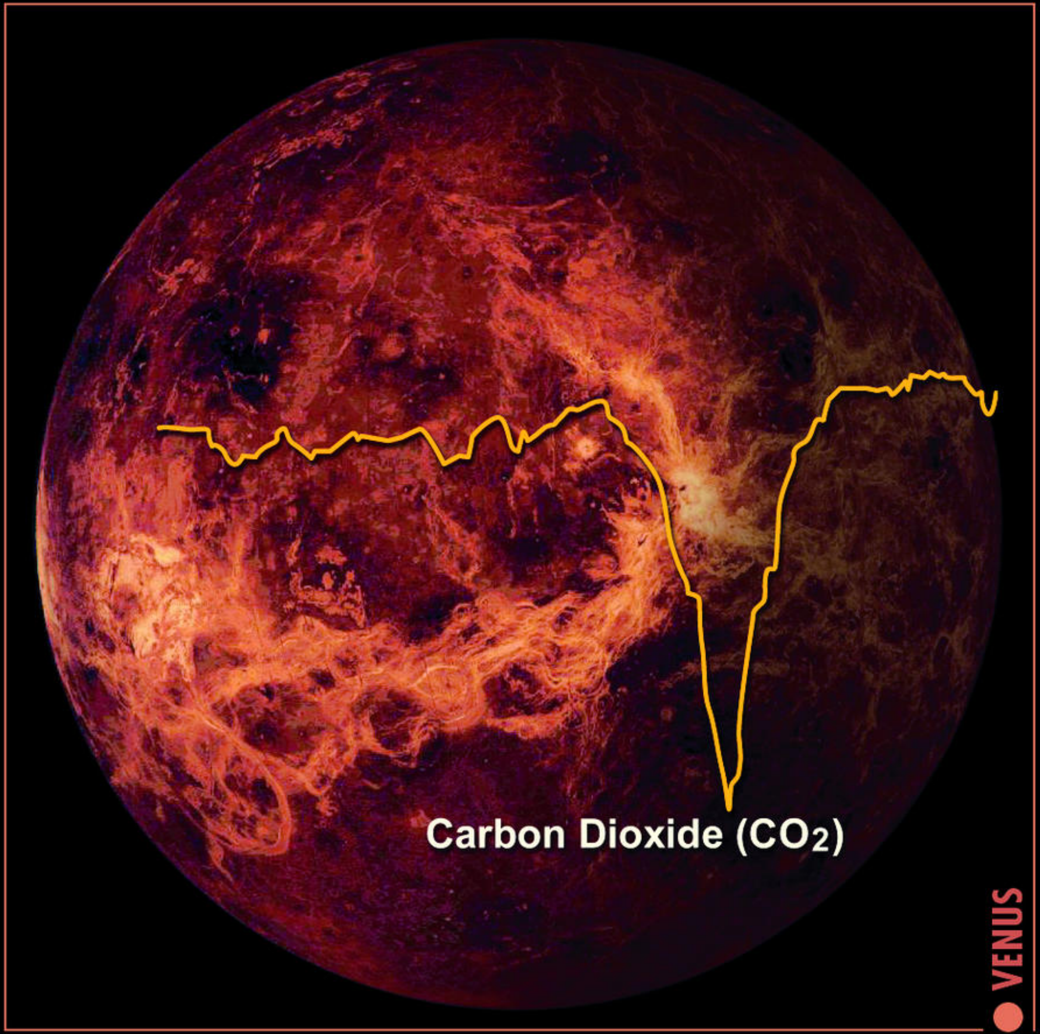
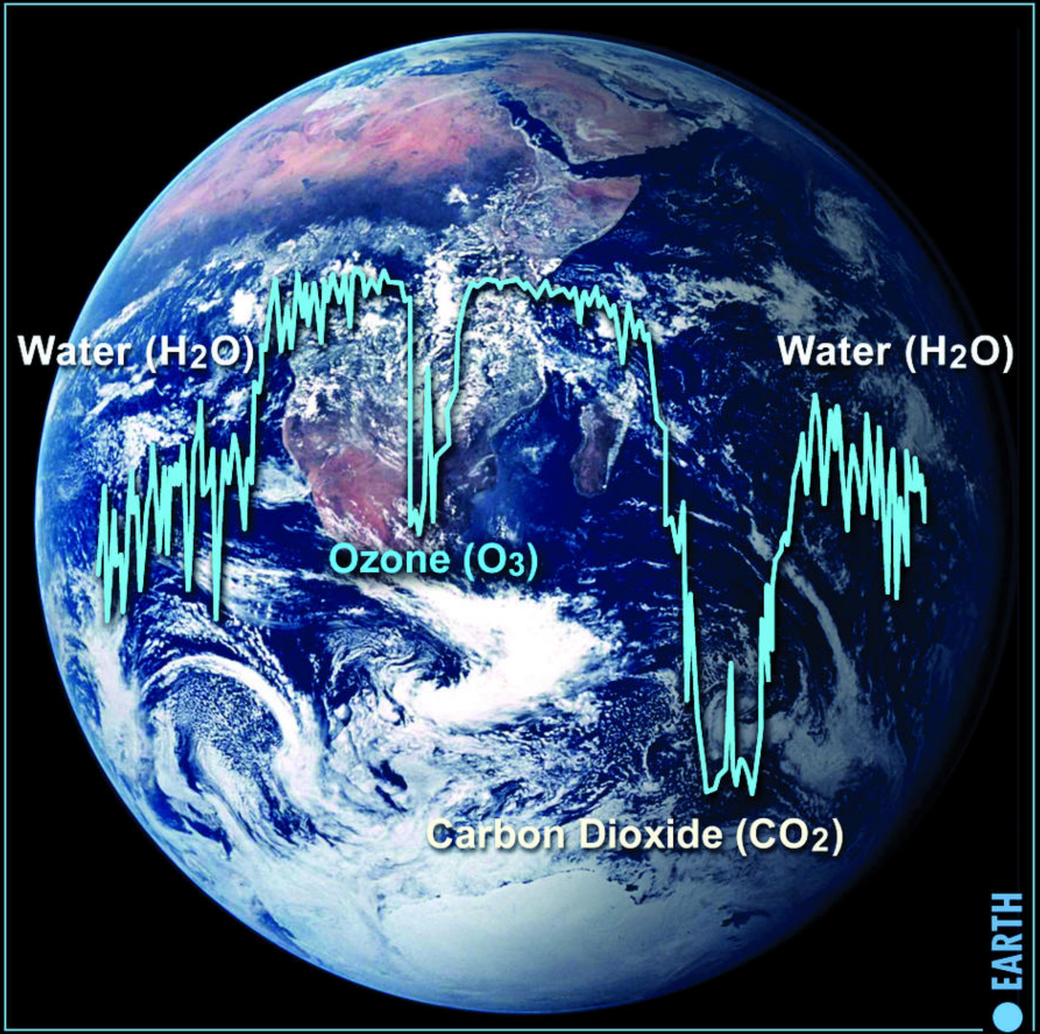
Planetary Habitability





Stephen Kane

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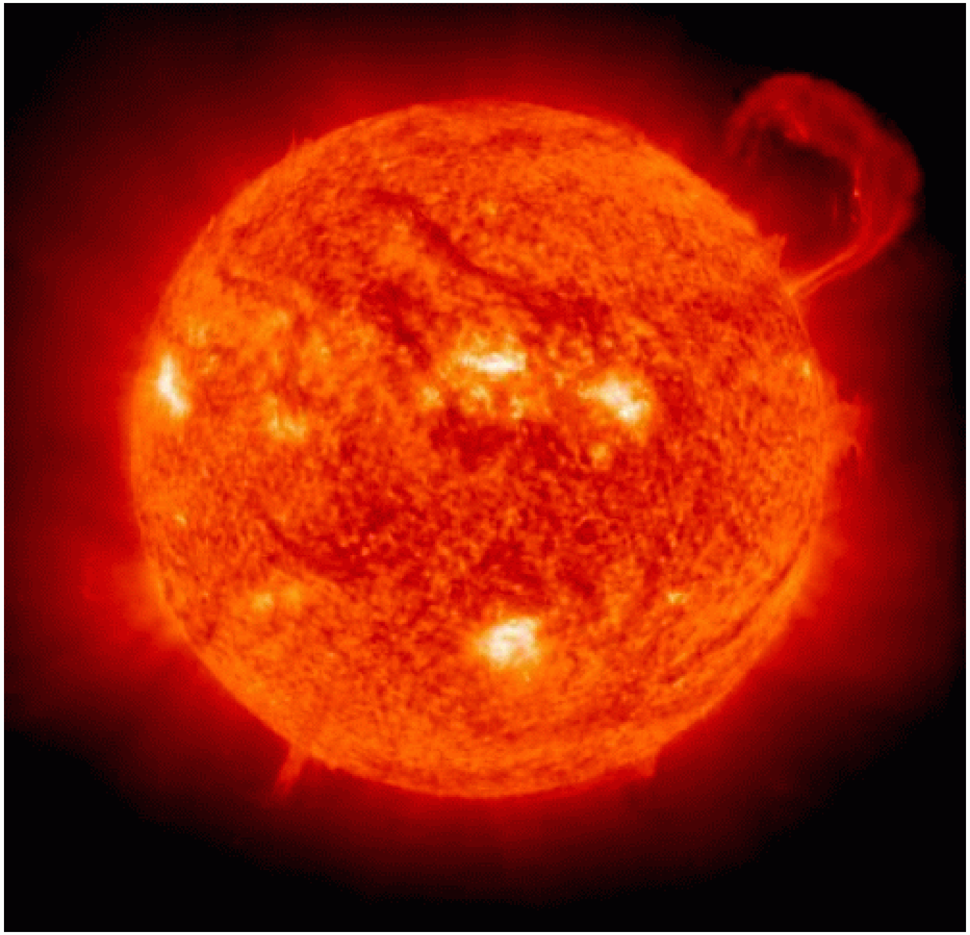
Topics

- Lecture 1 – Introduction
- Lecture 2 – Habitability Factors
- Lecture 3 - Stars
- Lecture 4 – Planetary Atmospheres
- Lecture 5 – Planetary Interiors
- Lecture 6 – Planetary Energy Balance
- Lecture 7 – Habitable Zone I
- Lecture 8 – Habitable Zone II
- Lecture 9 – Earth as a Living Planet
- Lecture 10 – Mars
- Lecture 11 – Icy Moons
- Lecture 12 – Venus
- Lecture 13 – Mercury & the Moon
- Lecture 14 – The Role of Giant Planets
- Lecture 15 – Stellar Influences
- Lecture 16 – Magnetic Fields
- Lecture 17 – Milankovitch Cycles
- Lecture 18 – Geological Cycles
- Lecture 19 – The Next Steps
- Lecture 20 – Summary/Discussion

Intrinsic Properties of Stars

- Mass
- Radius
- Effective Temperature
- Luminosity
- Composition (metallicity)
- Age

Numbers you should know: The Sun



source: SOHO/EIT

Mass ≈ 2 x 10^{30} kg = 1 $M_\odot$

Radius ≈ 7 x 10^{8} m = 1 $R_\odot$

Distance = 1.5 x 10^{11} m = 1 AU

Luminosity = 4 x 10^{26} W = 1 $L_\odot$

Surface temperature = 5800 K

age ≈ 4.5 Gyr

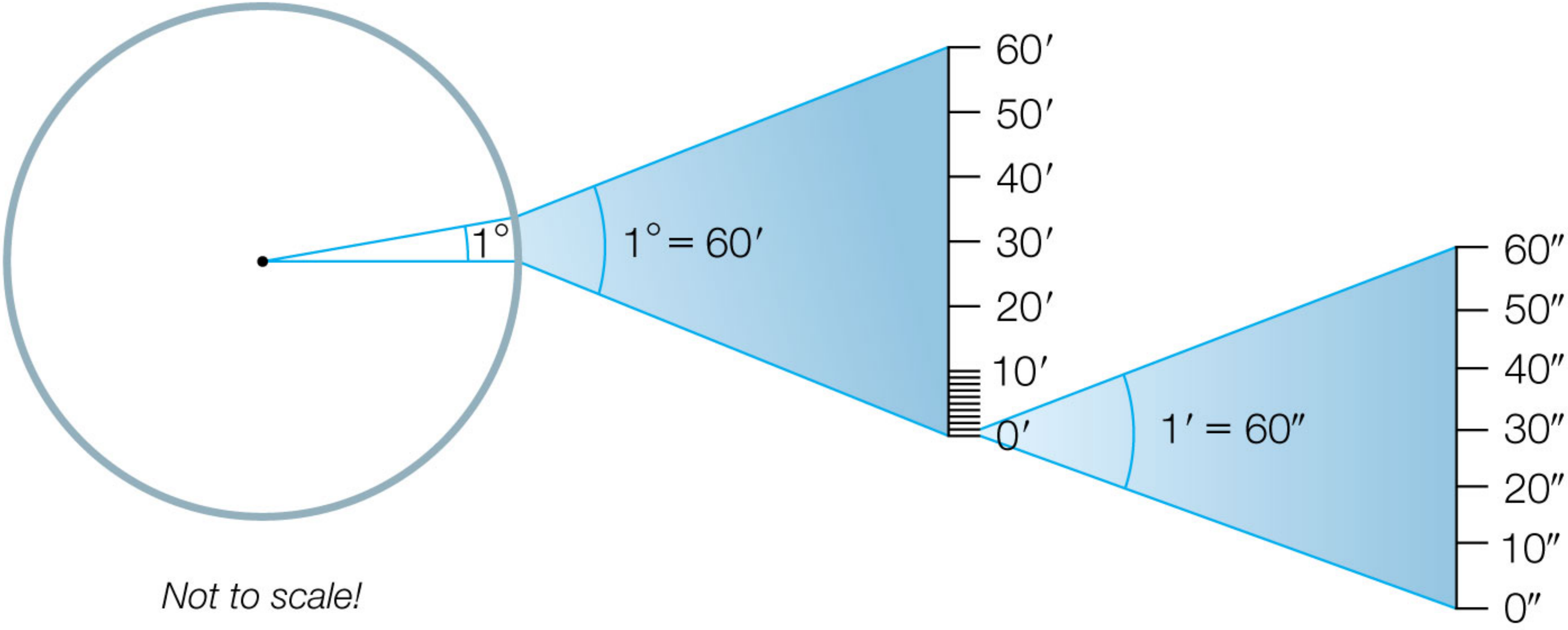
spectral type = G2 V

All other stars are scaled to these parameters for convenience.

Stellar Parallax

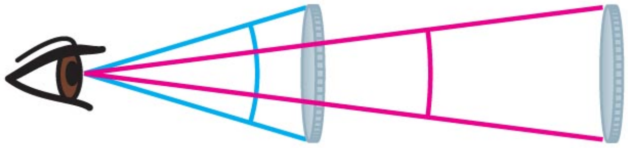
Angular Measurements

- Full circle = 360º
- 1º = 60´ (arcminutes)
- 1´ = 60˝ (arcseconds)

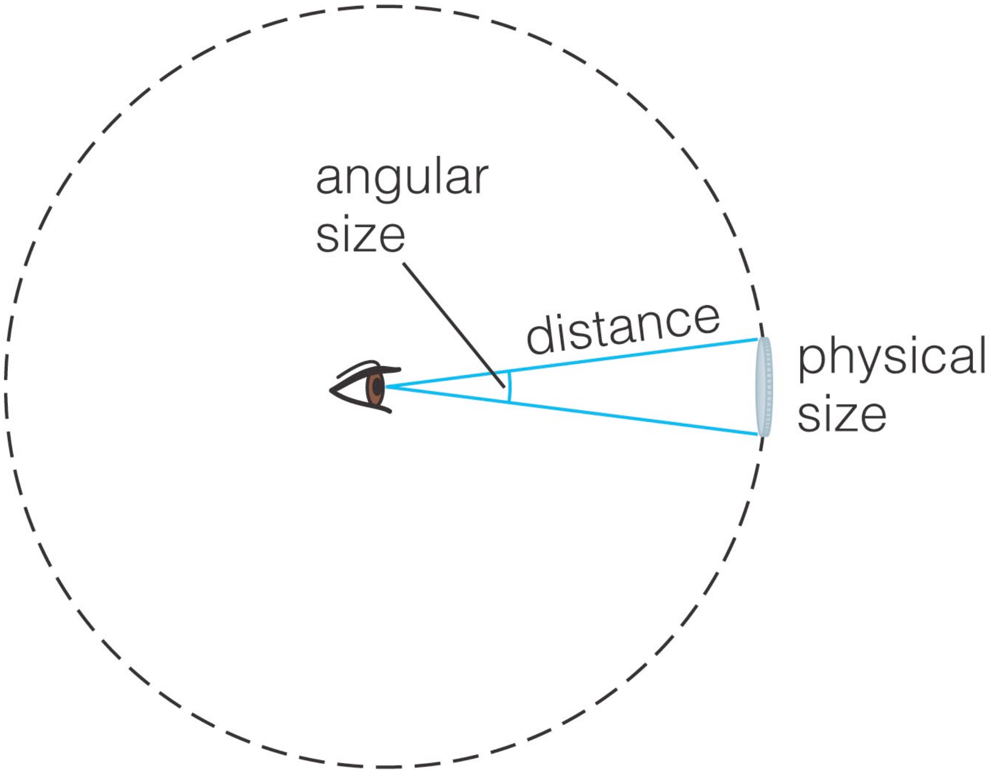


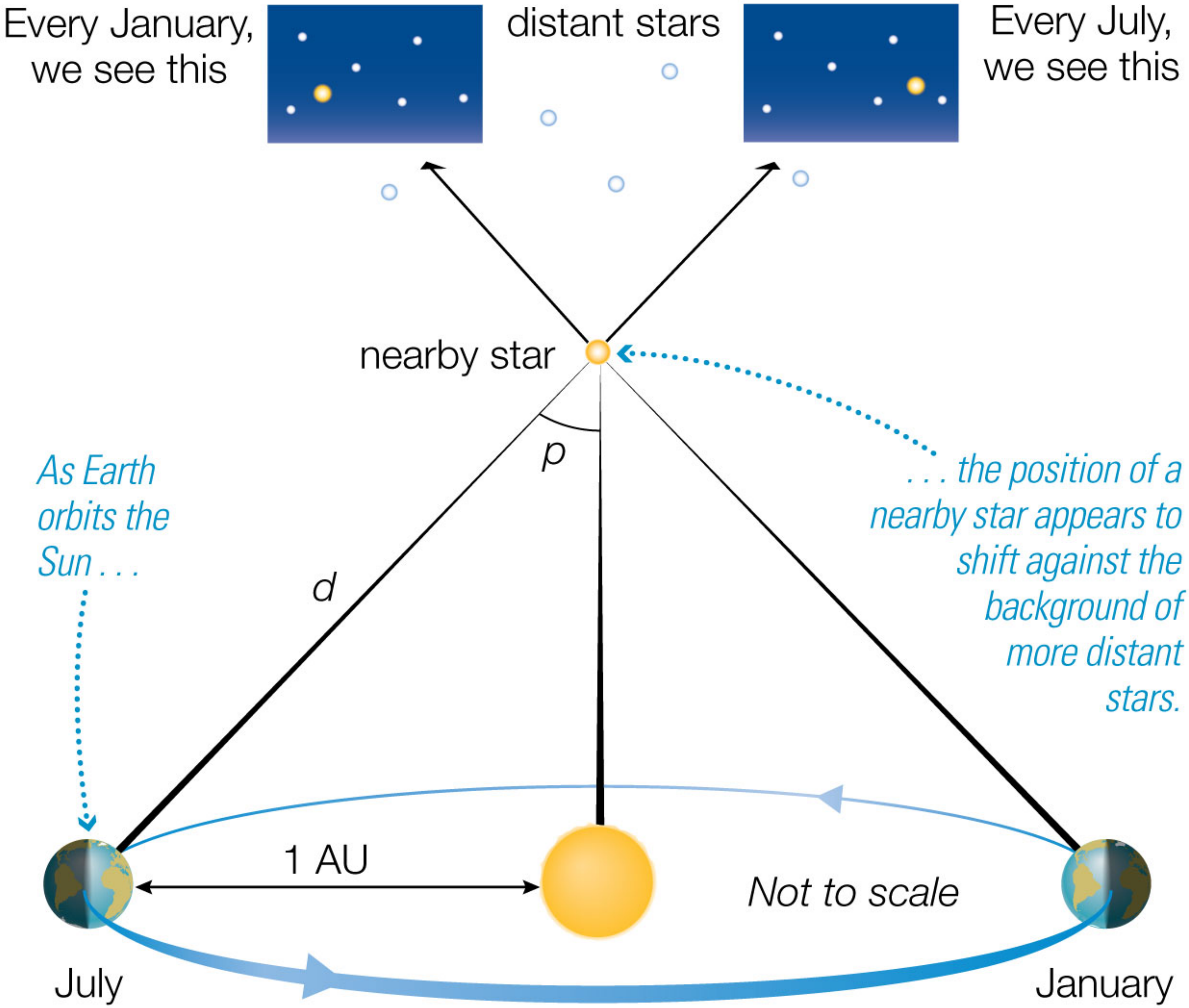
Angular Size

$$\text{angular size} = \text{physical size} \cdot \frac{360\ \text{degrees}}{2\pi \cdot \text{distance}}$$



An object’s angular size appears smaller if it is farther away.





As Earth orbits the Sun . . .

. . . the position of a nearby star appears to shift against the background of more distant stars.

Parallax and Distance

p = parallax angle

$$d \text{ (in parsecs)} = \frac{1}{p \text{ (in arcseconds)}}$$

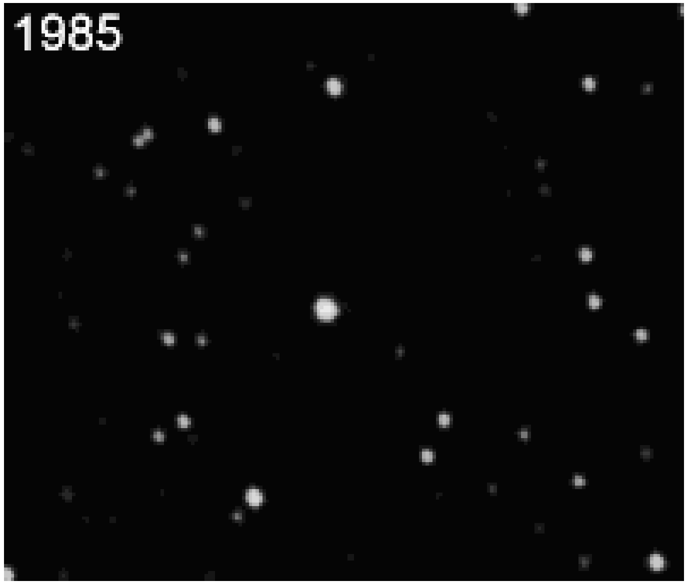
$$d \text{ (in light-years)} = 3.26 \; \frac{1}{p \text{ (in arcseconds)}}$$

One **parsec** is the distance at which the mean radius of the Earth's orbit subtends an angle of one second of arc.

Robert Innis – discovered Proxima in 1915

Proxima Centauri

Nearest star to the Solar System and Sun



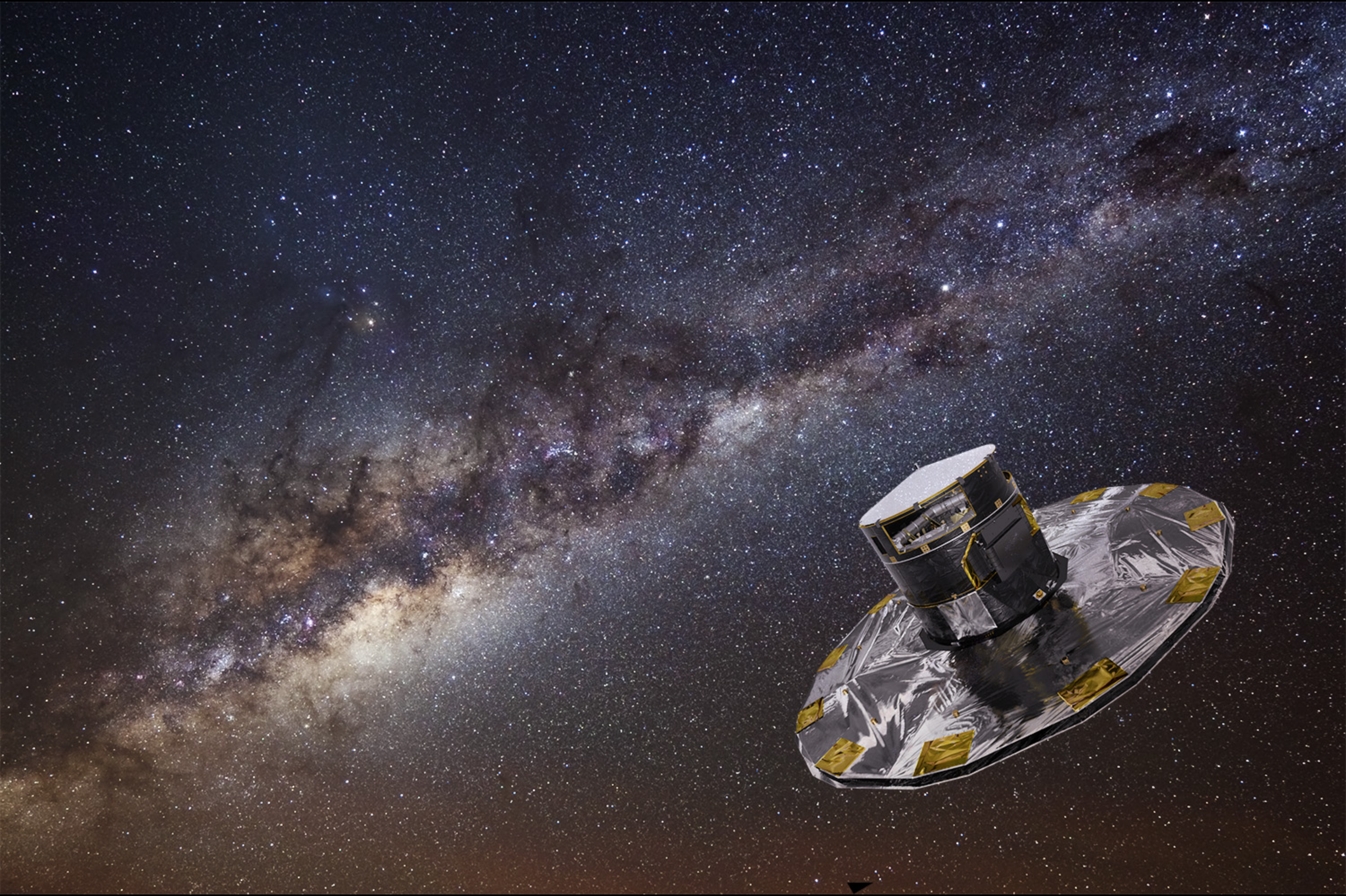
Proper motion over 25 years

Observed parallax shift on the sky over a six month time interval is

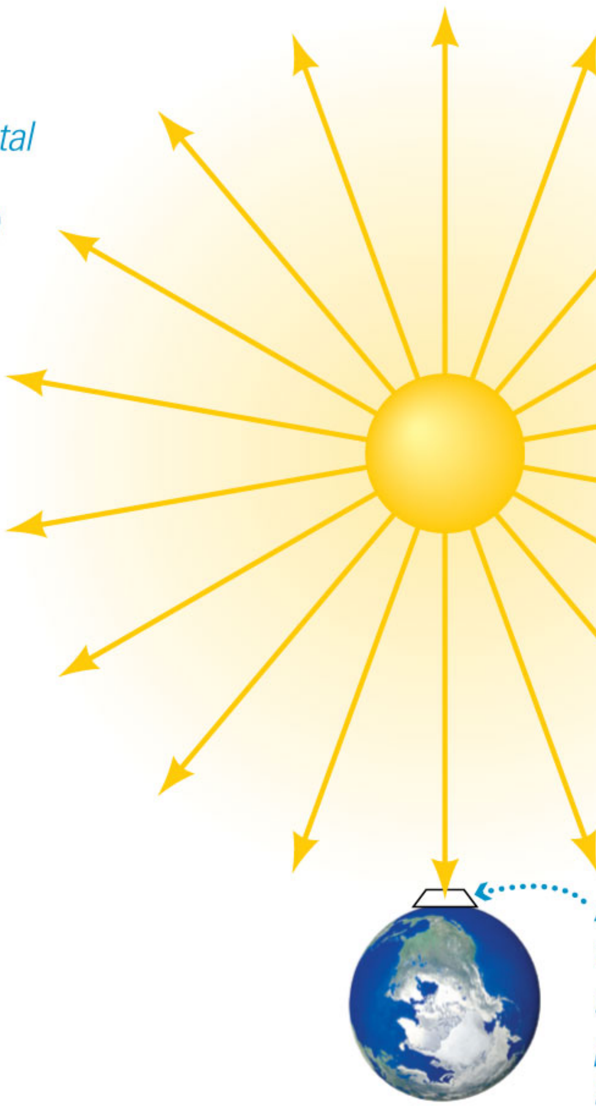
Angle = 1.5377 arc seconds
= 0.00042714 degrees
= 2 x P

Angle of parallax = P = 1.5377 / 2 = 0.76885 arc seconds

Distance to Proxima = 1 / P = 1/0.76885 = 1.301 parsecs



The Magnitude Scale



Luminosity is the total amount of power (energy per second) the star radiates into space.

Apparent brightness is the amount of starlight reaching Earth (energy per second per square meter).

Not to scale!

Luminosity:

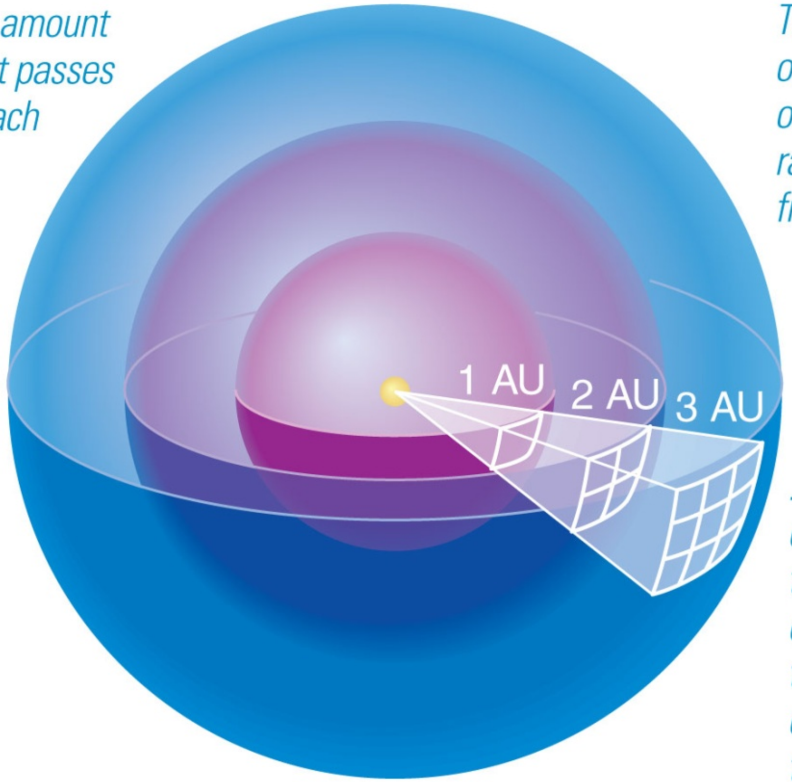
Amount of power a star radiates

(Joules per second = watts)

Apparent brightness:

Amount of starlight that reaches Earth

(energy per second per unit area)



The same amount of starlight passes through each sphere.

The surface area of a sphere depends on the square of its radius (distance from the star) . . .

. . . so the amount of light passing through each unit of area depends on the inverse square of its distance from the star.

Apparent brightness follows the **inverse square law**.

Luminosity passing through each sphere is the same.

Area of sphere:
$4\pi\ (\text{radius})^2$

Divide luminosity by area to get brightness.

The relationship between apparent brightness and luminosity depends on distance:

$$\text{Brightness} = \frac{\text{Luminosity}}{4\pi\,(\text{distance})^2}$$

We can determine a star's luminosity if we can measure its distance and apparent brightness:

$$\text{Luminosity} = 4\pi\,(\text{distance})^2 \times (\text{Brightness})$$

Flux and luminosity

- Flux decreases as we get farther from the star – like 1/distance^2

$$F = \frac{L}{4\pi D^2}$$

The Magnitude Scale

- **Apparent magnitude** is a description of how bright stars appear on the sky.
- A difference of 5 magnitudes represents a factor of 100 difference in brightness.
- **Absolute magnitude** is the apparent magnitude of a star at a distance of 10 parsecs.
- The absolute magnitude of the Sun is 4.8.

Object	Apparent Magnitude
Sun	– 26.5
Full moon	– 12.5
Venus (at brightest)	– 4.4
Mars (at brightest)	– 2.7
Jupiter (at brightest)	– 2.6
Sirius (brightest star)	– 1.4
Canopus (second brightest star)	– 0.7
Vega	0.0
Spica	1.0
Naked eye limit in urban areas	3–4
Uranus	5.5
Naked eye limit in rural areas	6–6.5
Bright asteroid	6
Neptune	7.8
Limit for typical binoculars	9–10
Limit for 15-cm (6-in.) telescope	13
Pluto	15
Limit for visual observation with largest telescopes	19.5
Limit for photographs with largest telescopes	23.5
Expected limit for Hubble Space Telescope	28±

Apparent magnitudes of selected objects

Hartmann/The Cosmic Journey, 4th ed., Fig. 16-T1; The Cosmic Voyage, Fig. 16-T1

Blackbody Radiation

Thermal (Blackbody) Radiation

- Nearly all large or dense objects emit thermal radiation, including stars, planets, and you.

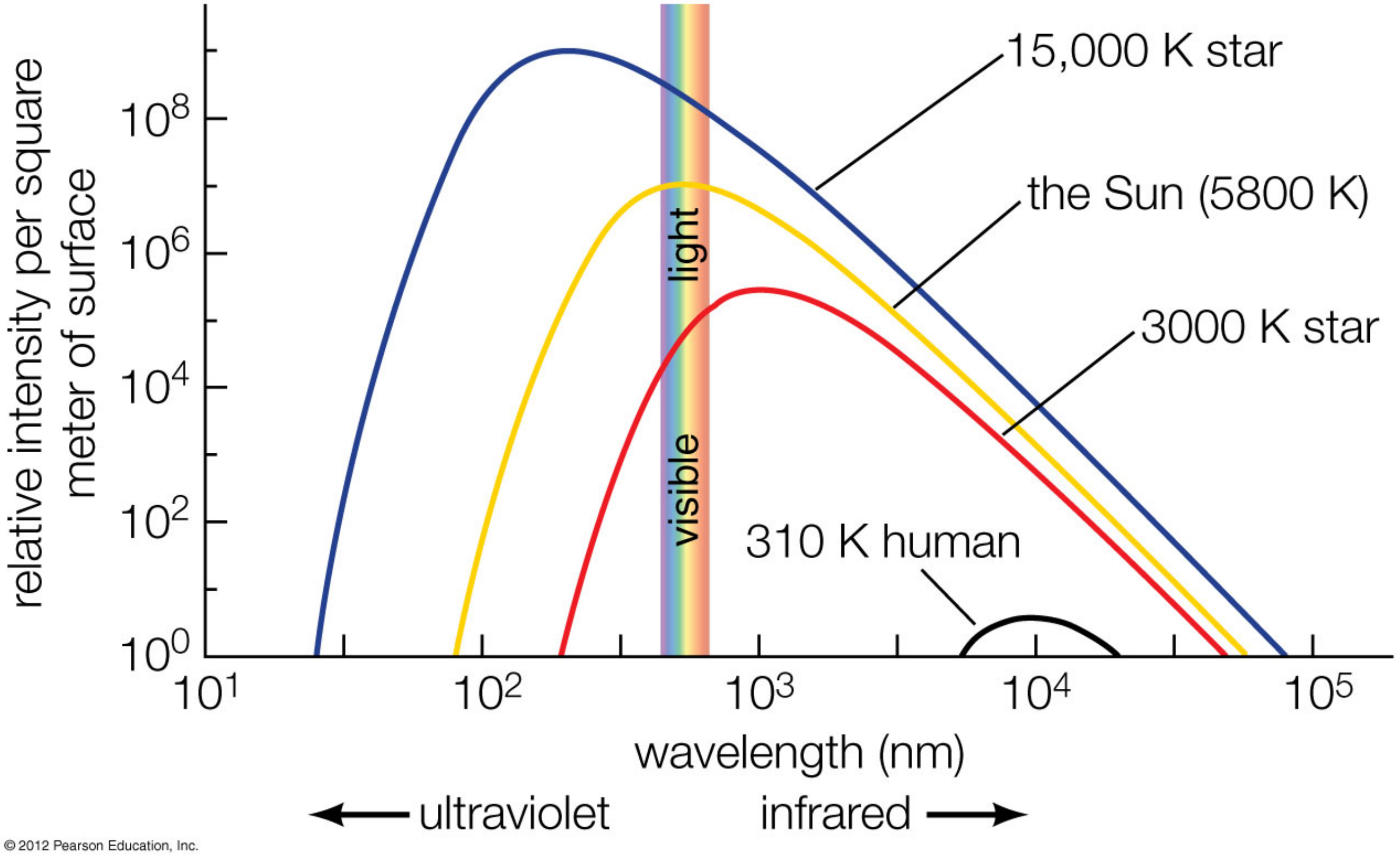
- An object’s thermal radiation spectrum depends on only one property: its **temperature.**

- A **blackbody** is an ideal emitter that absorbs all incident energy and reradiates the energy.

- We can use this to determine the temperatures of stars and planets.

Properties of Thermal Radiation

1. Hotter objects emit more light at all frequencies per unit area (Stefan-Boltzmann law).
2. Hotter objects emit photons with a higher average energy (Wien's law).



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Stefan-Boltzmann law

- Stefan-Bolzmann constant:

$$\sigma = 5.670400 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}.$$

- For a spherical star of radius R:

$$\boxed{L = 4\pi R^2 \sigma T_e^4.}$$

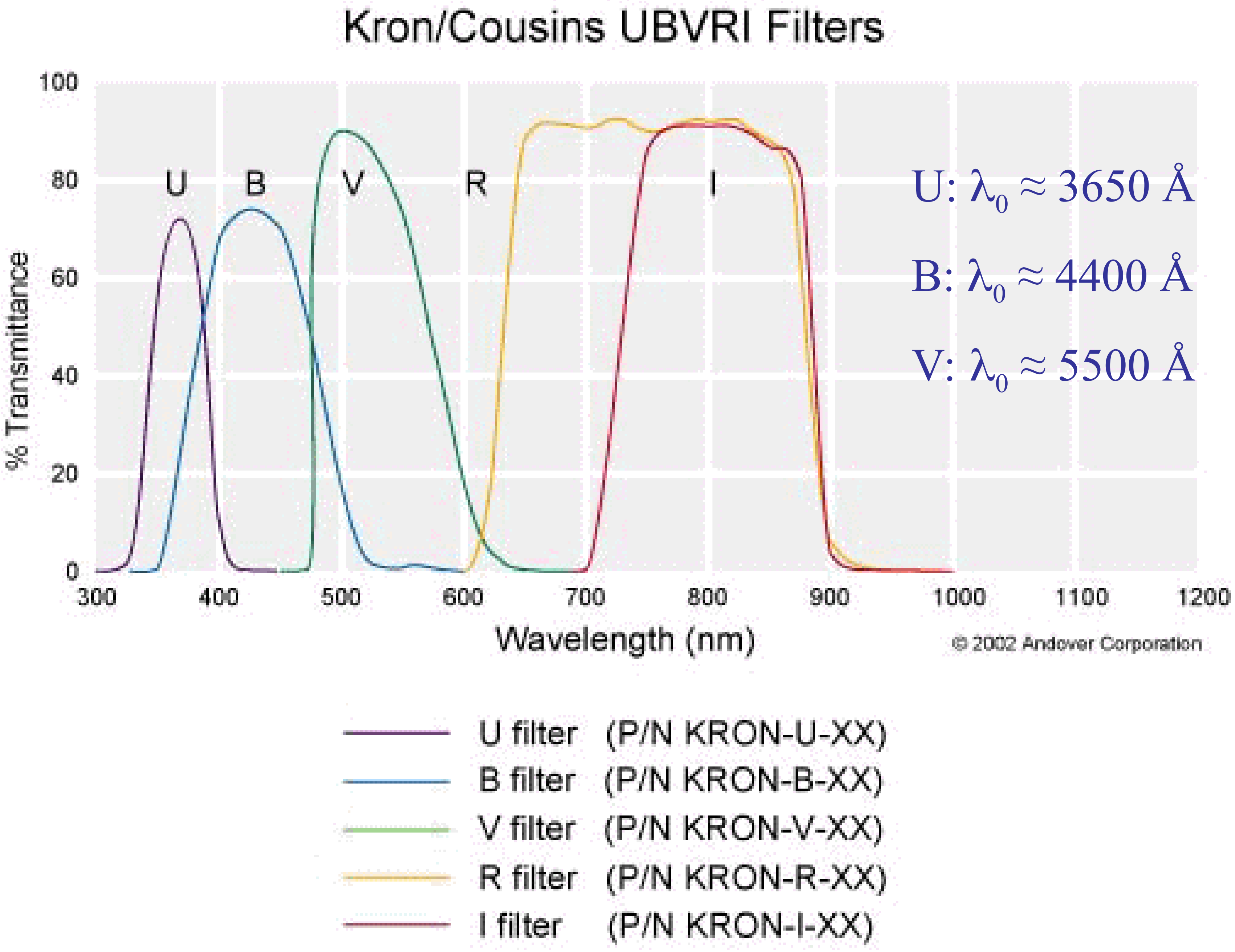
- The **Stefan-Boltzmann equation**.

Wien’s law

- Cooler objects produce radiation that peaks at lower energies = longer wavelengths = redder colors.
- Hotter objects produce radiation that peaks at higher energies = shorter wavelengths = bluer colors.
- Wavelength of peak radiation:
  Wien's Displacement Law

$$\boxed{\lambda_{\max} T = 0.002897755 \text{ m K}.}$$

Optical Wavelength Bands

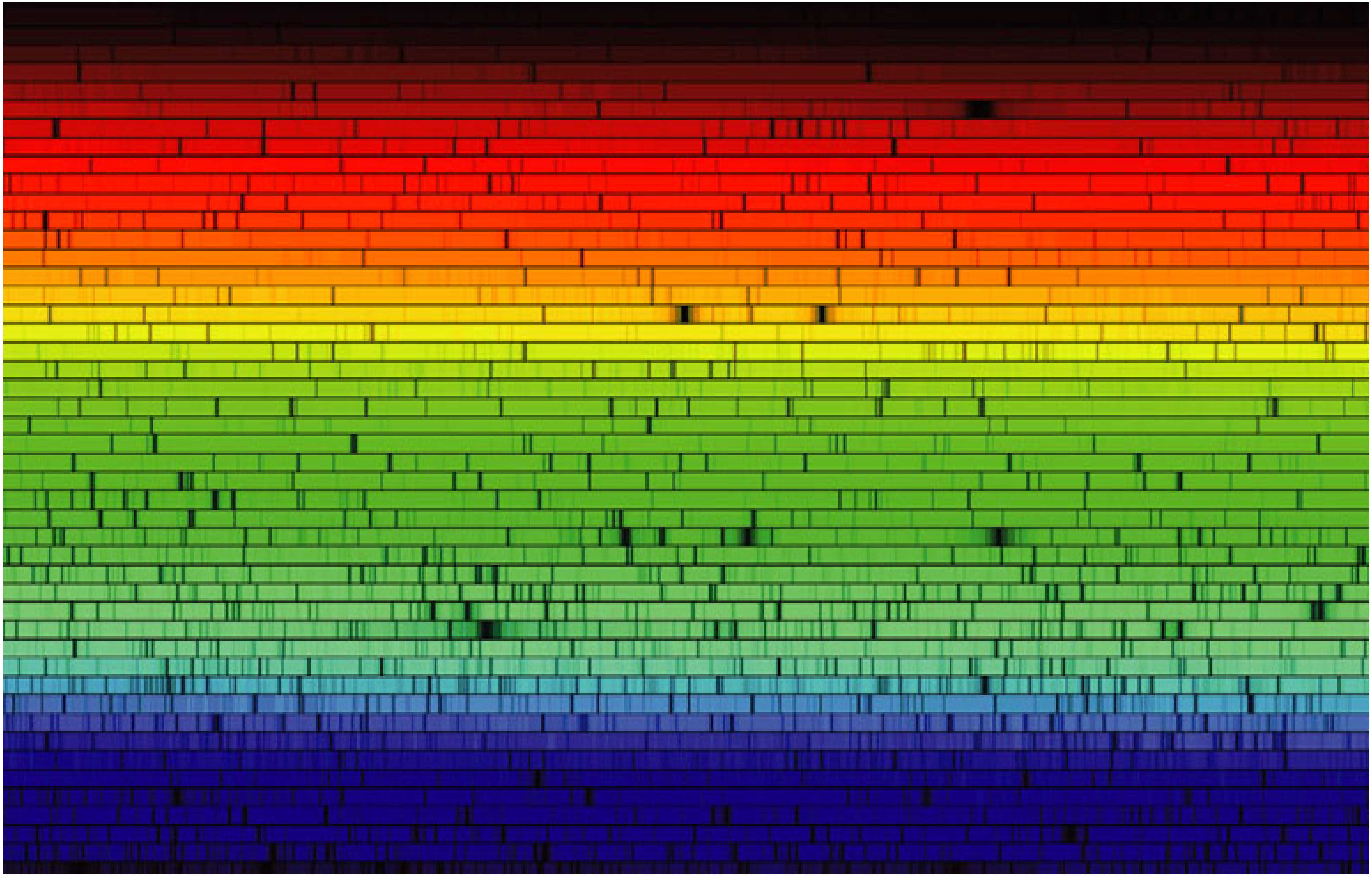


U: $\lambda_0 \approx 3650$ Å

B: $\lambda_0 \approx 4400$ Å

V: $\lambda_0 \approx 5500$ Å

Stellar Spectra



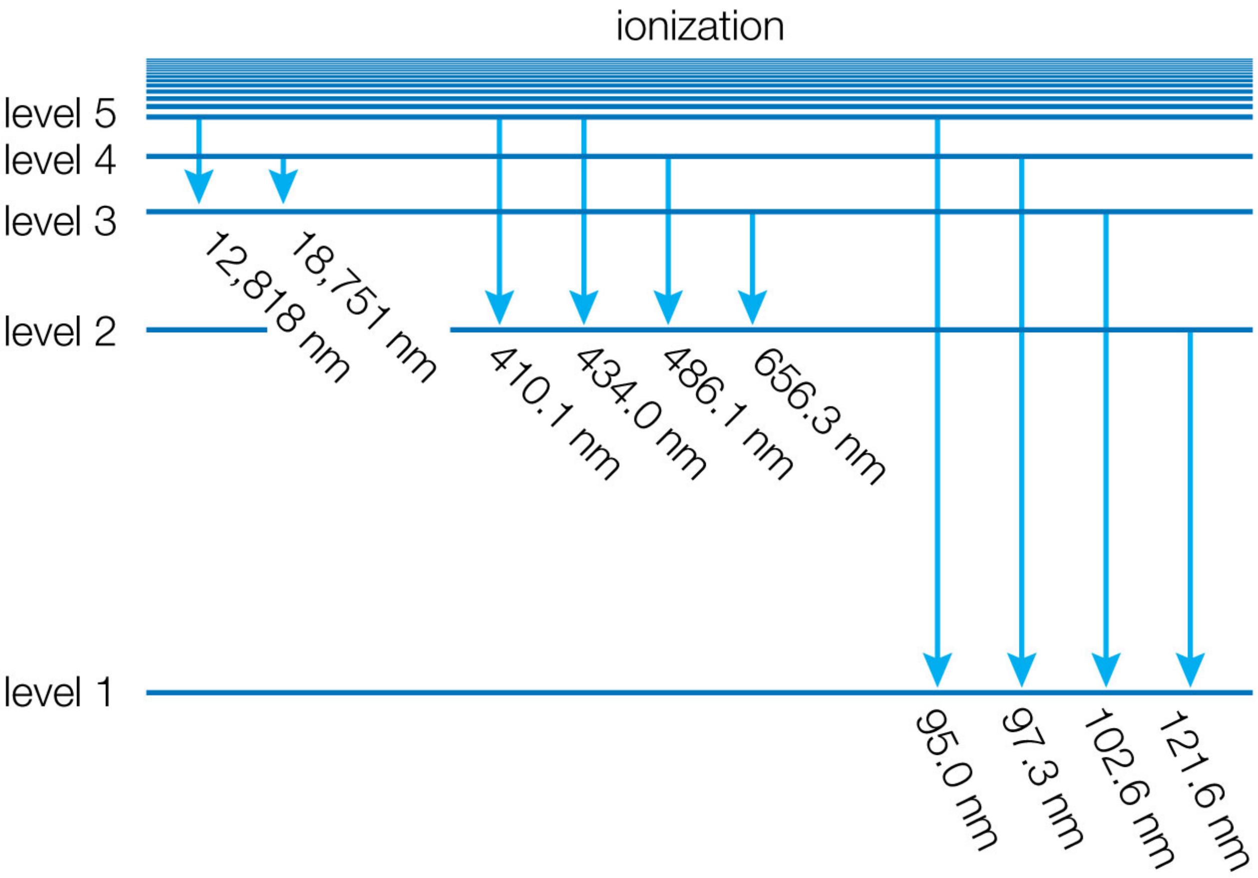
Absorption lines in the Sun’s spectrum
(Fraunhofer lines)

Kirchoff’s laws

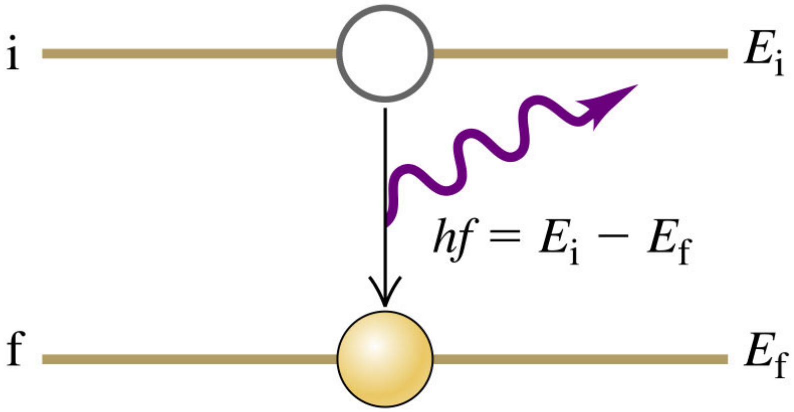
Chemical Analysis by Spectral Observations (Kirchoff & Bunsen)

- A hot solid, liquid, or dense gas produces a continuous spectrum.
- A thin gas in front of a cooler background produces an emission line spectrum.
- A thin gas in front of a hot source imprints absorption lines on the spectrum. This is mainly what we see from stars.

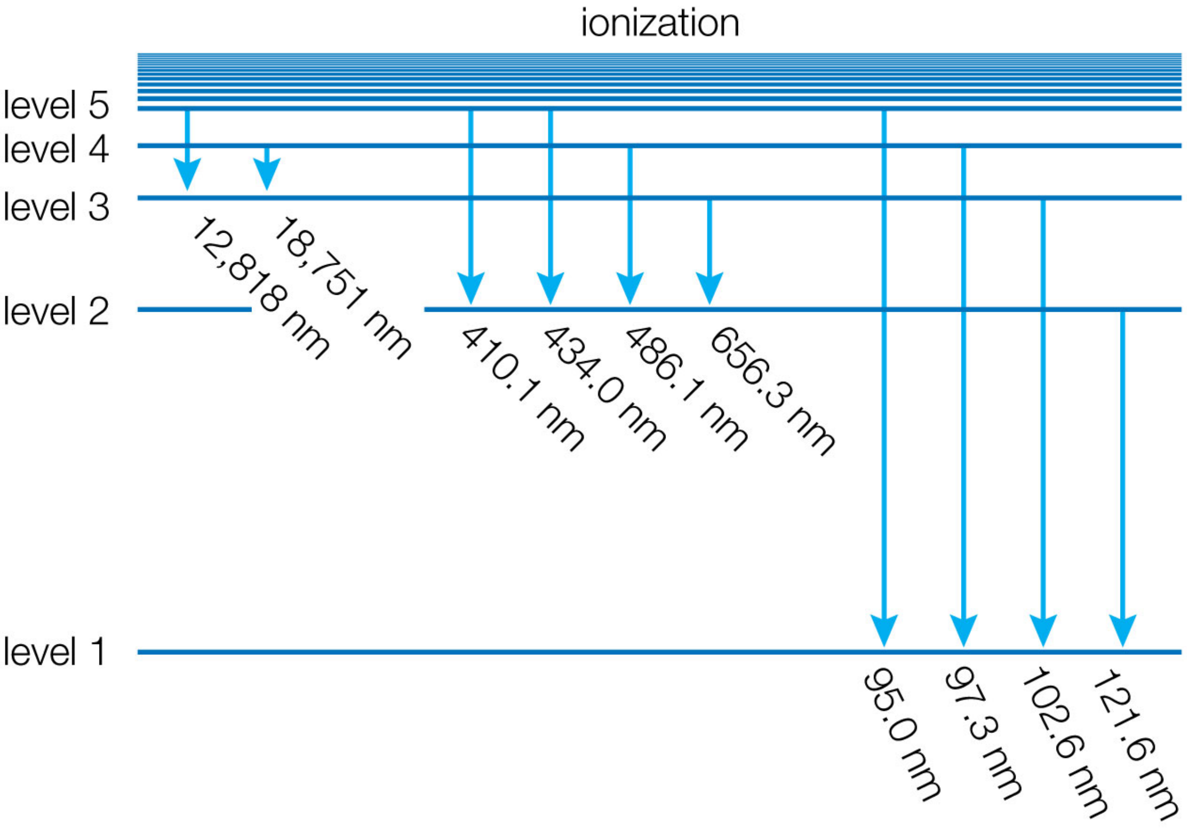
Chemical Fingerprints



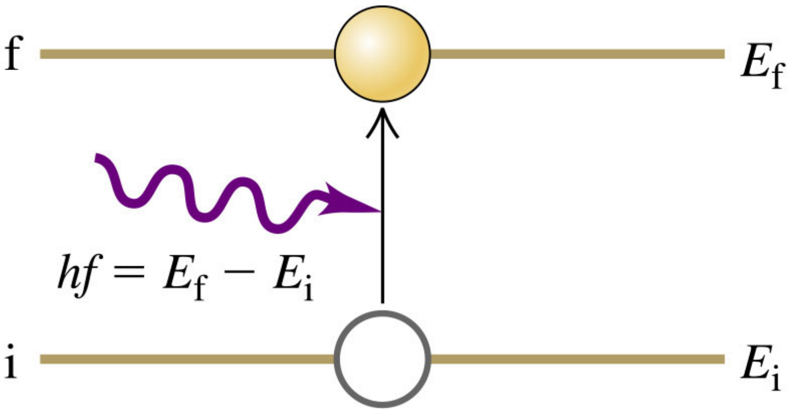
- Downward transitions produce a unique pattern of emission lines.



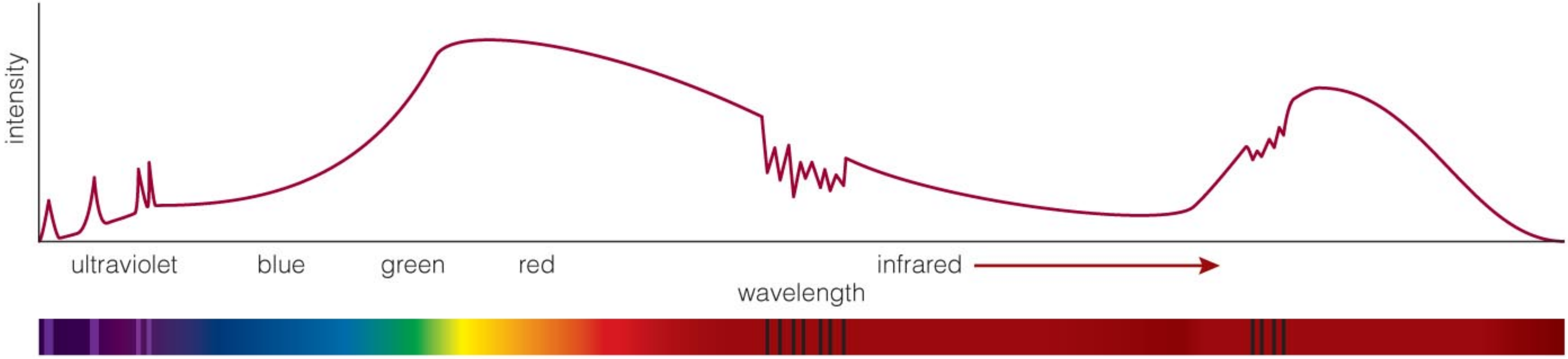
Chemical Fingerprints



- Because those atoms can absorb photons with those same energies, upward transitions produce a pattern of absorption lines at the same wavelengths.

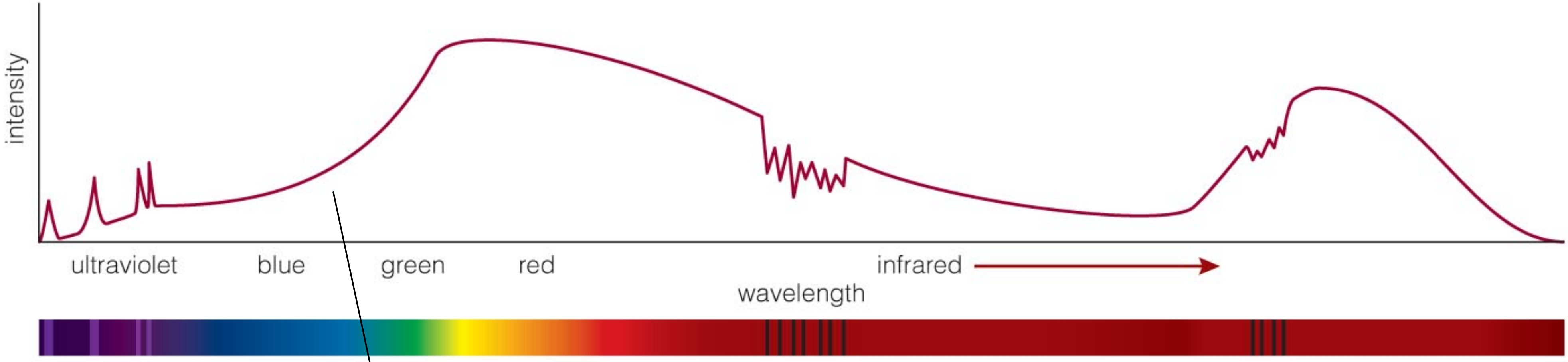


Interpreting an Actual Spectrum



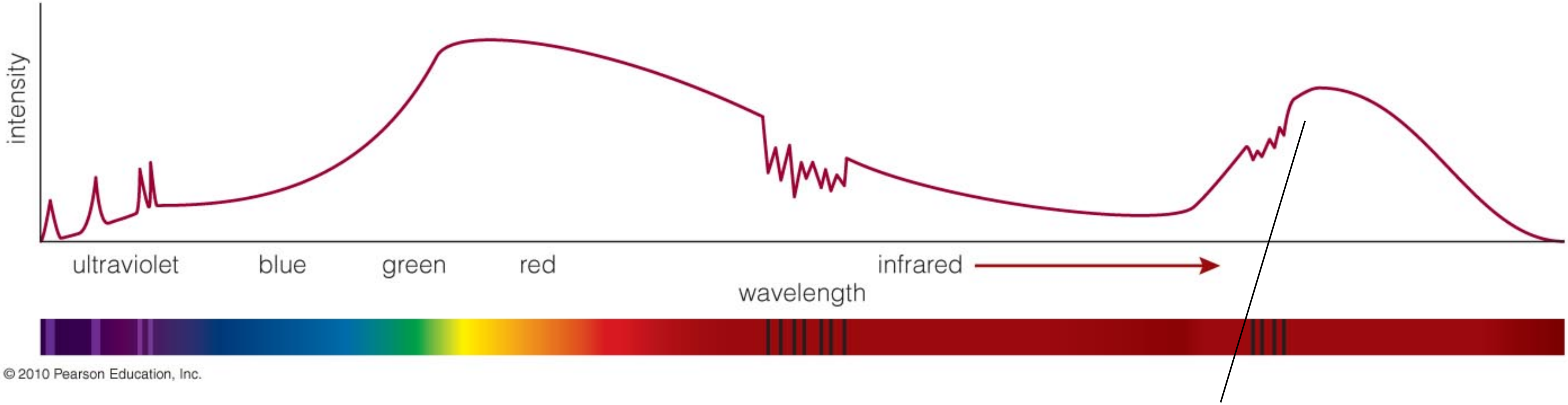
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

Interpreting an Actual Spectrum



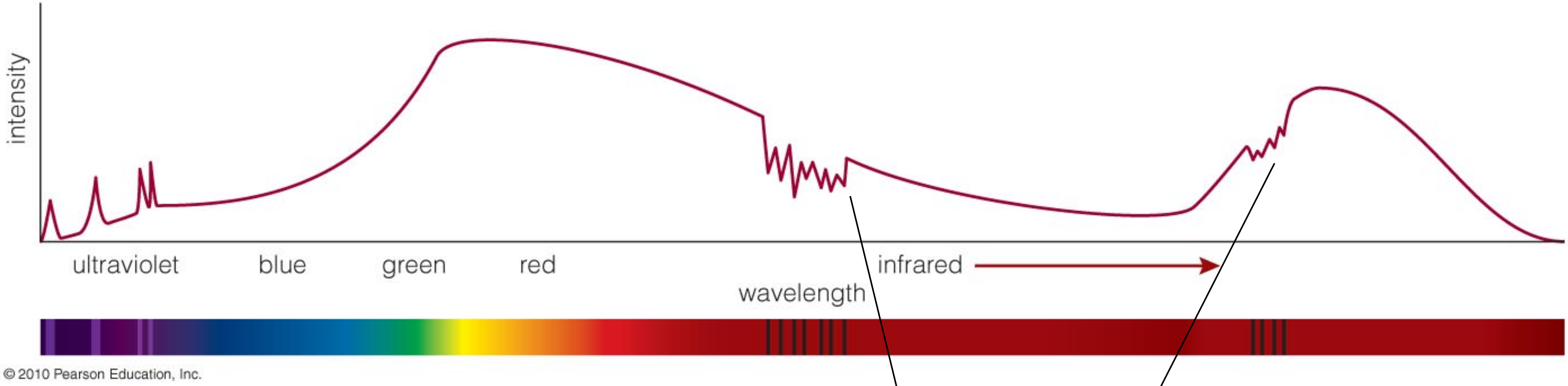
Reflected sunlight:
Continuous spectrum of
visible light is like the Sun's
except that some of the blue
light has been absorbed—
the object must look red.

Interpreting an Actual Spectrum



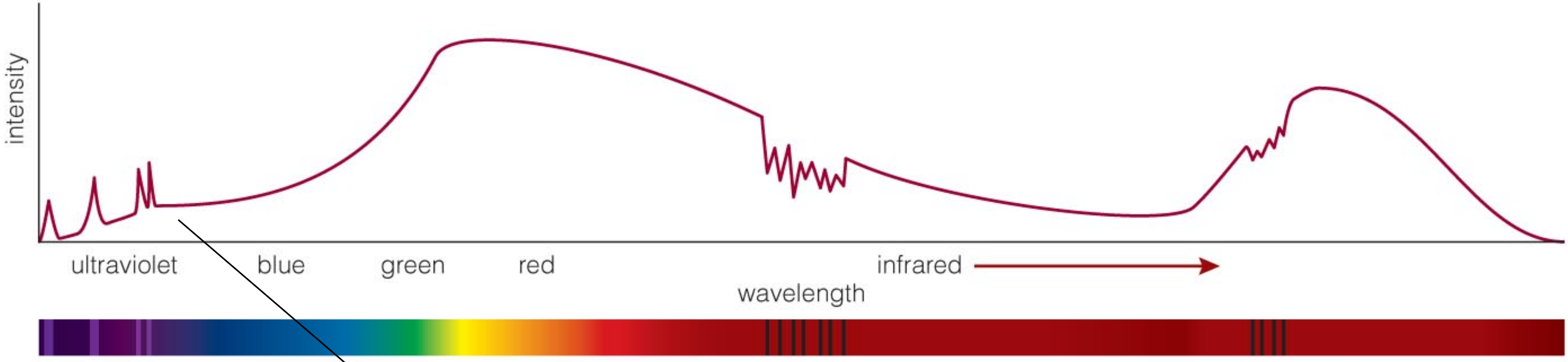
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K.

Interpreting an Actual Spectrum



Carbon dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere.

Interpreting an Actual Spectrum



Ultraviolet emission lines:
Indicate a hot upper
atmosphere

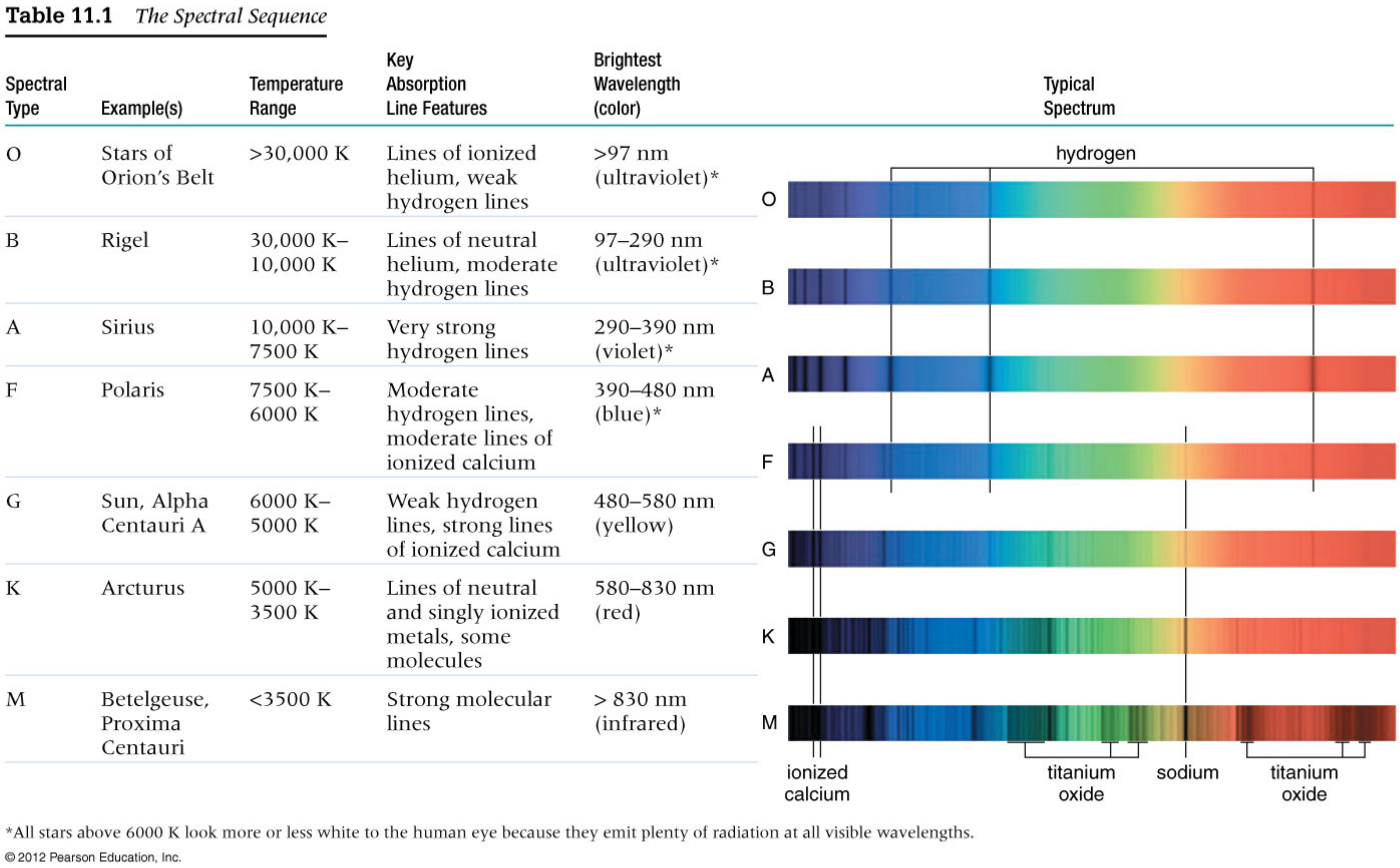


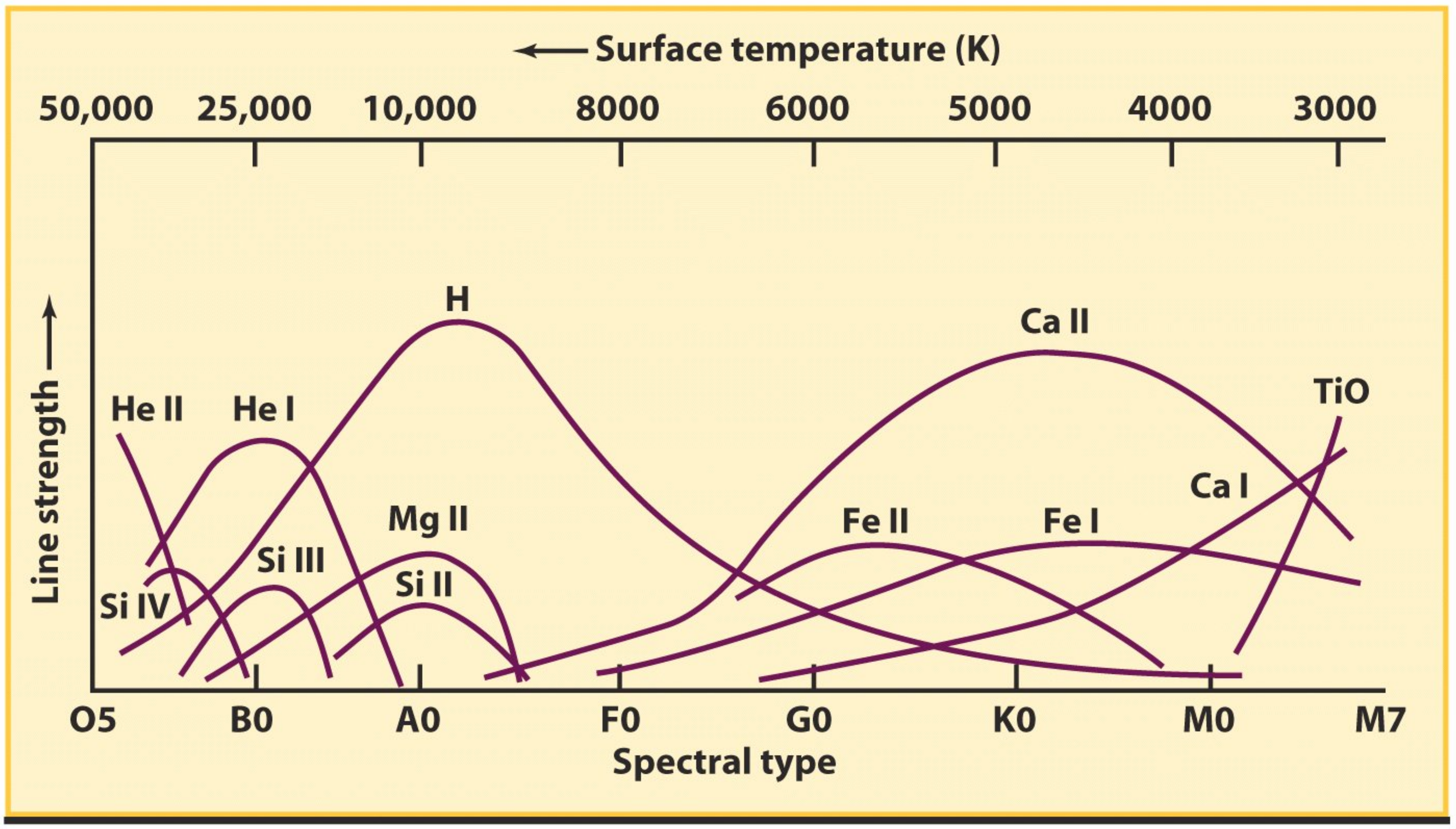
Table 11.1 *The Spectral Sequence*

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>30,000 K	Lines of ionized helium, weak hydrogen lines	>97 nm (ultraviolet)*
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*
A	Sirius	10,000 K–7500 K	Very strong hydrogen lines	290–390 nm (violet)*
F	Polaris	7500 K–6000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*
G	Sun, Alpha Centauri A	6000 K–5000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)
K	Arcturus	5000 K–3500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)
M	Betelgeuse, Proxima Centauri	<3500 K	Strong molecular lines	> 830 nm (infrared)

*All stars above 6000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

Lines in a star's spectrum correspond to a ***spectral type*** that reveals its temperature:

(Hottest) O B A F G K M (Coolest)



- The spectral class of a star is directly related to its surface temperature
  - O stars are the hottest
  - M stars are the coolest

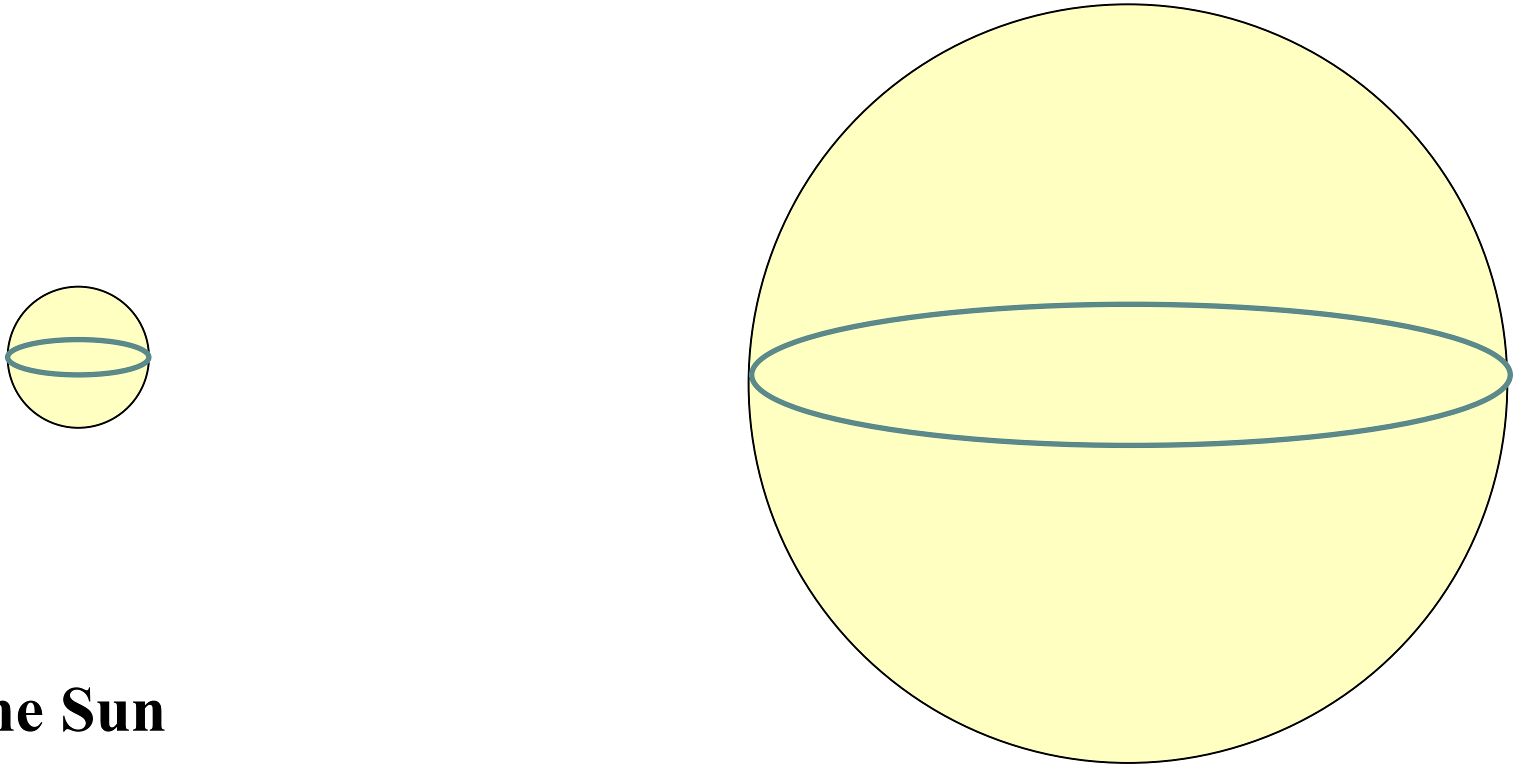
A star's full classification includes spectral type (line identities) and luminosity class (line shapes, related to the size of the star):

I — supergiant
II — bright giant
III — giant
IV — subgiant
V — main sequence

Examples: Sun — G2 V
Sirius — A1 V
Proxima Centauri — M5.5 V
Betelgeuse — M2 I

Luminosity Class Implies Size

- Consider the Sun and Capella



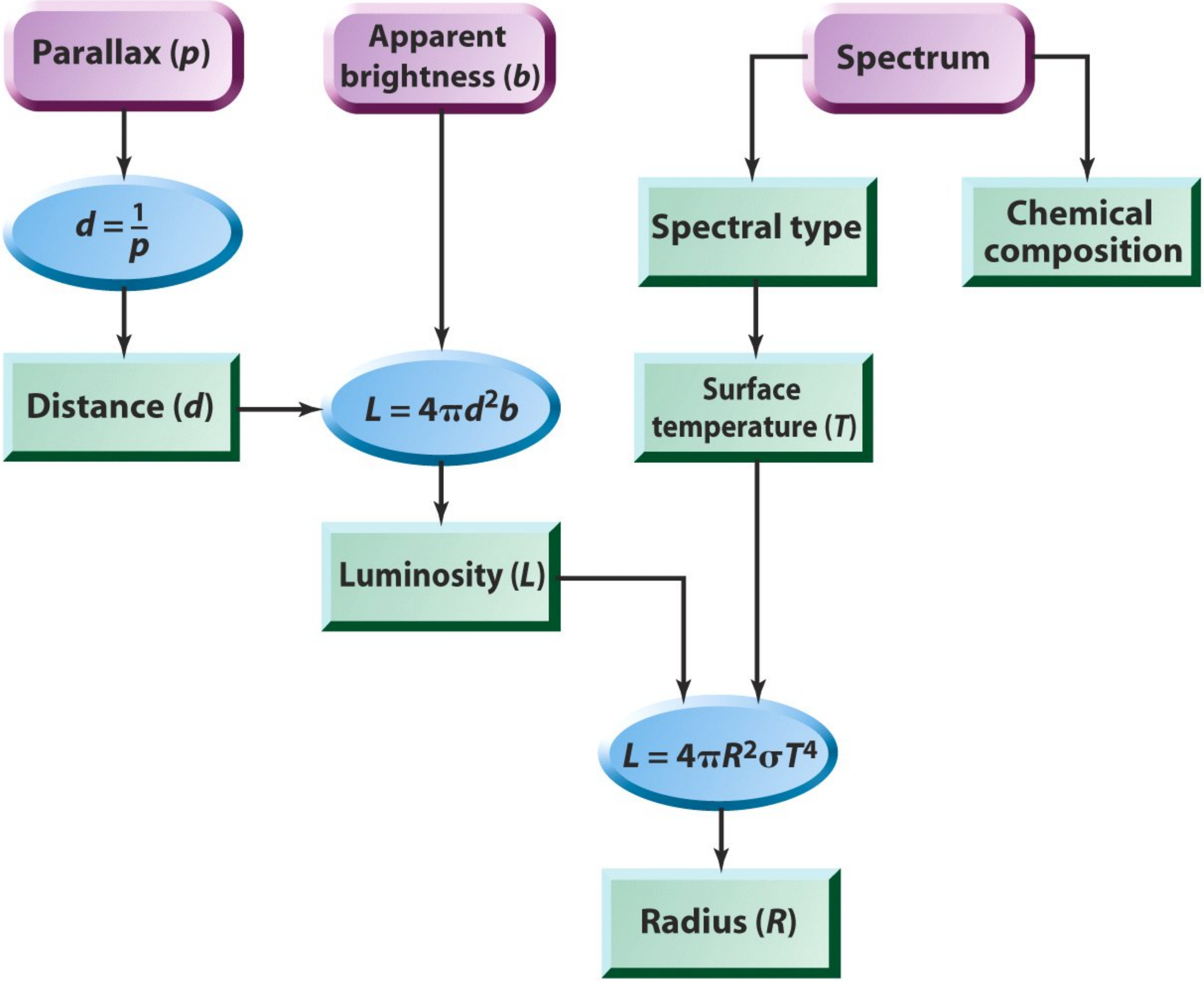
The Sun
G2V M=5

Capella
G2III M=0

Luminosity Class Implies Size

- Equal sized pieces of each star are equally bright
- Capella is 100X brighter (5 magnitudes)
- Capella must have 100X as much area
- Surface area $\propto$ radius^2
- Capella must be 10X larger than Sun.

Flowchart of Key Stellar Parameters



Parallax (p)

$d = \frac{1}{p}$

Distance (d)

Apparent brightness (b)

$L = 4\pi d^2 b$

Luminosity (L)

Spectrum

Spectral type

Chemical composition

Surface temperature (T)

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

Radius (R)

Stellar Mass

- Fuel burning rate
- Lifetime $10^{10}\,\mathrm{yr}\,(M/M_{\mathrm{Sun}})^{-2.8}$
- Luminosity $L \propto M^{3.8}$
- Impossible to measure for isolated stars

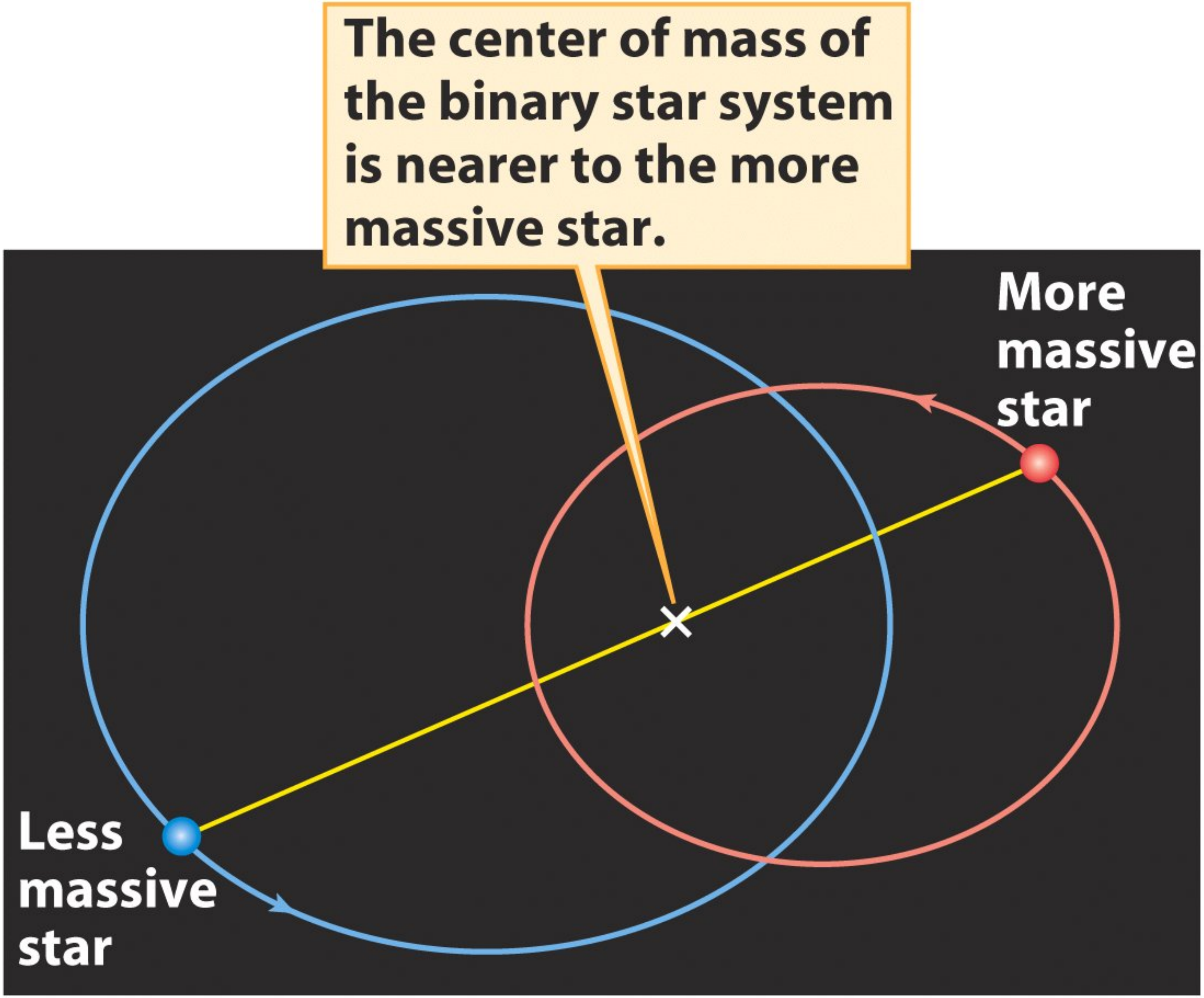
How do we measure stellar masses?

Binary Star Orbits

Two stars held in orbit around each other by their mutual gravitational attraction.

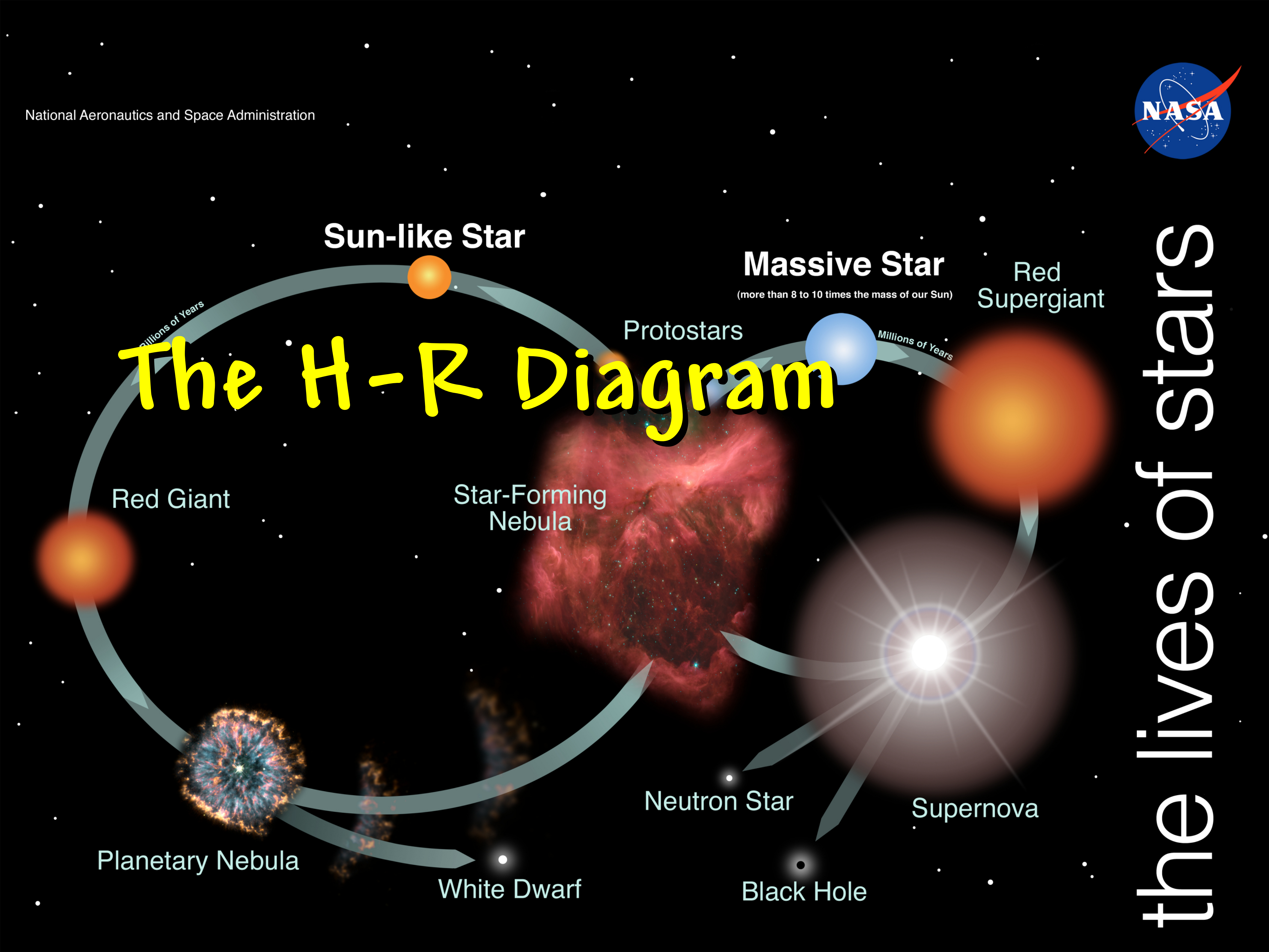
Each of the two stars in a binary system moves in an elliptical orbit about the center of mass of the system.

Orbit of a binary star system depends on the component masses.


The center of mass of the binary star system is nearer to the more massive star.

A binary star system

The H-R Diagram



The Hertzsprung-Russell Diagram

- Distances
- Radial velocity
- Proper motion & tangential velocity
- Flux – distance – luminosity
- Apparent magnitudes
- Absolute magnitudes
- Spectral types
- Ionization vs temperature
- Diameters of stars
- Masses of stars
- Spectroscopic binaries
- Mass-luminosity relationship

The Hertzsprung-Russell diagram can visualize all of these things

Hertzsprung-Russell Diagram