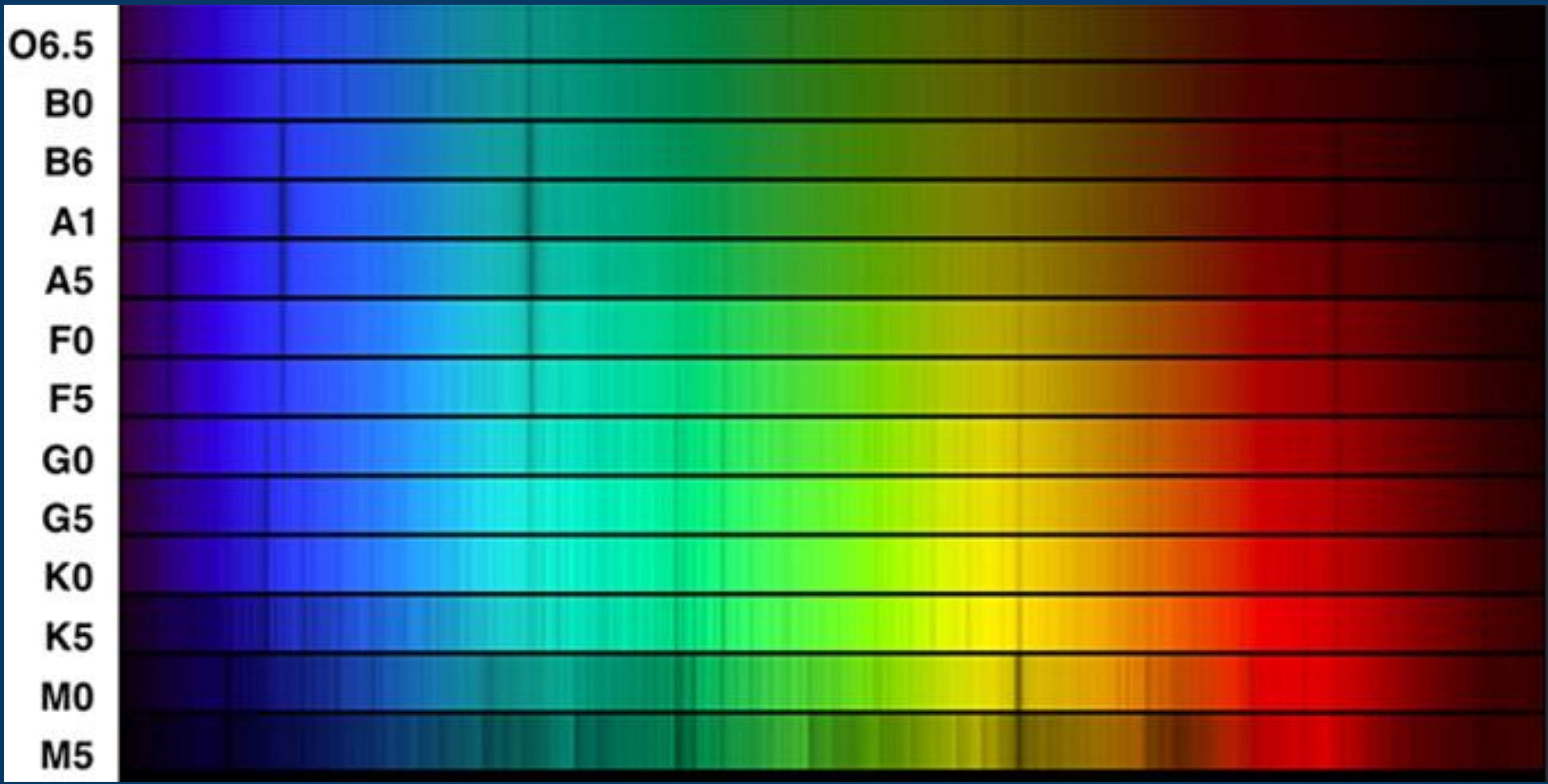
Oh, Be A Fine Girl (Guy), Kiss Me

In the 1890s, Annie Jump Cannon revised this classification system, focusing on just a few letters from the original system: A, B, F, G, K, M, and O.

Instead of starting over, Cannon also rearranged the existing classes—in order of decreasing temperature—into the sequence we have learned: O, B, A, F, G, K, M.

Spectral Classes for Stars

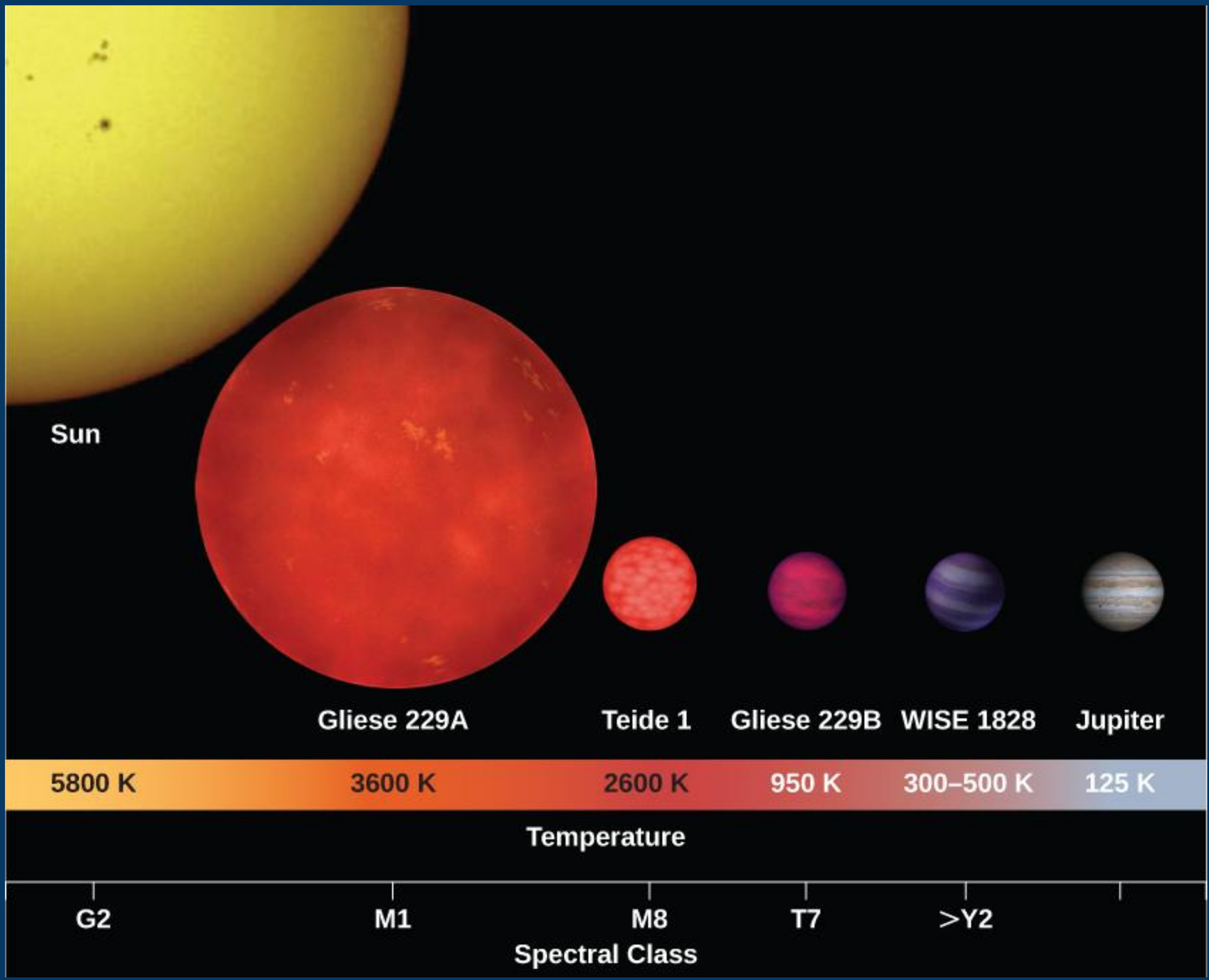
Spectral Class	Color	Approximate Temperature (K)	Principal Features	Examples
O	Blue	> 30,000	Neutral and ionized helium lines, weak hydrogen lines	10 Lacertae
B	Blue-white	10,000–30,000	Neutral helium lines, strong hydrogen lines	Rigel, Spica
A	White	7500–10,000	Strongest hydrogen lines, weak ionized calcium lines, weak ionized metal (e.g., iron, magnesium) lines	Sirius, Vega
F	Yellow-white	6000–7500	Strong hydrogen lines, strong ionized calcium lines, weak sodium lines, many ionized metal lines	Canopus, Procyon
G	Yellow	5200–6000	Weaker hydrogen lines, strong ionized 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
L	Red	1300–2400	Metal hydride lines, alkali metal lines (e.g., sodium, potassium, rubidium)	Teide 1
T	Magenta	700–1300	Methane lines	Gliese 229B
Y	Infrared	< 700	Ammonia lines	WISE 1828+2650



Spectra of Stars with Different Spectral Classes

This image compares the spectra of the different spectral classes. The spectral class assigned to each of these stellar spectra is listed at the left of the picture. The strongest four lines seen at spectral type A1 (one in the red, one in the blue-green, and two in the blue) are Balmer lines of hydrogen. Note how these lines weaken at both higher and lower temperatures, as Figure 17.5 also indicates. The strong pair of closely spaced lines in the yellow in the cool stars is due to neutral sodium (one of the neutral metals in Figure 17.5).

(Credit: modification of work by NOAO/AURA/NSF)



Brown Dwarfs

Objects with masses less than about 7.5% of the mass of our Sun (about 0.075 MSun) do not become hot enough for hydrogen fusion to take place. Even before the first such "failed star" was found, this class of objects, with masses intermediate between stars and planets, was given the name **brown dwarfs**.

This illustration shows the sizes and surface temperatures of brown dwarfs Teide 1, Gliese 229B, and WISE1828 in relation to the Sun, a red dwarf star (Gliese 229A), and Jupiter.

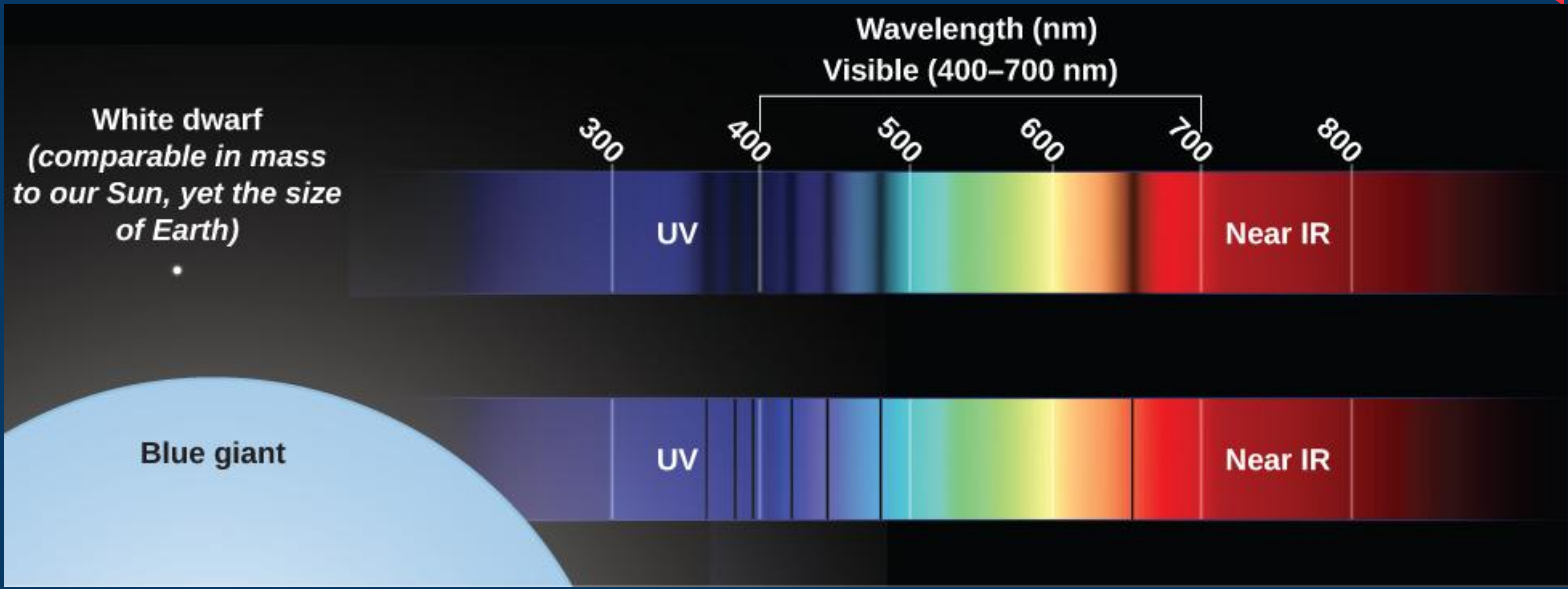
(credit: modification of work by MPIA/V. Joergens)

17.4 Using Spectra to Measure Stellar Radius, Composition, and Motion

LEARNING OBJECTIVES

By the end of this section, you will be able to:

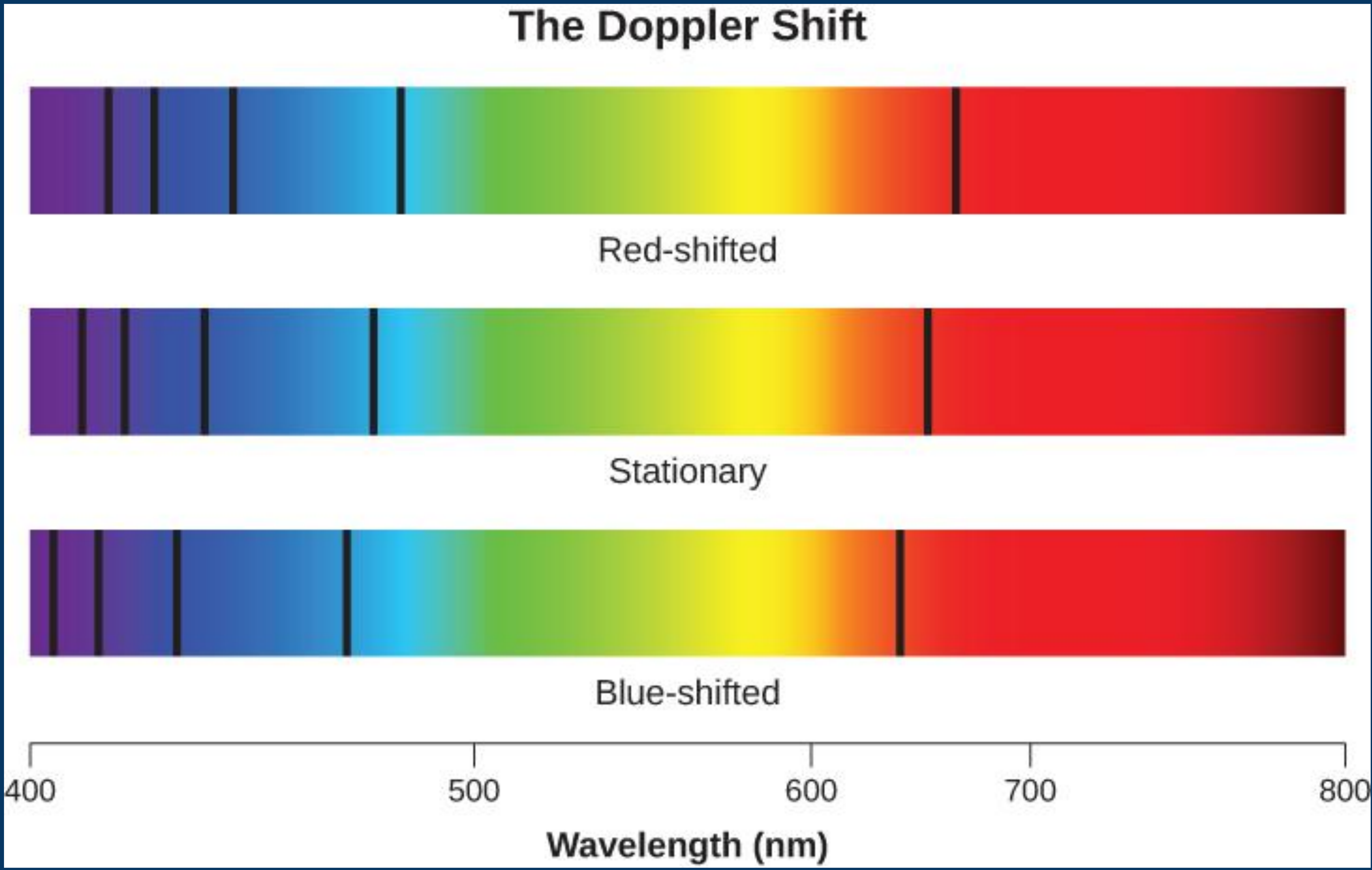
- Understand how astronomers can learn about a star's radius and composition by studying its spectrum
- Explain how astronomers can measure the motion and rotation of a star using the Doppler effect
- Describe the proper motion of a star and how it relates to a star's space velocity



Clues to the Size of a Star: Spectral Lines

This figure illustrates one difference in the spectral lines from stars of the same temperature but different pressures. A giant star with a very-low-pressure photosphere shows very narrow spectral lines (bottom), whereas a smaller star with a higher-pressure photosphere shows much broader spectral lines (top).

(credit: modification of work by NASA, ESA, A. Field, and J. Kalirai (STScI))



Doppler-Shifted Stars

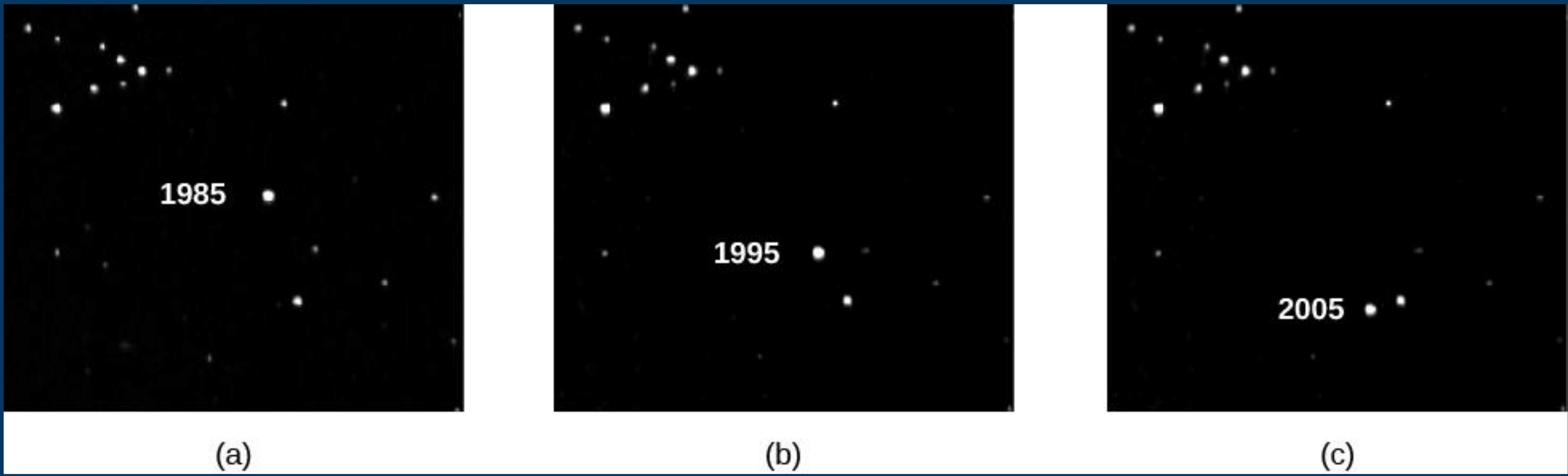
When the spectral lines of a moving star shift toward the red end of the spectrum, we know that the star is moving away from us. If they shift toward the blue end, the star is moving toward us.

The greater the shift, the faster the star is moving. Such motion, along the line of sight between the star and the observer, is called radial velocity and is usually measured in kilometers per second.

Activity 17.2 Spectrum Constructor

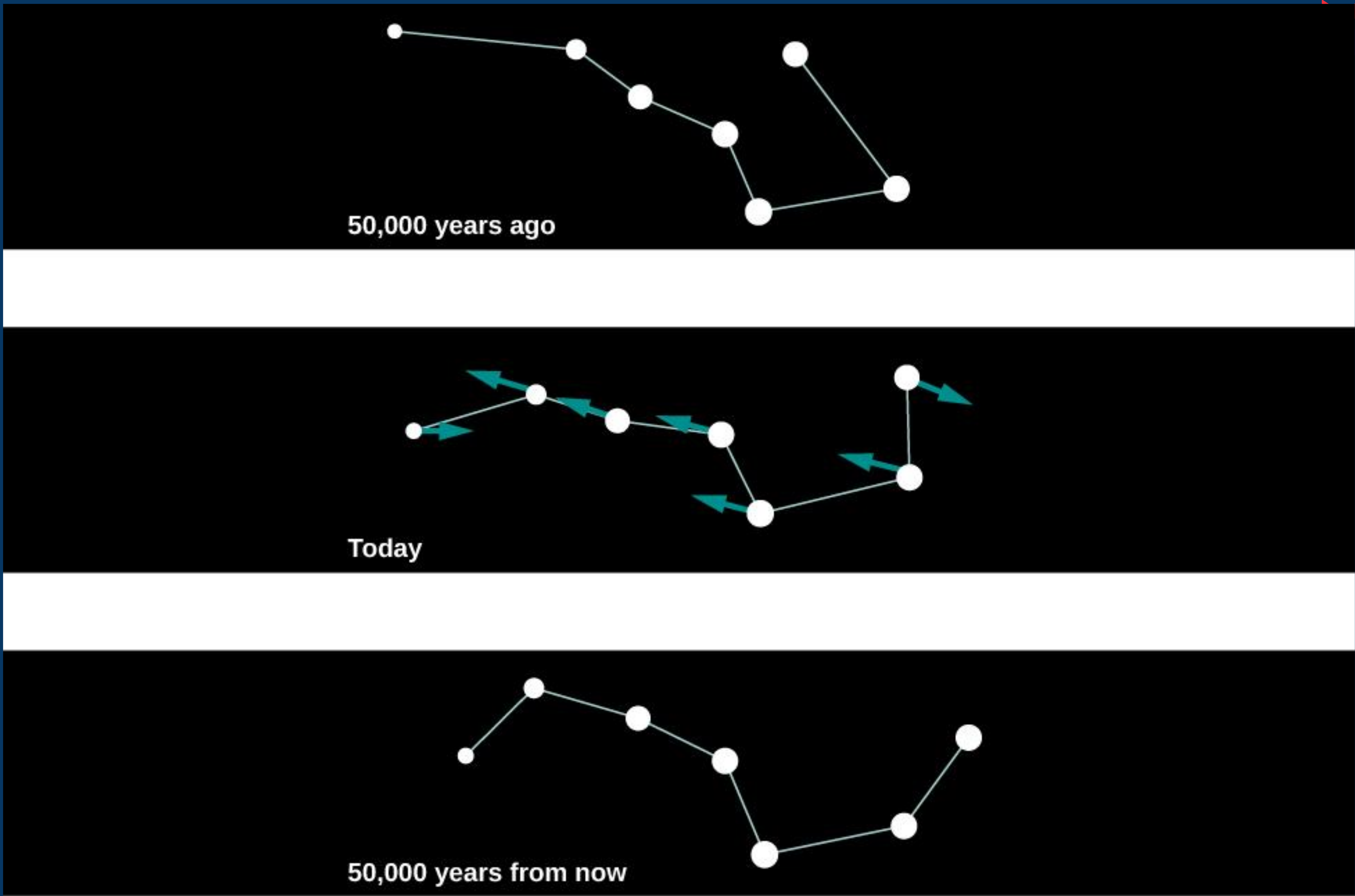
In the Spectrum Constructor, you can add absorption lines to the spectrum. Then adjust the velocity; negative indicates the star is moving toward the observer, and positive indicates it is moving away. Explore how the absorption lines are seen to shift to shorter and longer wavelengths.

https://foothillastrosims.github.io/Spectrum-Constructor/



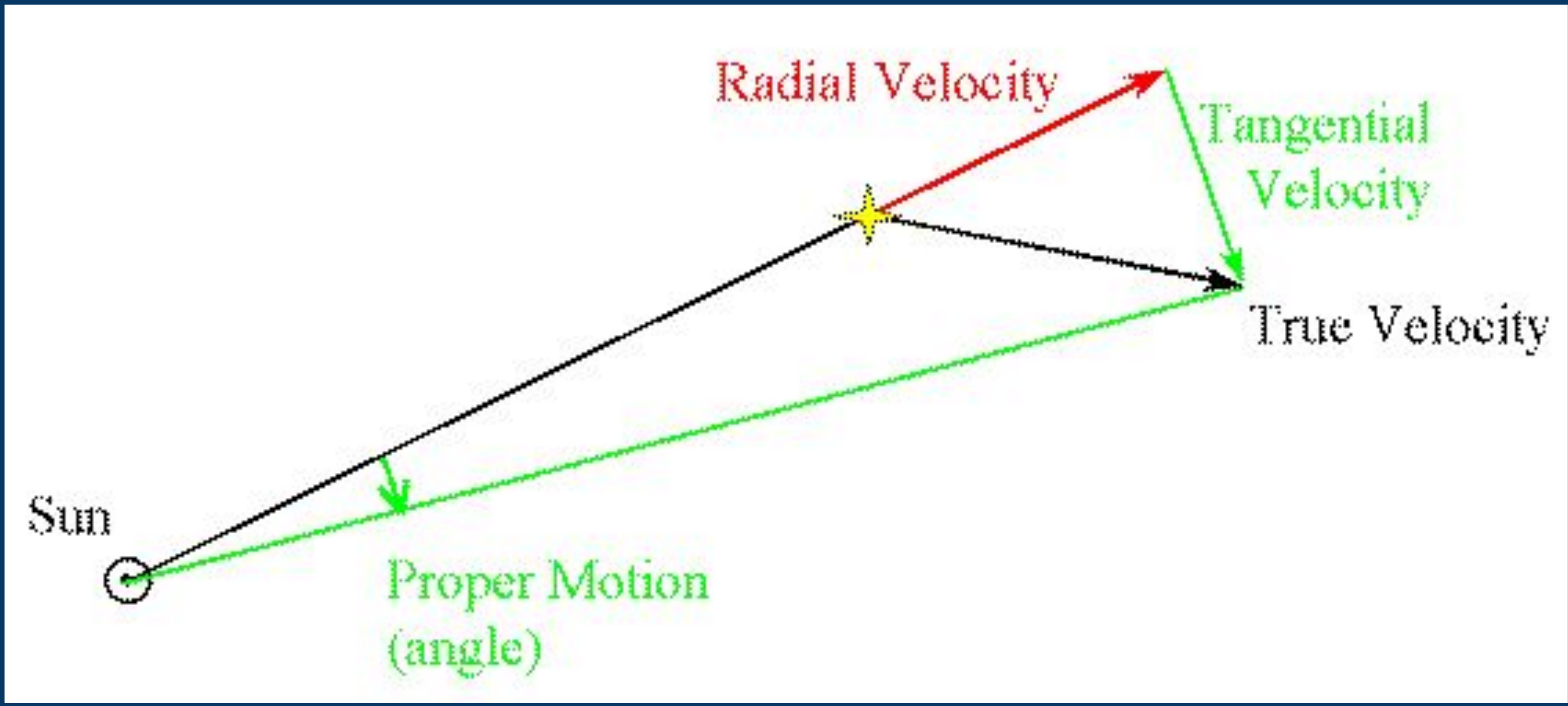
Proper Motion

Figure 17.11 Large Proper Motion. Three photographs of Barnard’s star, the star with the largest known proper motion, show how this faint star has moved over a period of 20 years. (modification of work by Steve Quirk)



Changes in the Big Dipper

Figure 17.12. This figure shows changes in the appearance of the Big Dipper due to proper motion of the stars over 100,000 years.



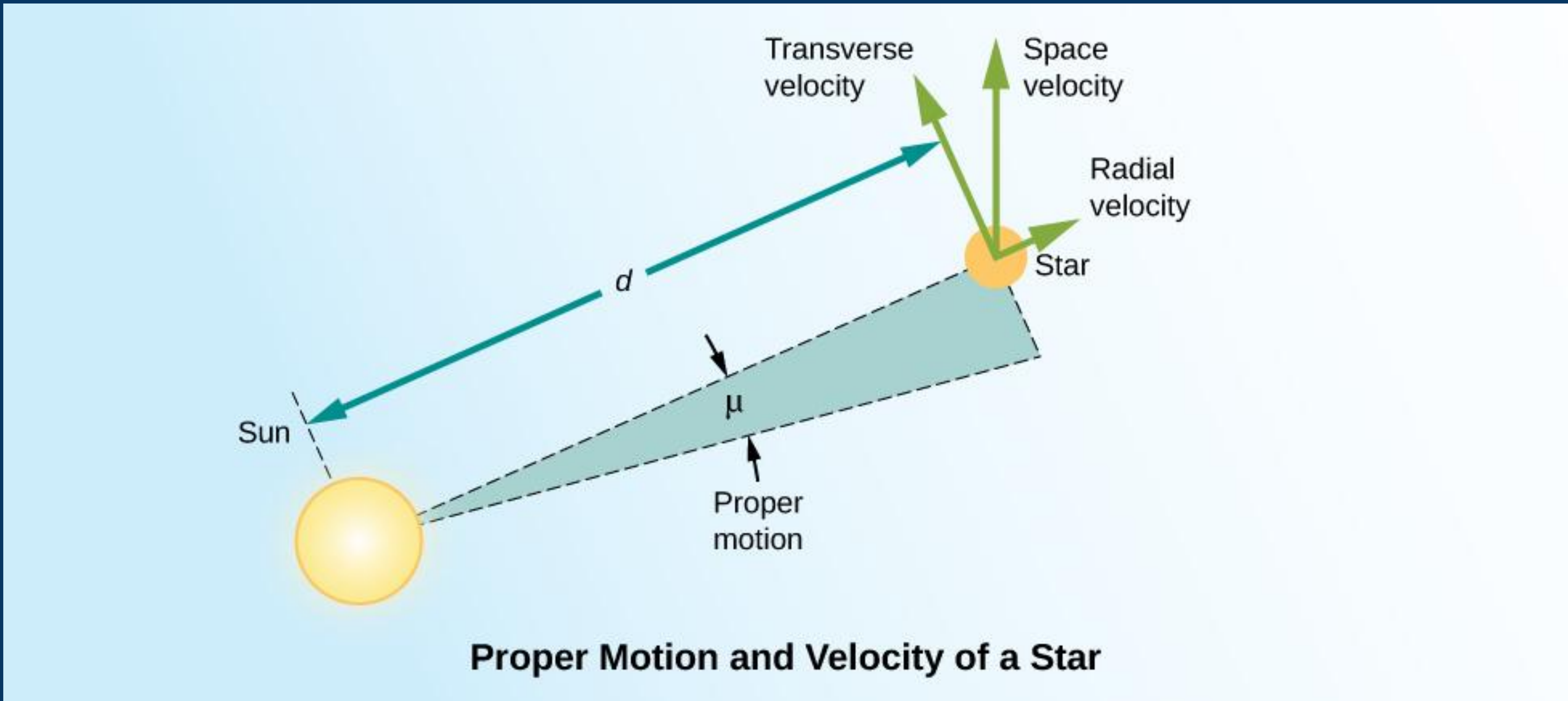
Radial Velocity

Radial velocity (vr): along the line of sight
⇒ measure it using the Doppler Shift of its spectrum.
Star’s radial velocity can be obtained by measuring the shift in wavelengths of certain spectral lines:

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$$

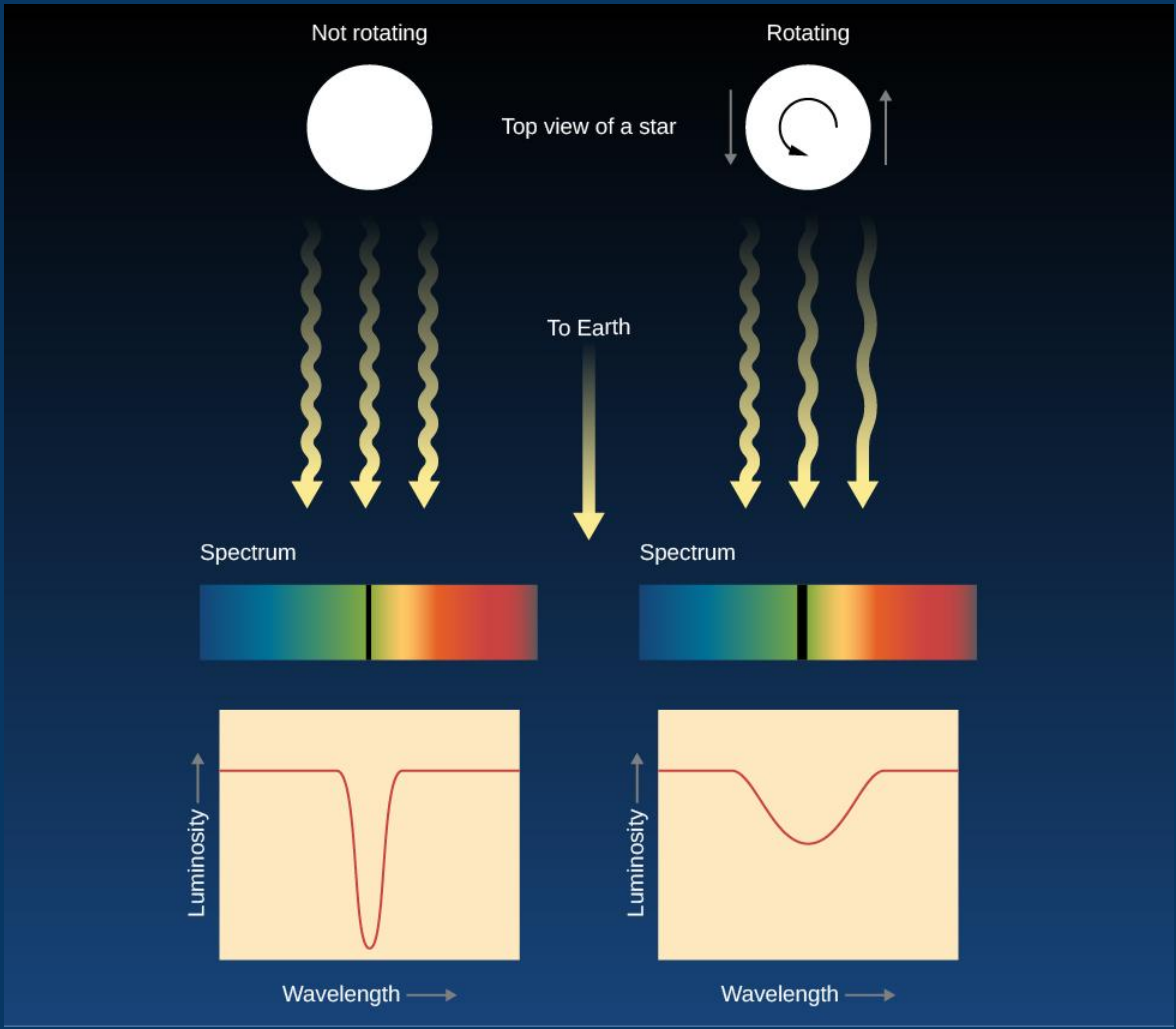
where:

- λ is the reference wavelength in the laboratory
- $\Delta\lambda$ is the measured shift in the spectral line from the star.
- c is the speed of light



Space Velocity and Proper Motion

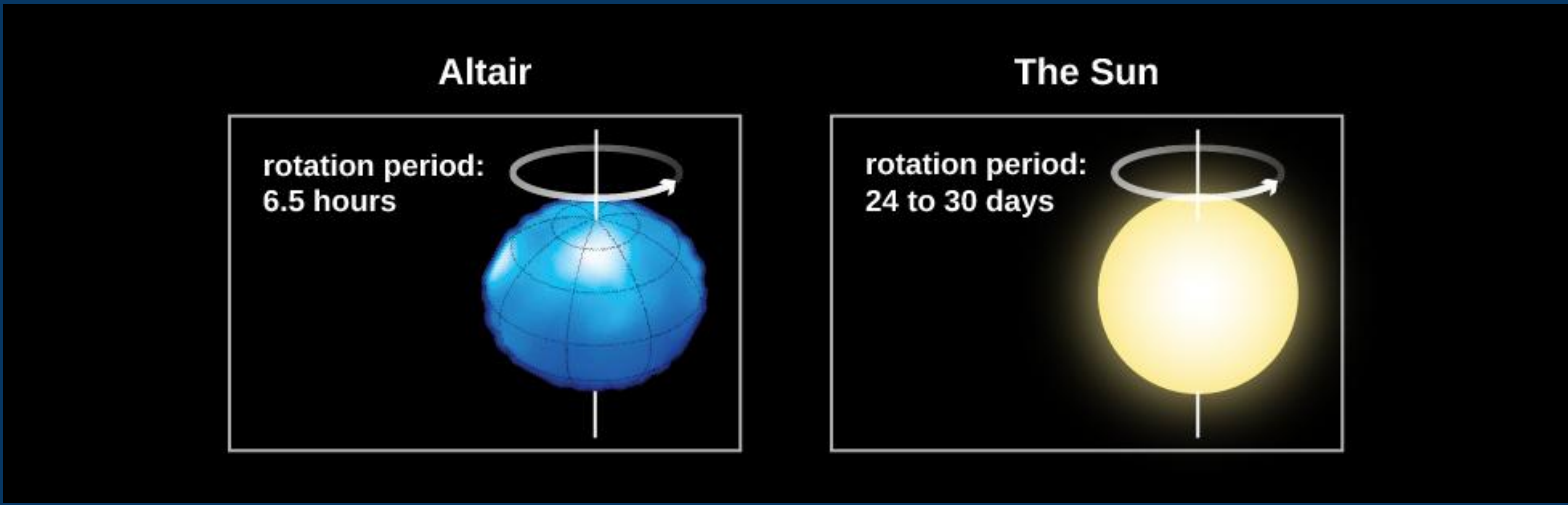
Figure 17.13. This figure shows the true space velocity of a star. The radial velocity is the component of the space velocity projected along the line of sight from the Sun to a star. The transverse velocity is a component of the space velocity projected on the sky. What astronomers measure is proper motion (μ), which is the change in the apparent direction on the sky measured in fractions of a degree. To convert this change in direction to a speed in, say, kilometers per second, it is necessary to also know the distance (d) from the Sun to the star.



Rotation of the star

Figure 17.14 Using a Spectrum to Determine Stellar Rotation. A rotating star will show broader spectral lines than a nonrotating star.

- many stars rotate faster than the Sun
- some with periods of less than a day!
- The more rapid, the shape are more flattened.
- Young star rotates very quickly ~ a day or less
- Very old star has rotational period of several months
- Our Sun has a period of about a month.



Rotation of the star

Figure 17.15 Comparison of Rotating Stars. This illustration compares the more rapidly rotating star Altair to the slower rotating Sun.

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Thank you!