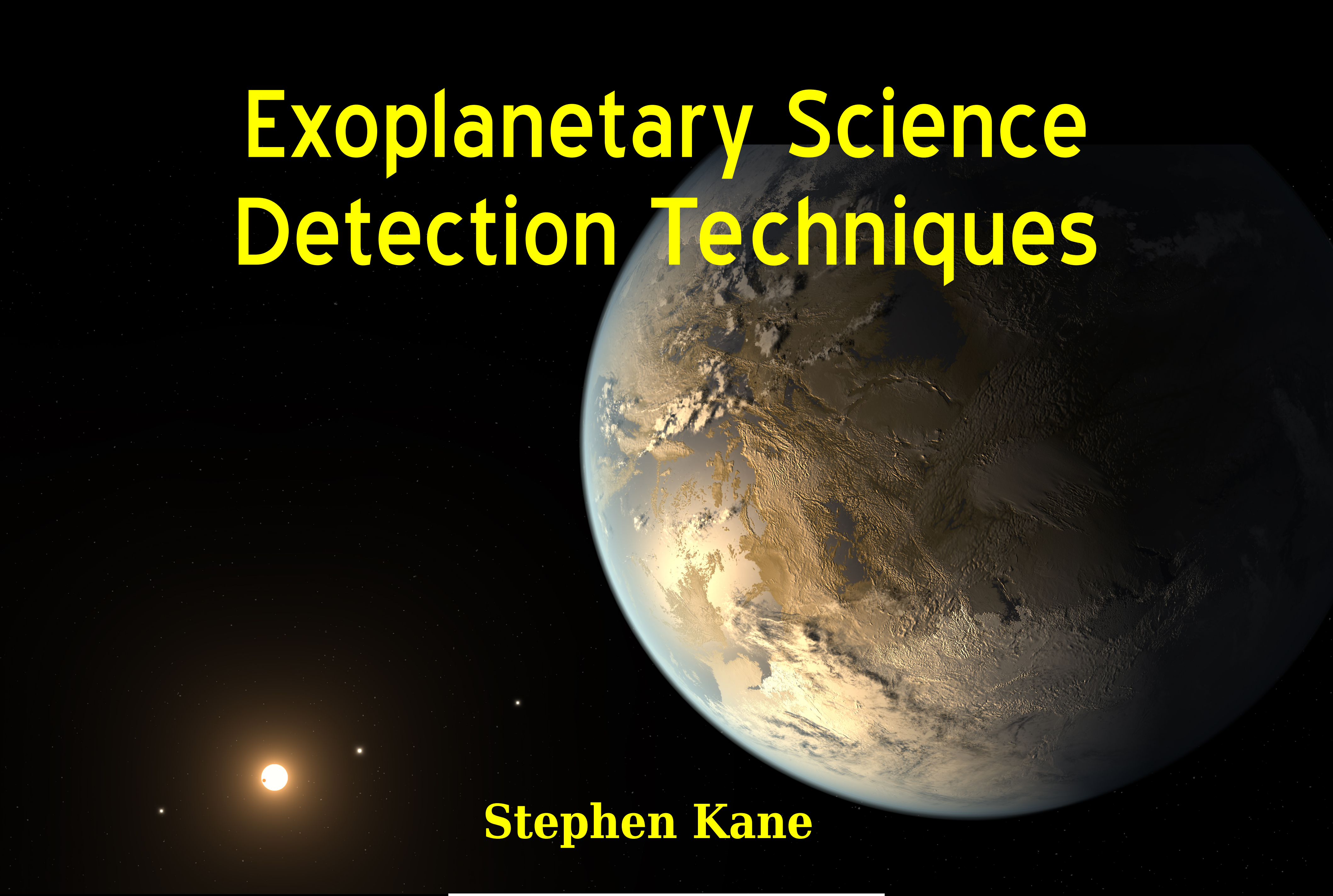
Exoplanetary Science
Detection Techniques



Stephen Kane

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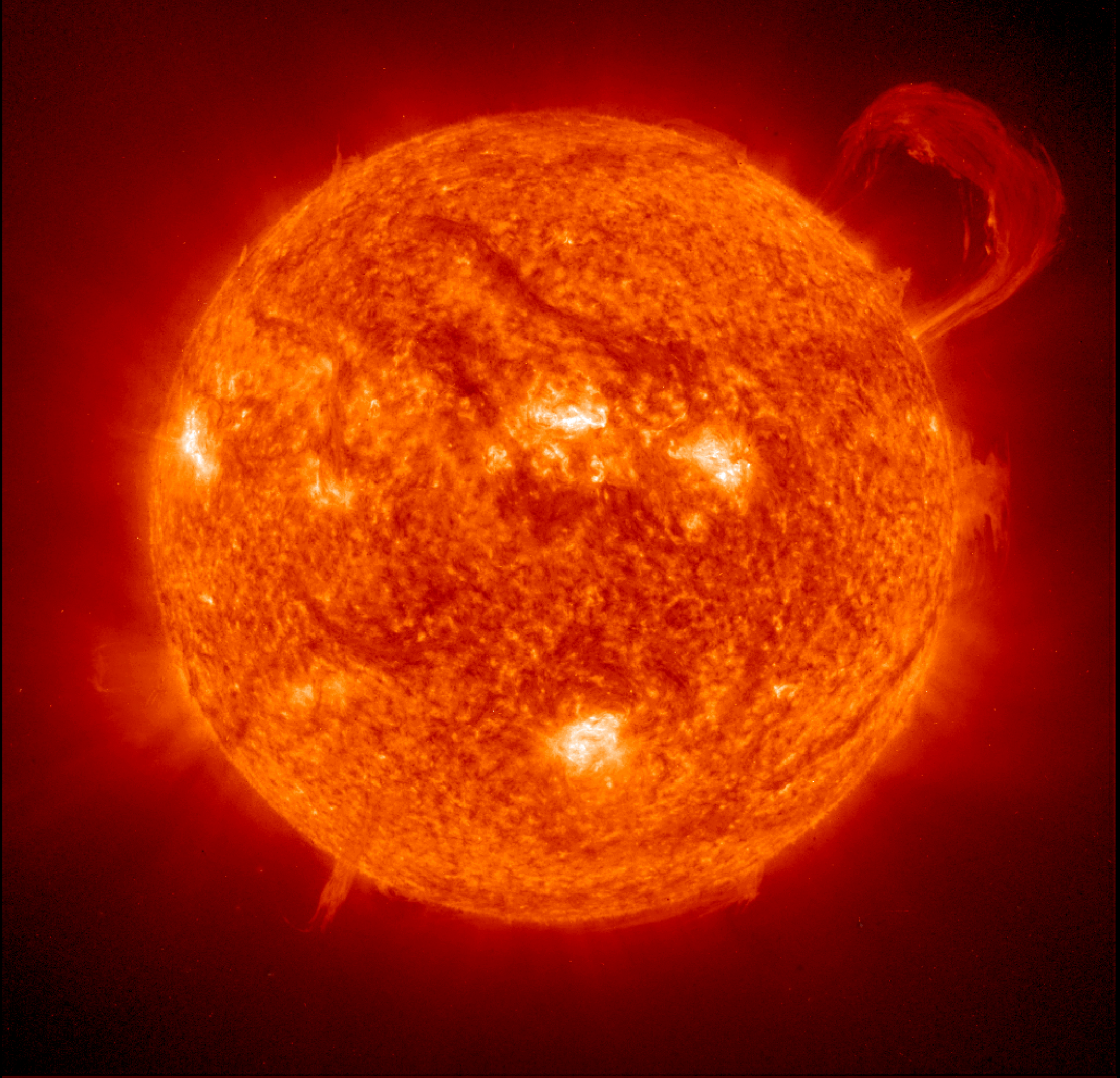
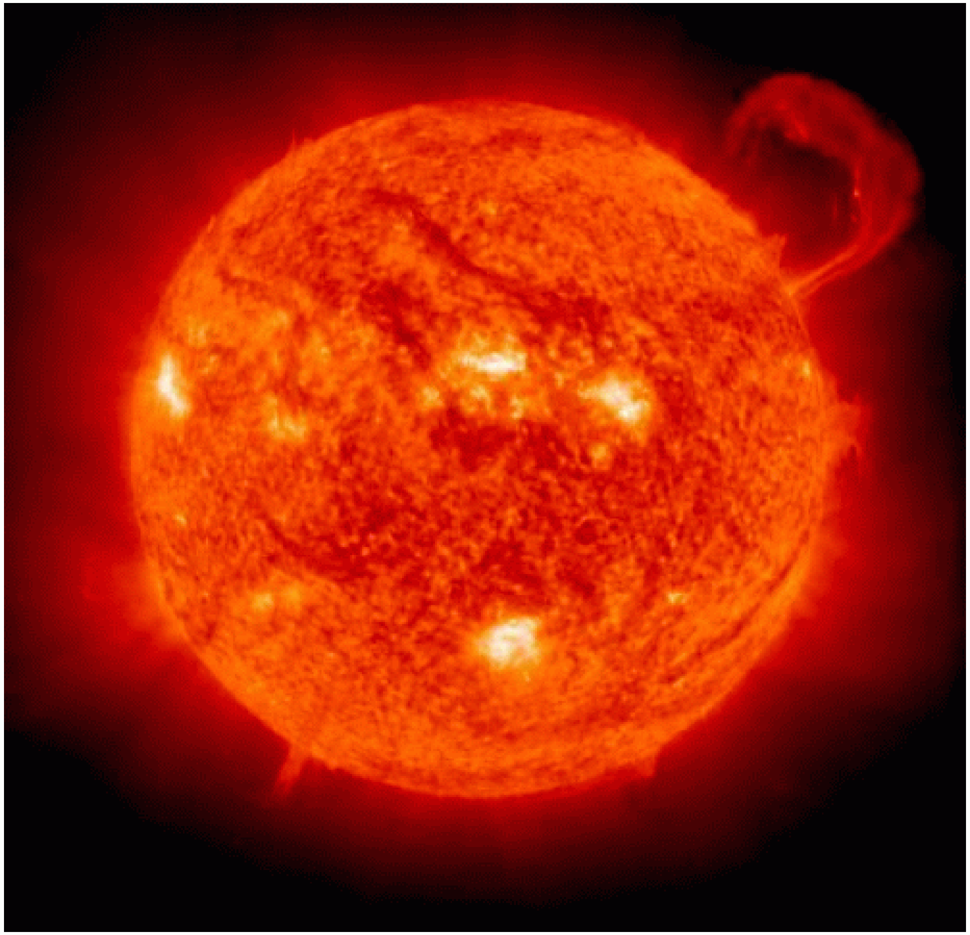


Star: self-gravitating mass of plasma that produces energy through fusion reactions and remains in thermal and hydrodynamic near-equilibrium for long periods of time.

Intrinsic Properties of Stars

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

Numbers you should know: The Sun



source: SOHO/EIT

Mass ≈ 2×10^{30} kg = 1 $M_\odot$

Radius ≈ 7×10^{8} m = 1 $R_\odot$

Distance = 1.5×10^{11} m = 1 AU

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

Surface temperature = 5800 K

age ≈ 4.5 Gyr

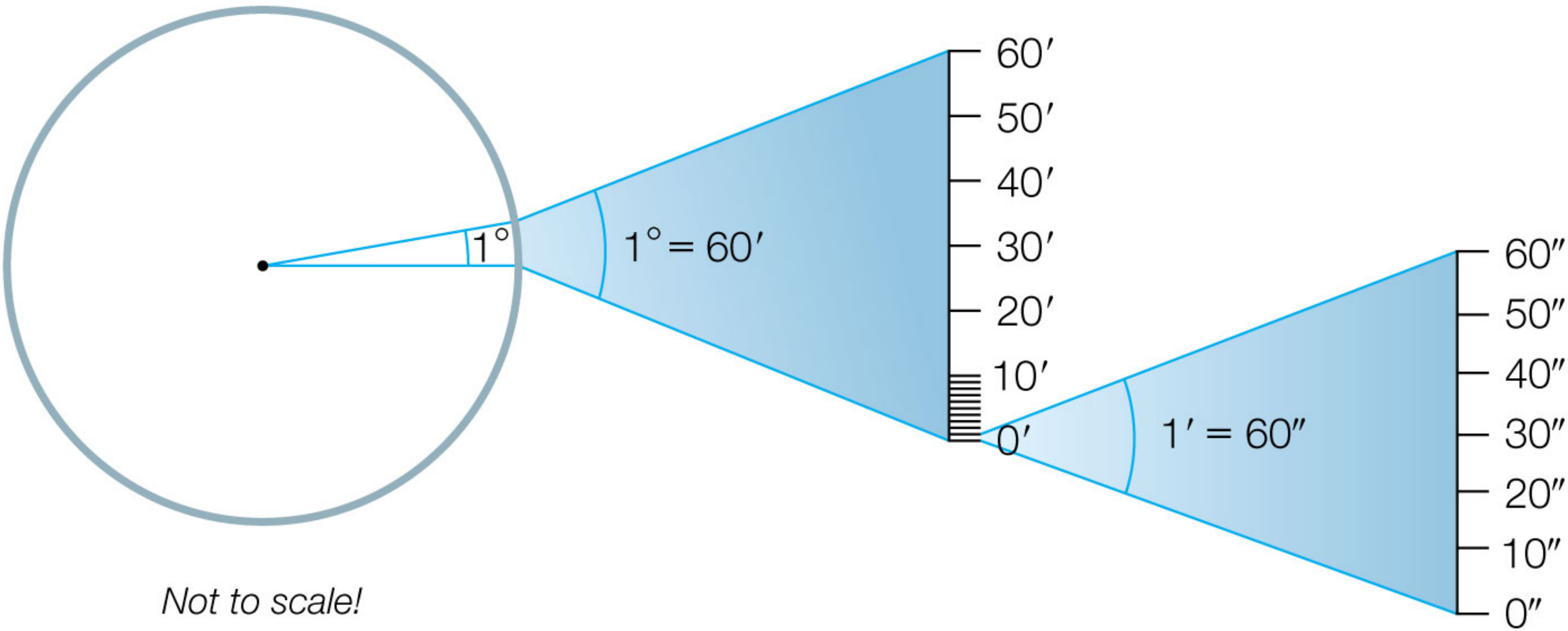
spectral type = G2 V

All other stars are scaled to these parameters for convenience.

Stellar Parallax

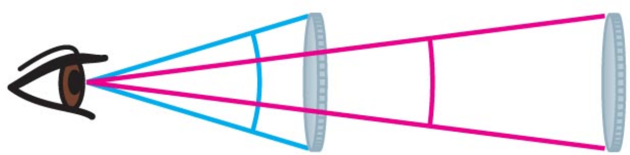
Angular Measurements

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

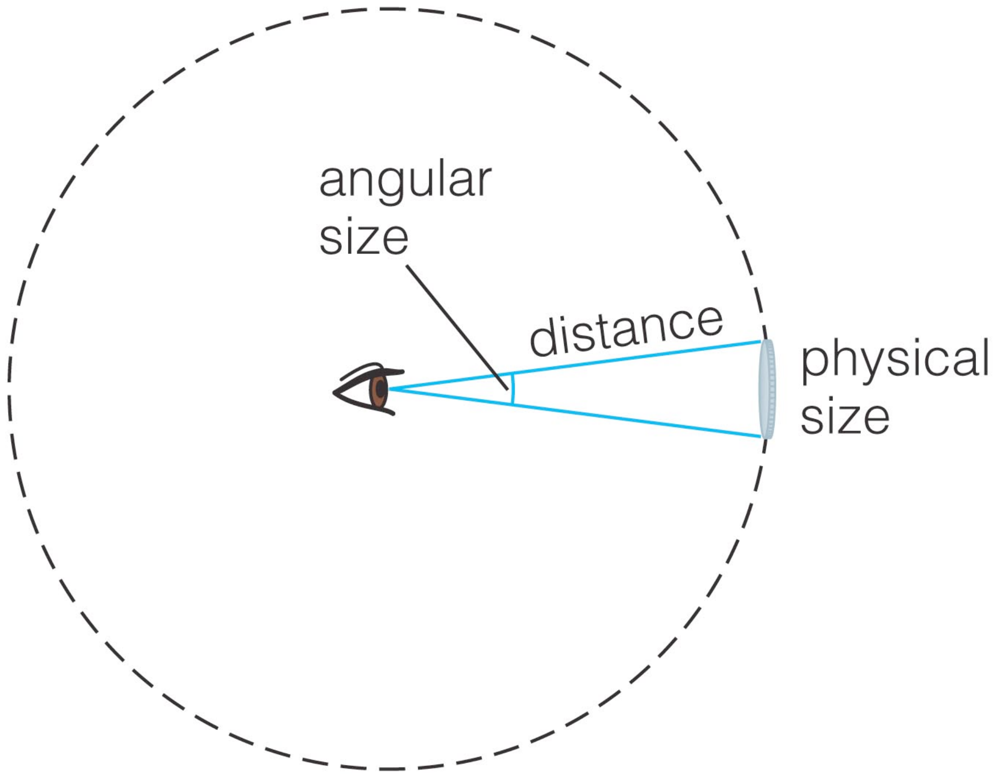


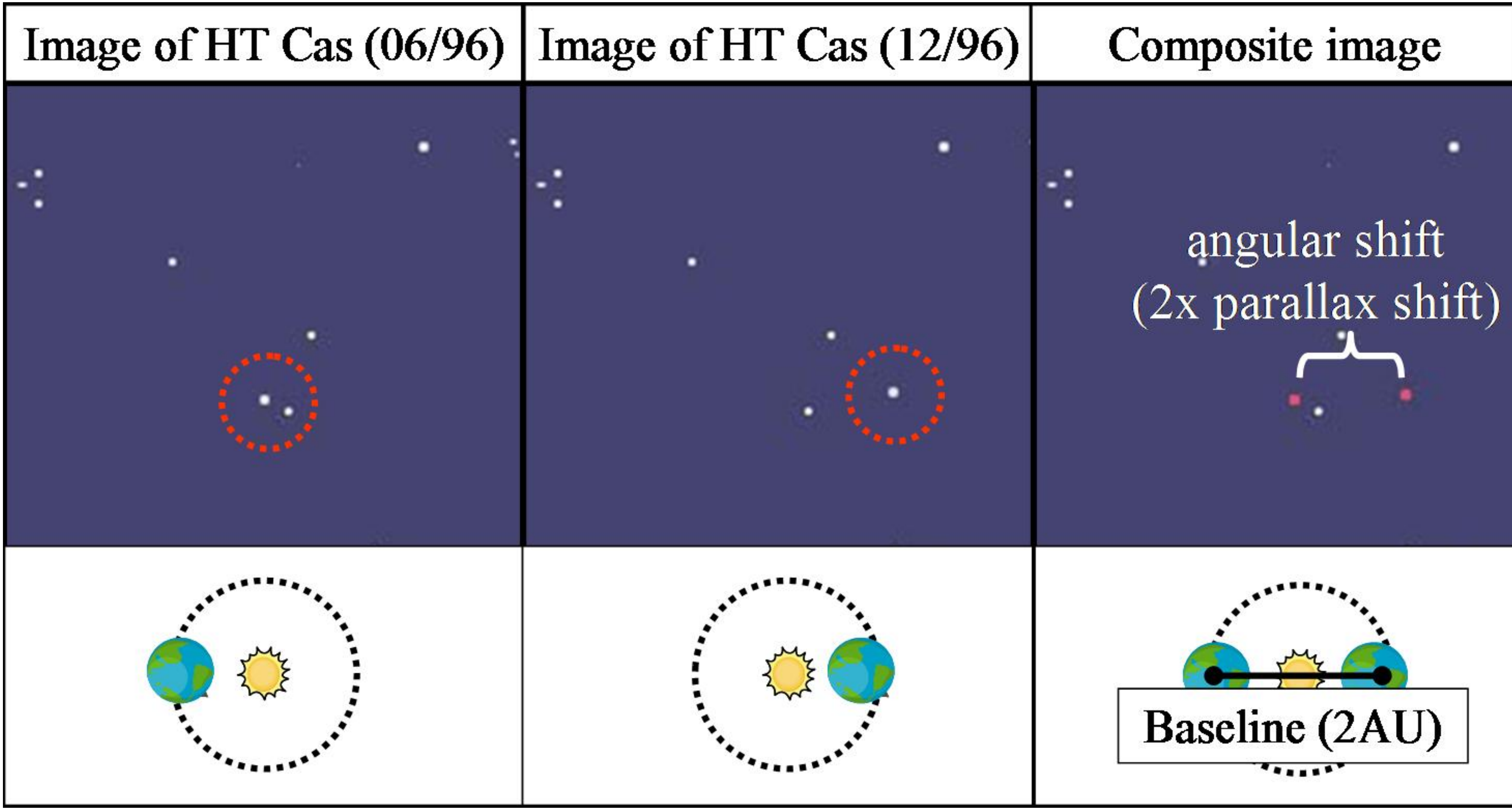
Angular Size

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



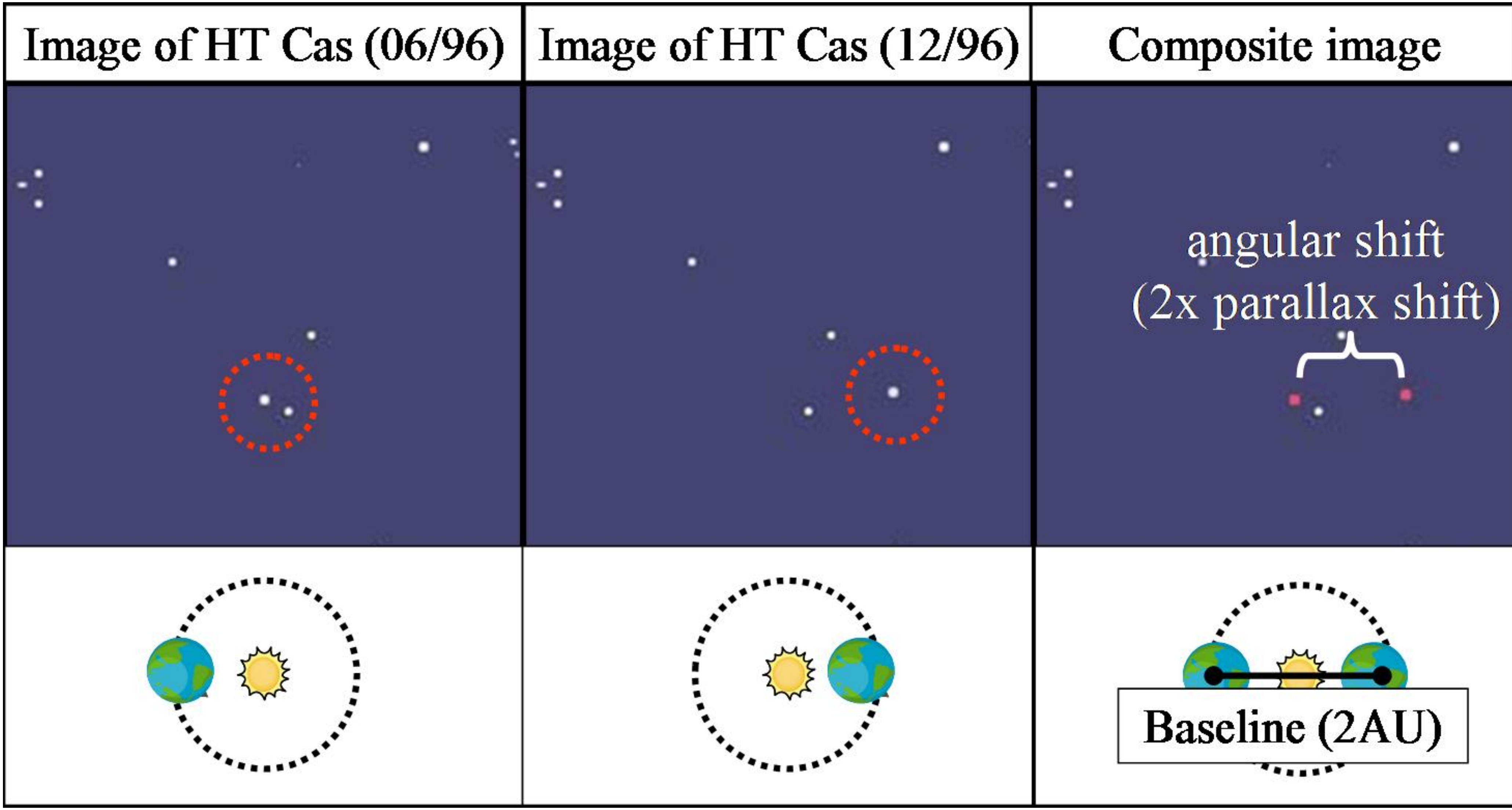
An object's angular size appears smaller if it is farther away.



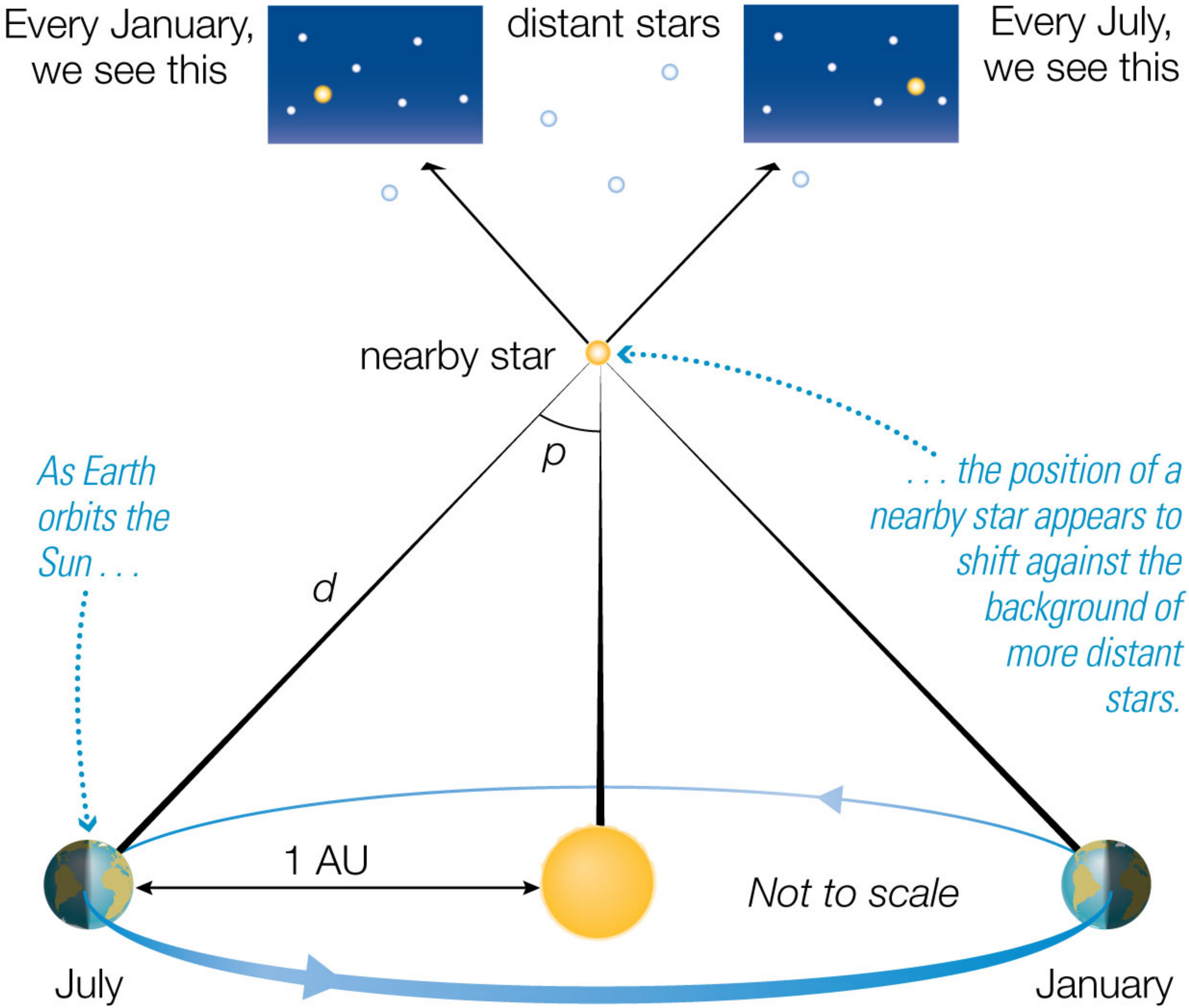


Parallax

is the apparent shift in position of a nearby object against a background of more distant objects.



Apparent positions of the nearest stars shift by about an arcsecond as Earth orbits the Sun.
Angle depends on distance.


Every January, we see this
distant stars
Every July, we see this
nearby star
p
d
As Earth orbits the Sun . . .
. . . the position of a nearby star appears to shift against the background of more distant stars.
1 AU
Not to scale
July
January

Parallax and Distance

p = parallax angle

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

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

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

Parallax isn't easy

- Parallax shifts are fractions of an arc second
  - ground based limits: P > 0.05 arcsec. (d < 20 pc)
  - space based limits: P > 0.002 arcsec. (d < 500 pc)

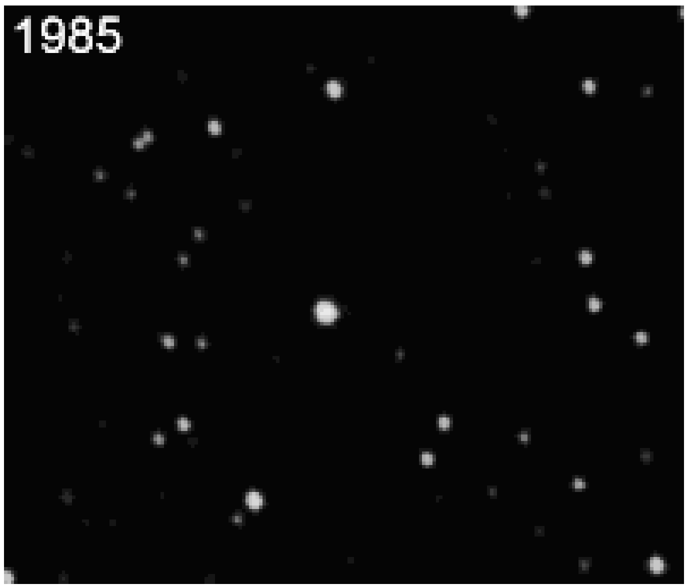
- Beyond about 500 pc must use indirect methods
- Find and calibrate "standard candles"

Definition: Objects of known luminosity (e.g. sun-like stars)

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

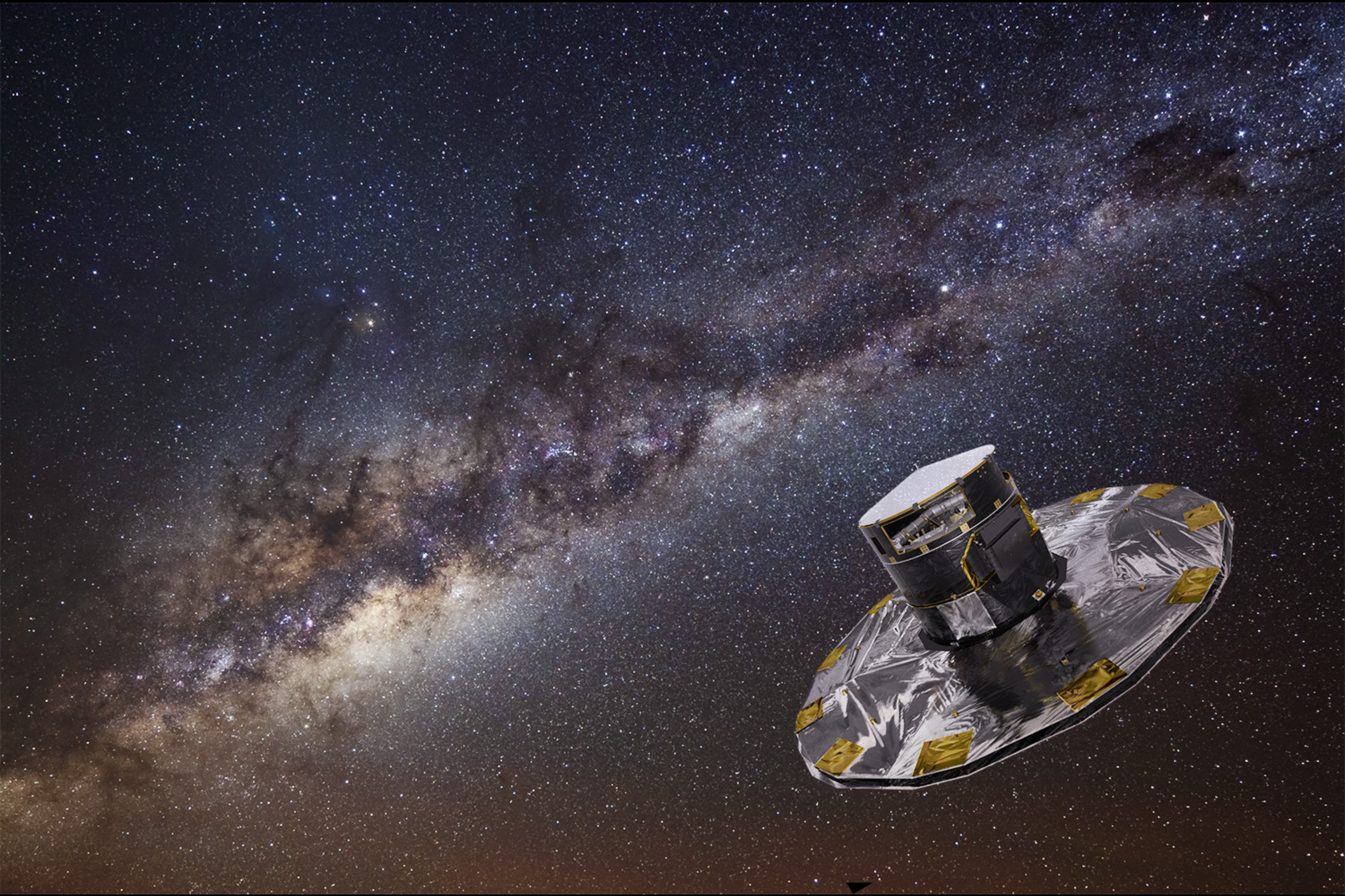
Angle = 1.5377 arc seconds
= 0.00042714 degrees
= 2 x P

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

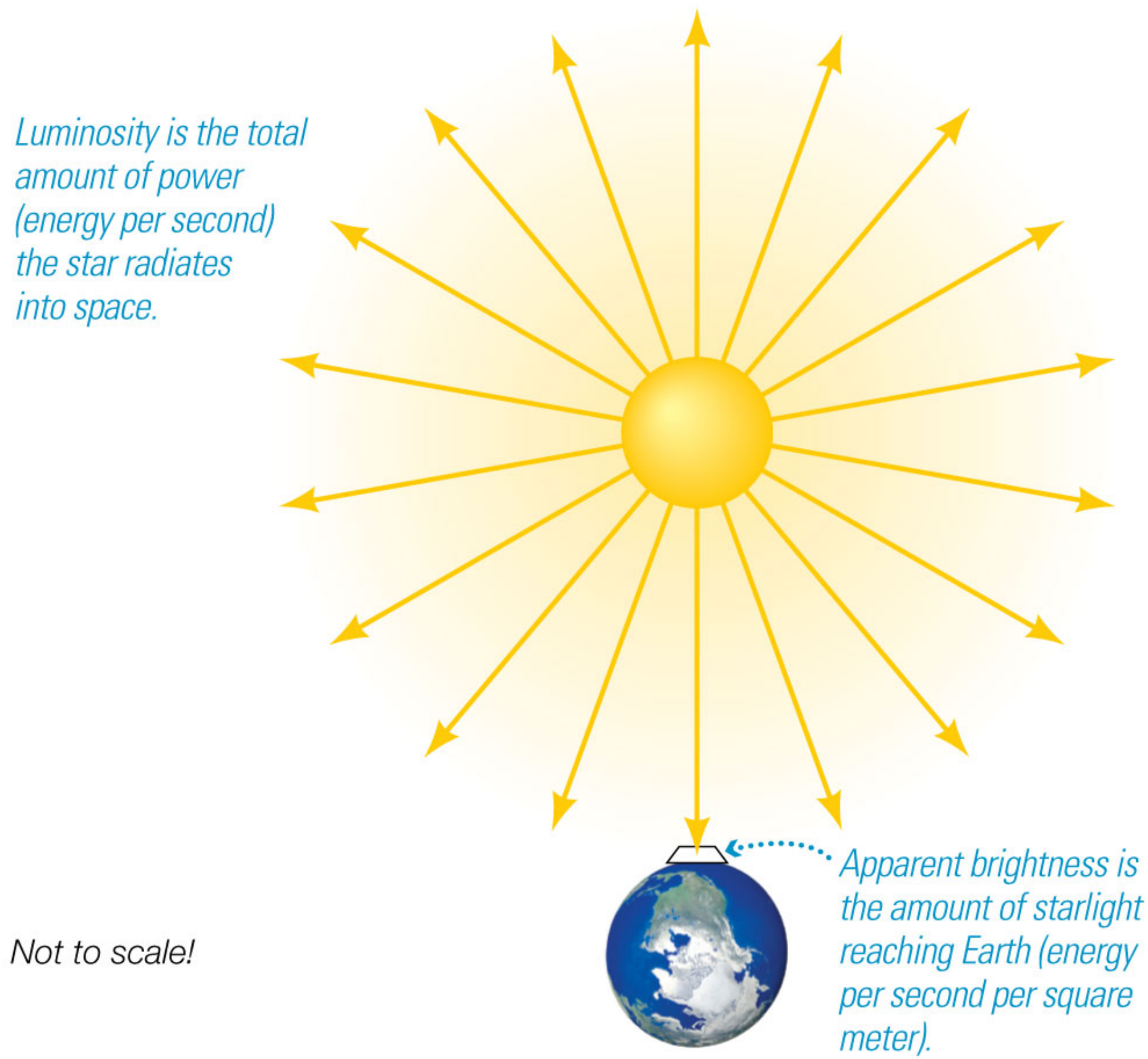
Distance to Proxima = 1 / P = 1/0.76885 = 1.301 parsecs

First parallax numbers (1837)

Star	Parallax (arcsec)	Distance (pc)	Spectral type	Apparent magnitude
α Cen A	0.750	1.3	G2 (Sun-like star)	-0.01
Vega	0.123	8.1	A0	0.04
61 Cyg	0.292	3.4	K5	5.22



The Magnitude Scale



Luminosity:

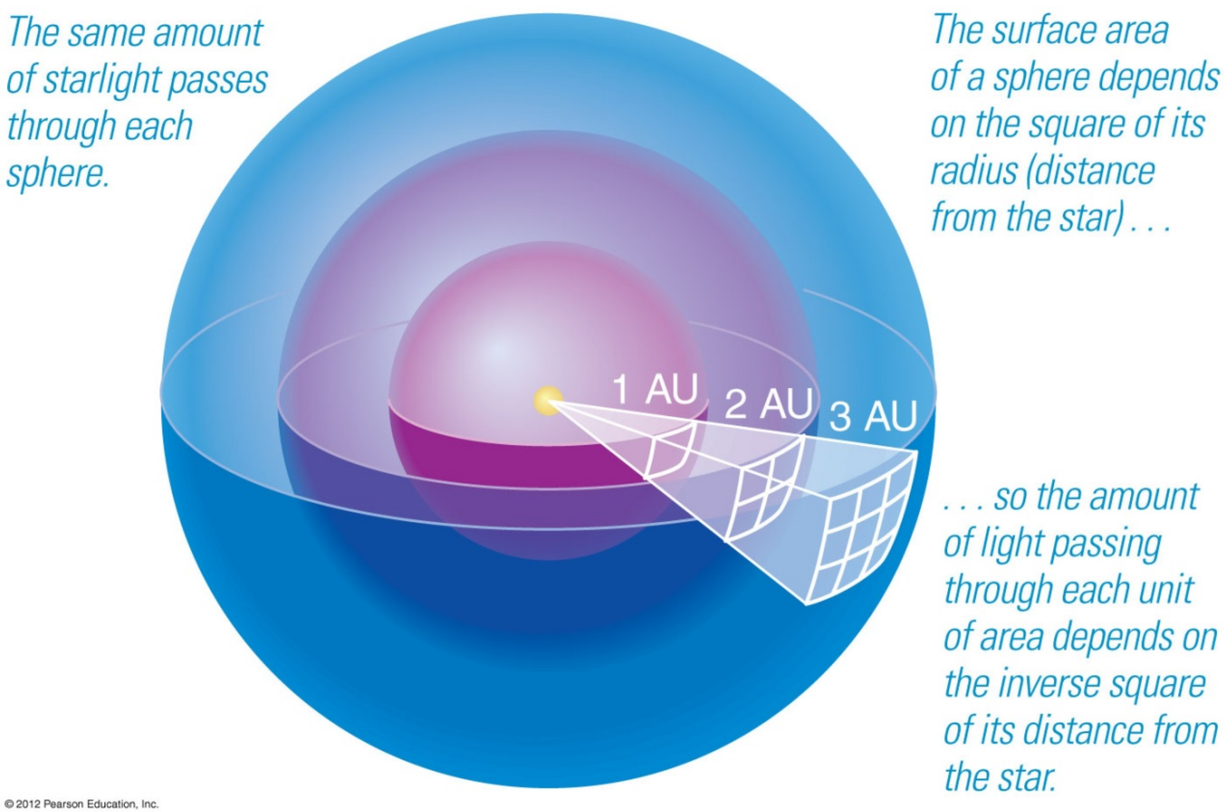
Amount of power a star radiates

(Joules per second = watts)

Apparent brightness:

Amount of starlight that reaches Earth

(energy per second per unit area)



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

Luminosity passing through each sphere is the same.

Area of sphere:
4π (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

Compare some stars:

Absolute	Apparent
$M_{Sun} = 4.8$	$m_{Sun} = -26$
$M_{Sirius} = 1.4$	$m_{Sirius} = -1.46$
$M_{Betelgeuse} = -5.6$	$m_{Betelgeuse} = 0.50$

Which star looks brightest from Earth?

Which star is brightest?

Apparent Magnitude

Consider two stars, 1 and 2, with apparent magnitudes m_1 and m_2 and fluxes F_1 and F_2. The relation between apparent magnitude and flux is:

$$\frac{F_1}{F_2} = 10^{(m_2 - m_1)/2.5}$$

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{F_1}{F_2}\right)$$

For $m_2 - m_1 = 5$, $F_1/F_2 = 100$.

Absolute Magnitude and Distance Modulus

m – M is a measure of the distance to a star and is called the **distance modulus**.

$$\boxed{m - M = 5\log_{10}(d) - 5 = 5\log_{10}\left(\frac{d}{10\ \mathrm{pc}}\right).}$$

The absolute magnitude of the Sun is $M = 4.83$.
The luminosity of the Sun is $L = 3.846\times10^{26}$ W

$$\boxed{M = M_{\mathrm{Sun}} - 2.5\log_{10}\left(\frac{L}{L_\odot}\right),}$$

Note the M includes only light in the visible band, so this is accurate only for stars with the same spectrum as the Sun.

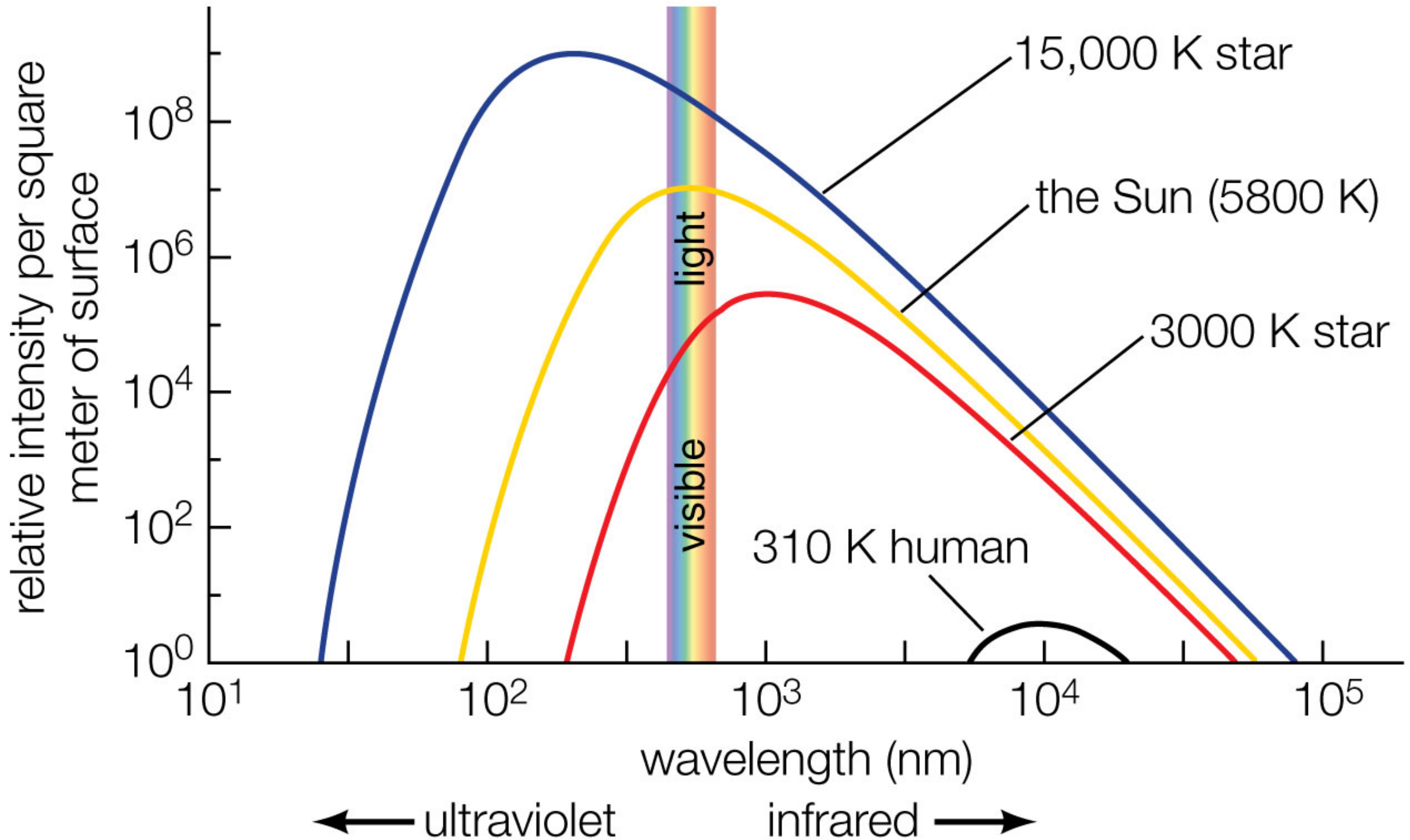
Blackbody Radiation

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).



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

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

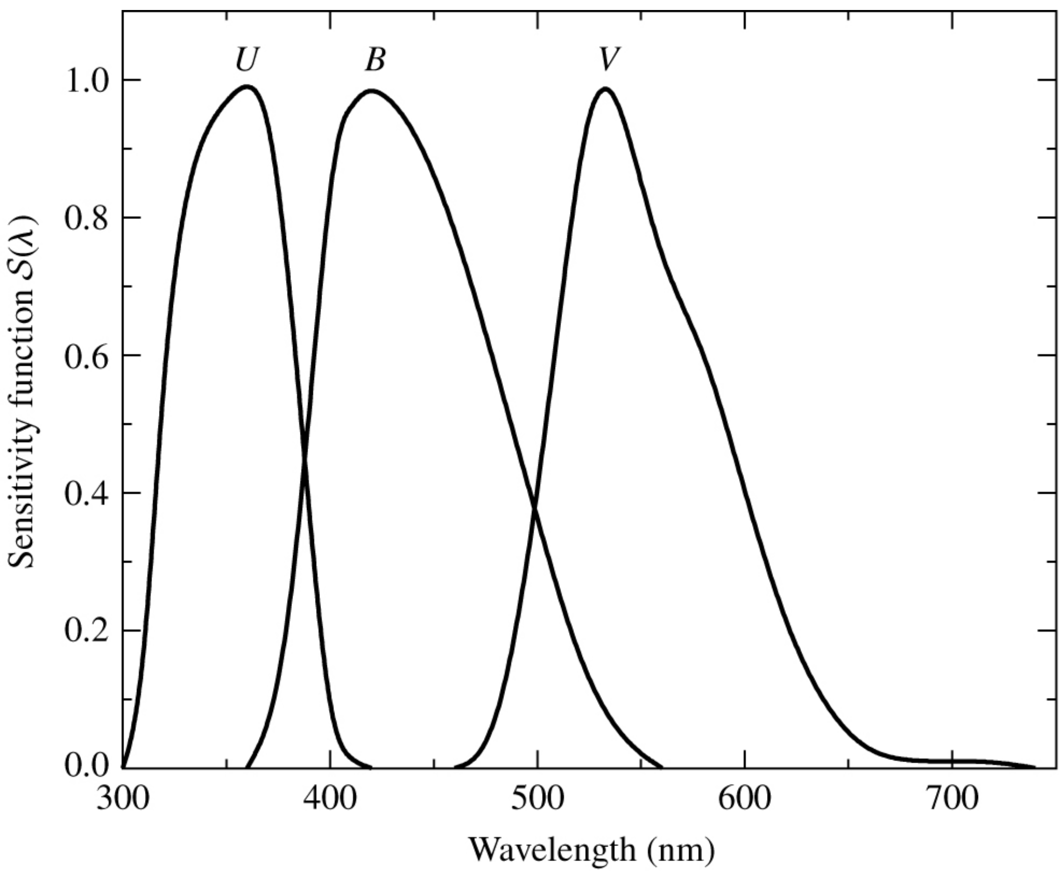
UBV Wavelength Filters

Bolometric Magnitude: measured over all wavelengths.

UBV wavelength filters: The color of a star may be precisely determined by using filters that transmit light only through certain narrow wavelength bands:

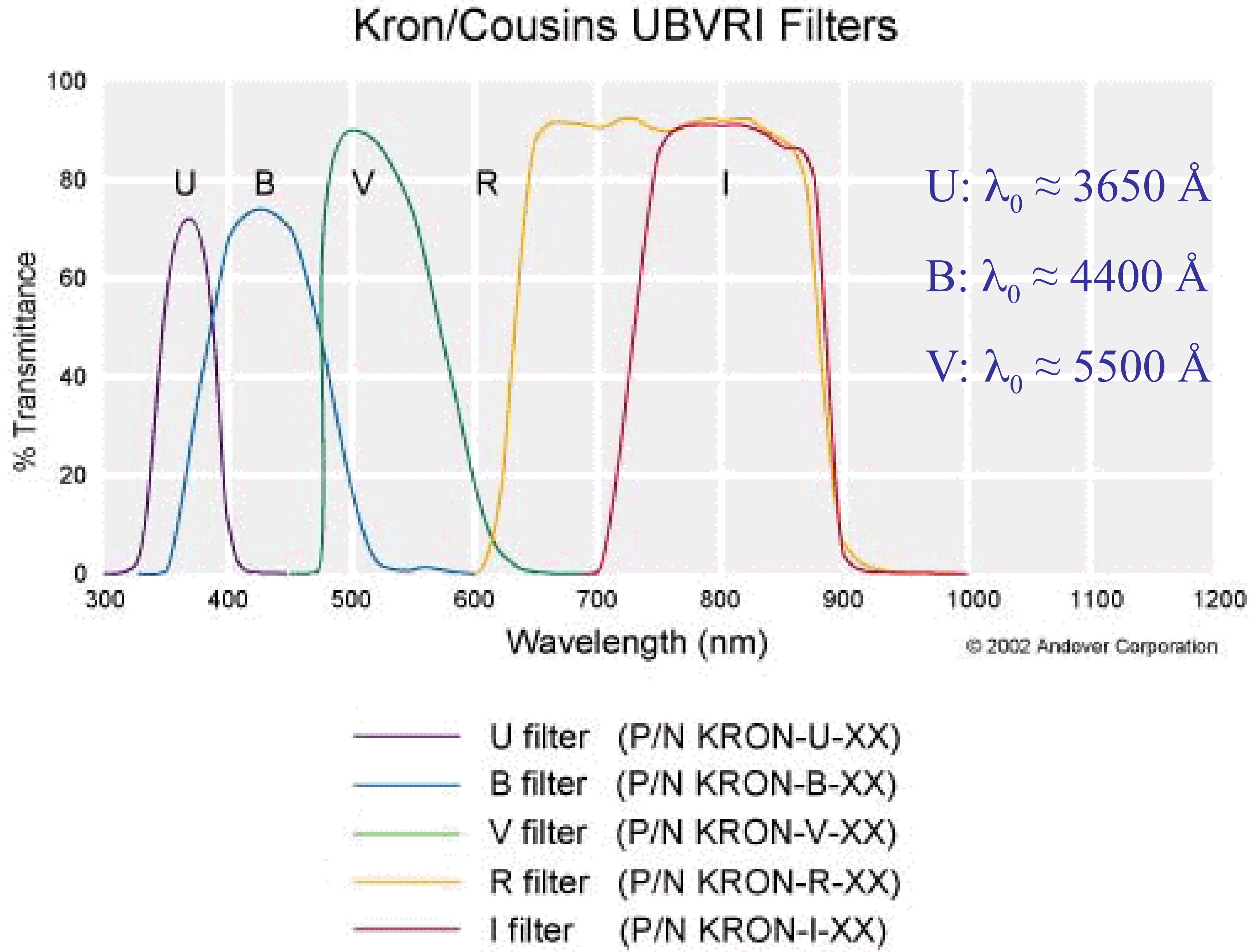
- **U**, the star's ultraviolet magnitude. Measured through filter centered at 365nm and effective bandwidth of 68nm.
- **B**,the star's blue magnitude. Measured through filter centered at 440nm and effective bandwidth of 98nm.
- **V**,the star's visual magnitude. Measured through filter centered at 550nm and effective bandwidth of 89nm

U,B,and V are apparent magnitudes



Sensitivity Function S(λ)

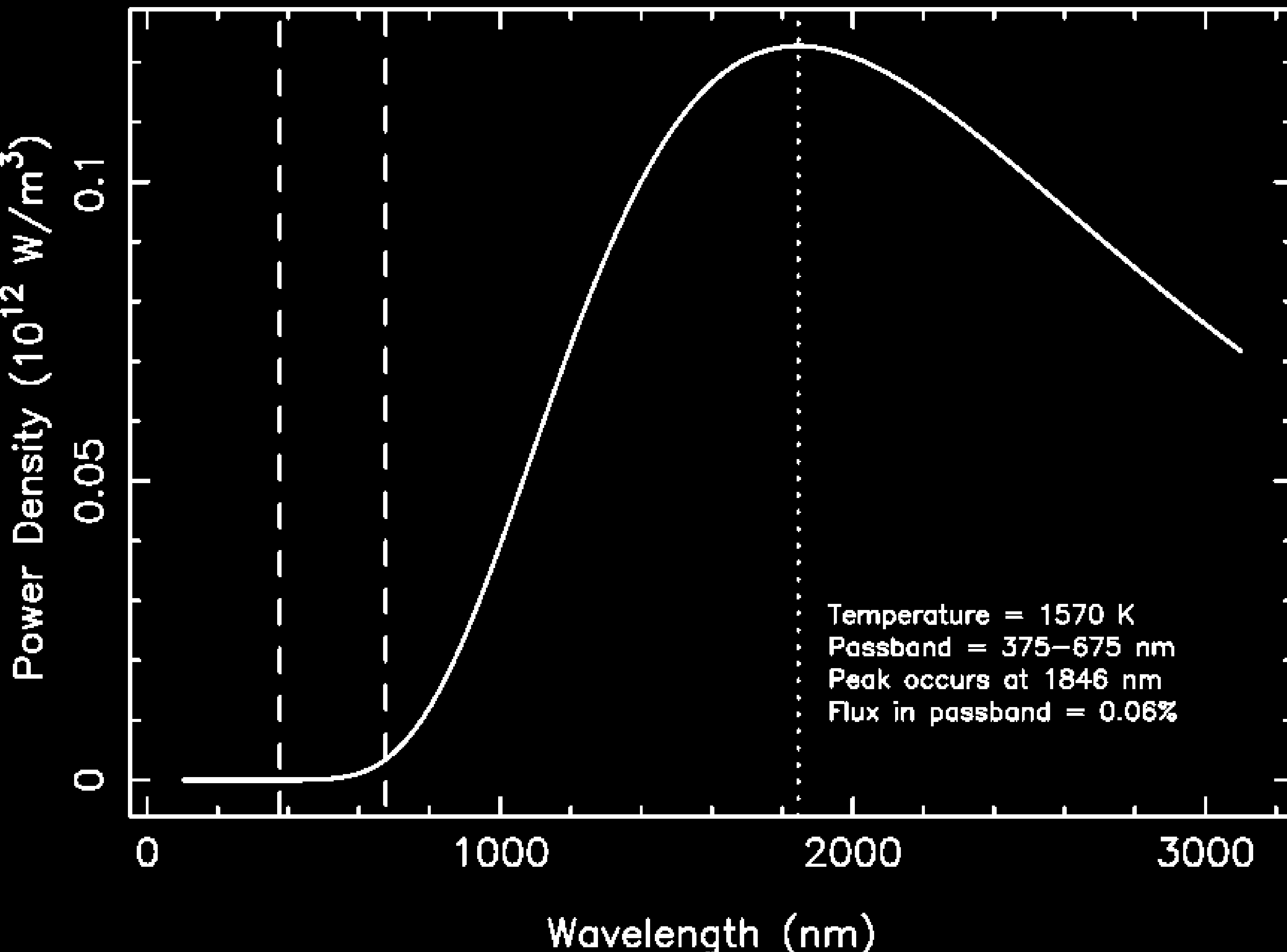
Optical Wavelength Bands



U: $\lambda_0 \approx 3650$ Å

B: $\lambda_0 \approx 4400$ Å

V: $\lambda_0 \approx 5500$ Å



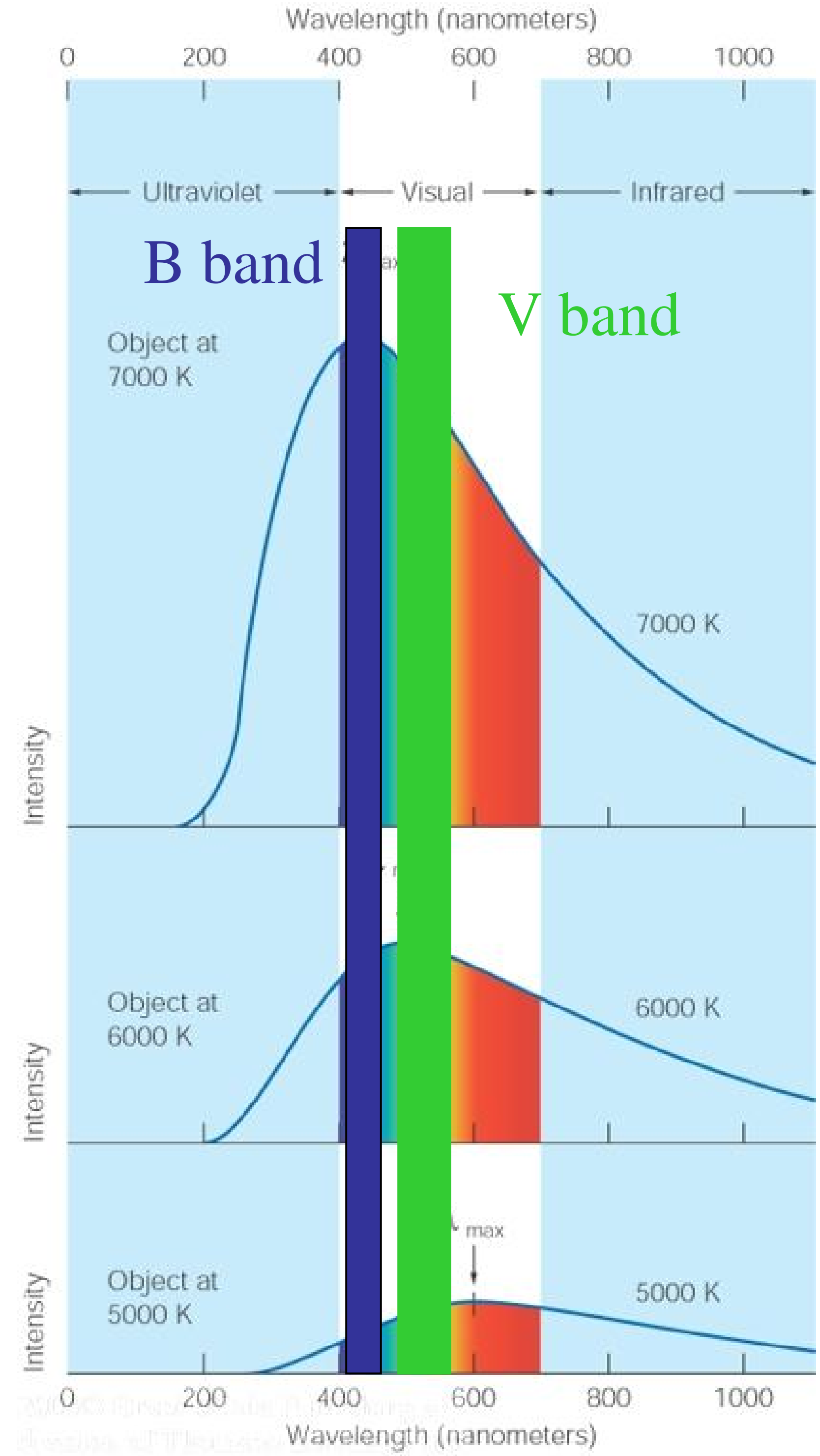
Power Density (10^{12} W/m^3)
0
0.05
0.1
0
1000
2000
3000
Wavelength (nm)
Temperature = 1570 K
Passband = 375–675 nm
Peak occurs at 1846 nm
Flux in passband = 0.06%

The Color Index

The color of a star is measured by comparing its brightness in different wavelength bands:

The blue (B) band and the visual (V) band.

We define B-band and V-band magnitudes just as we did before for total magnitudes.



The Color Index

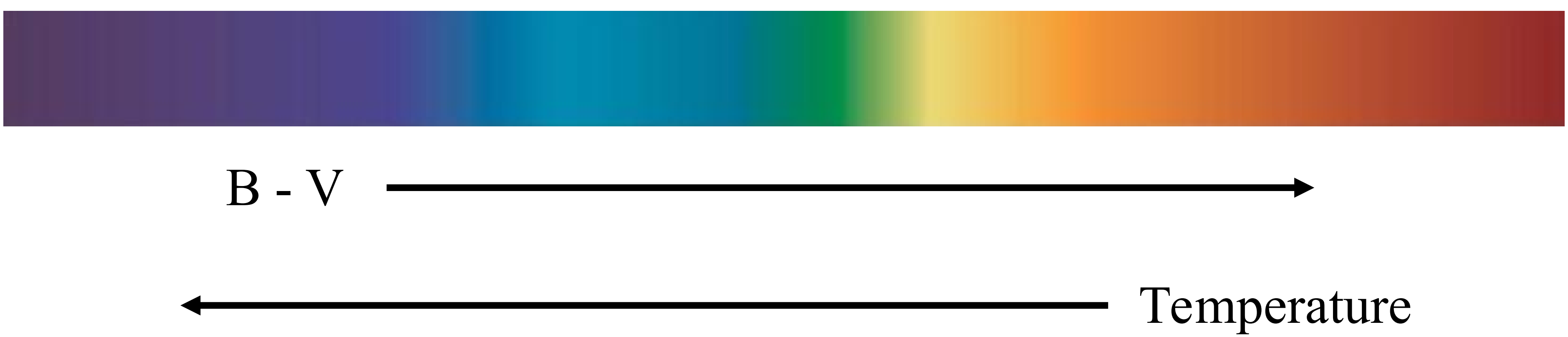
We define the Color Index

$$B - V$$

(i.e., B magnitude – V magnitude)

The bluer a star appears, the smaller the color index B – V.

The hotter a star is, the smaller its color index B – V.

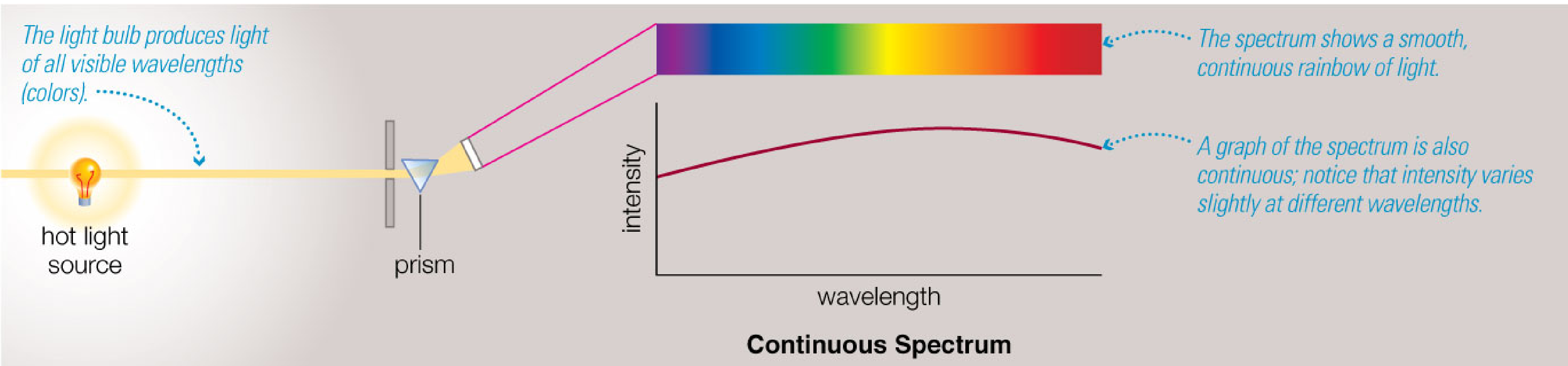


Stellar Spectra

How do light and matter interact?

- Emission
- Absorption
- Transmission
  - Transparent objects transmit light.
  - Opaque objects block (absorb) light.
- Reflection or scattering

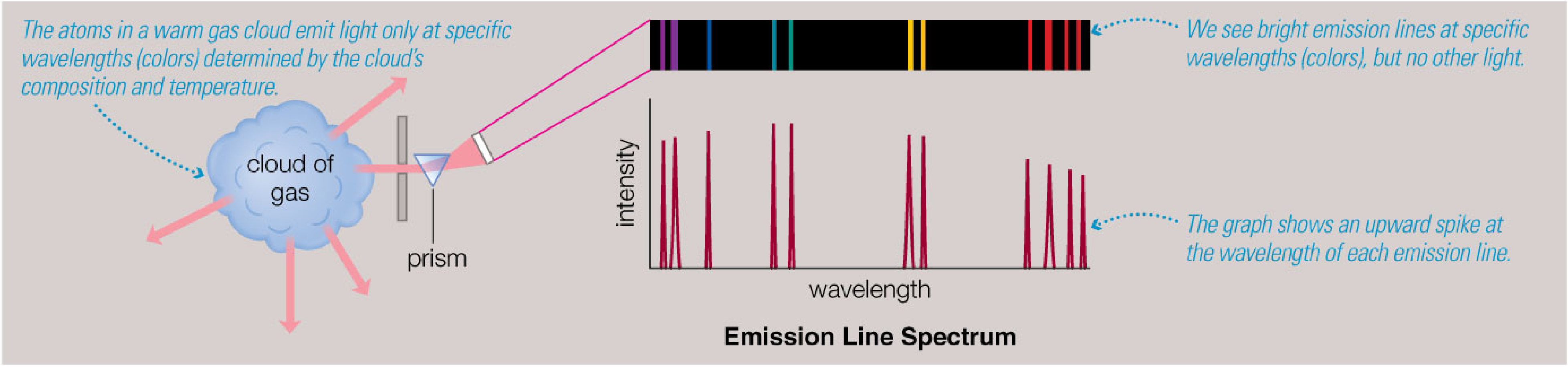
Continuous Spectrum



a

- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption.

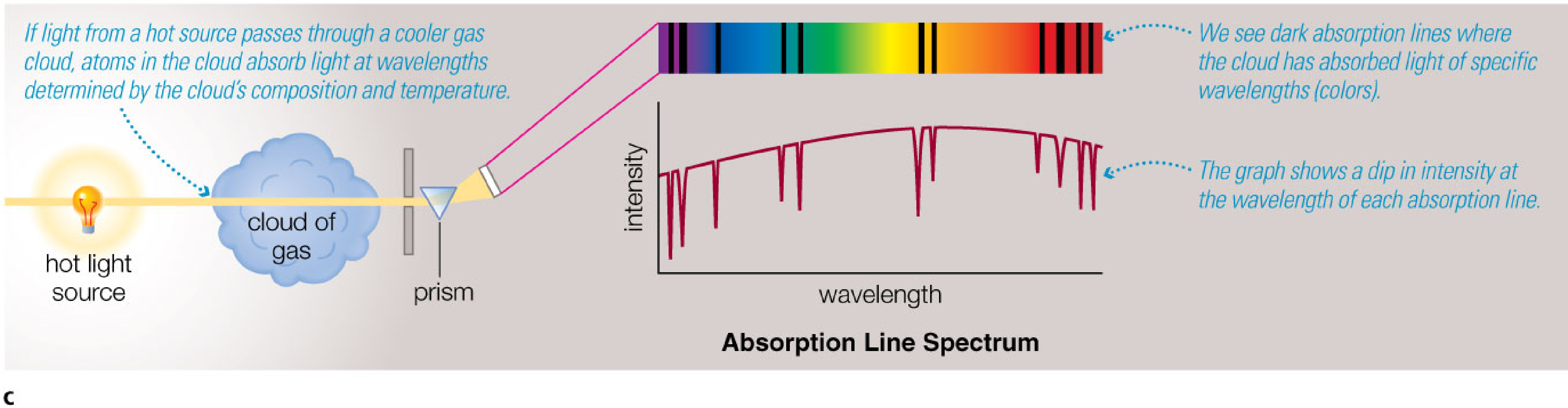
Emission Line Spectrum



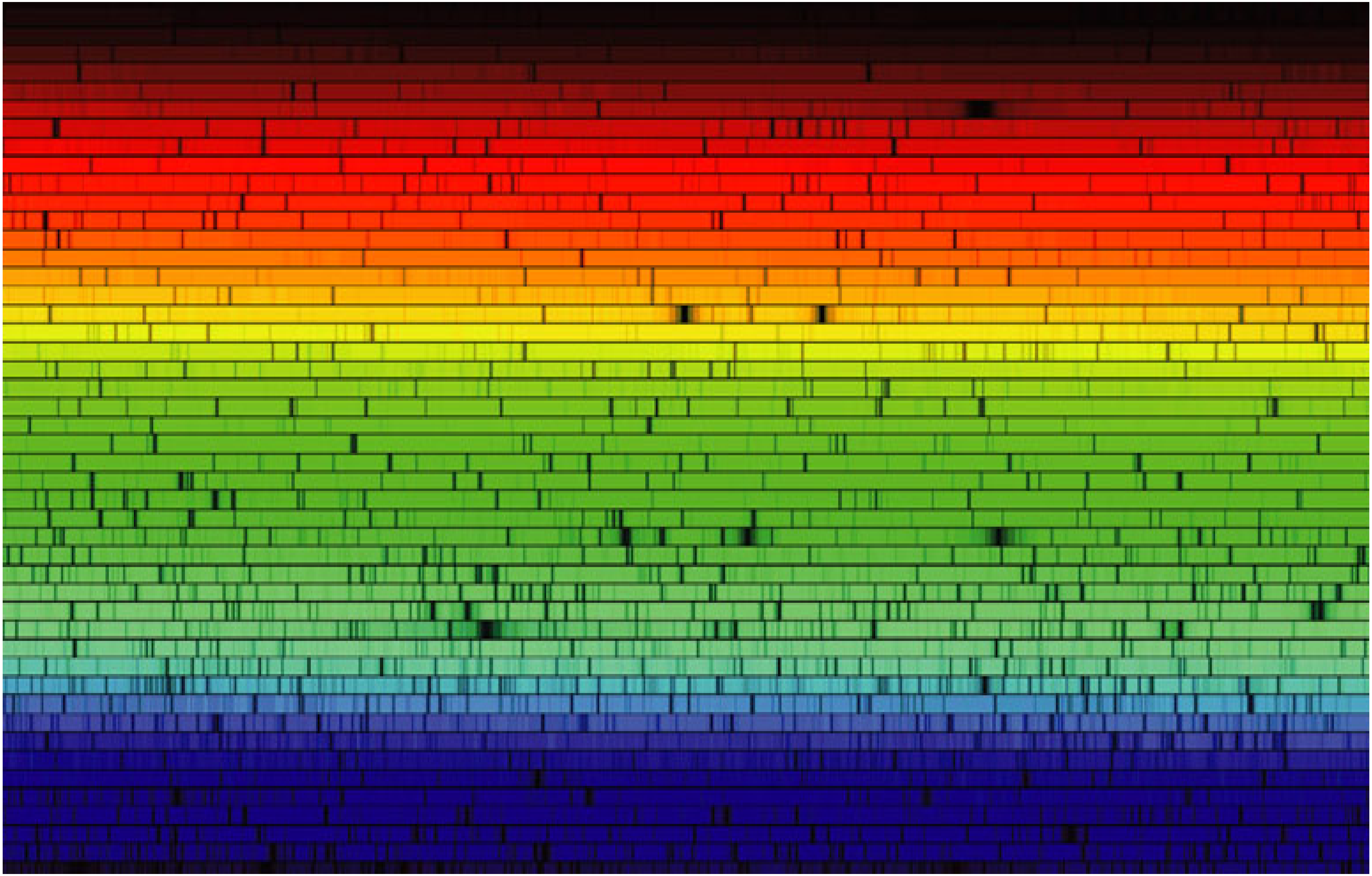
b

- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines.

Absorption Line Spectrum



- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.



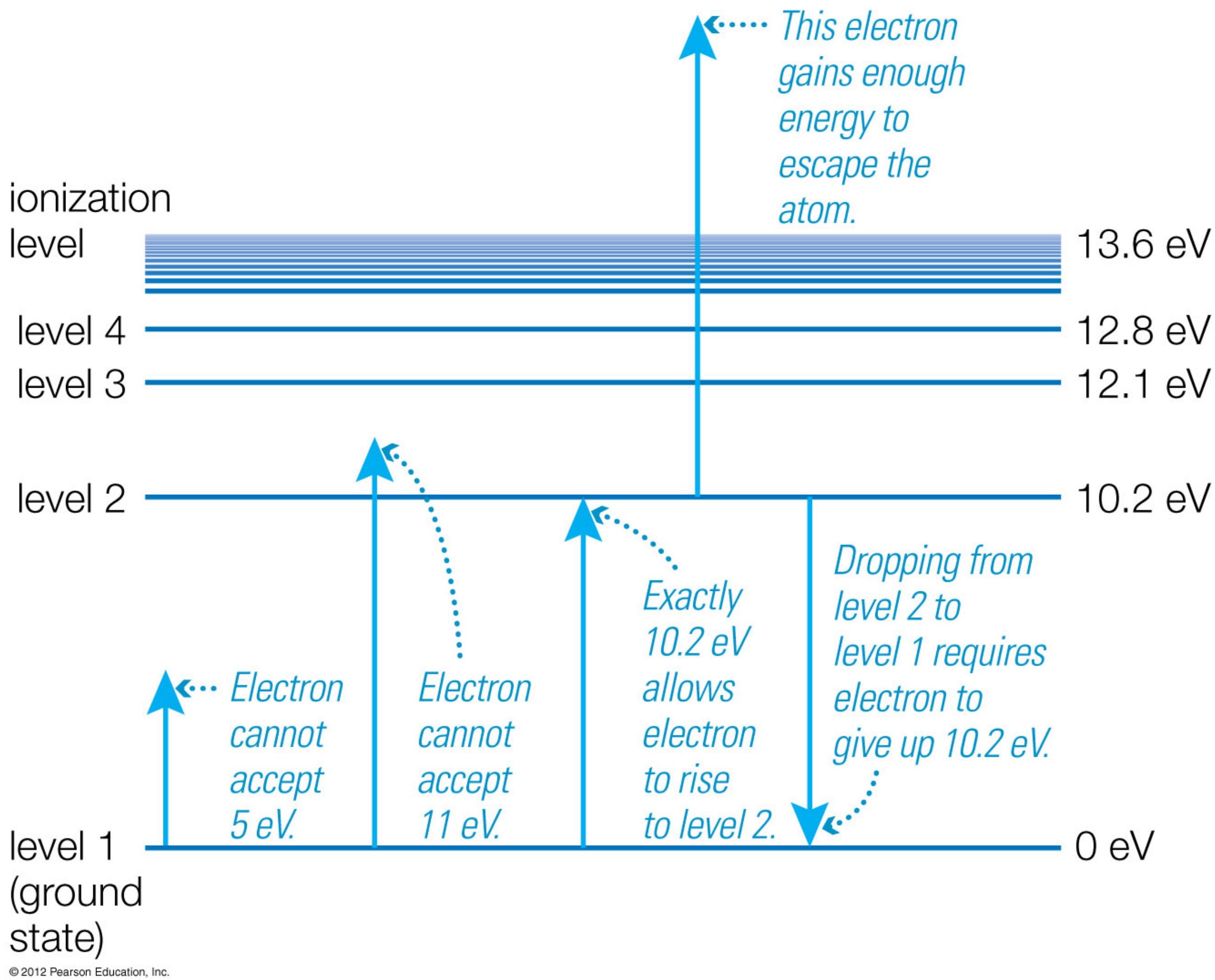
Absorption lines in the Sun’s spectrum
(Fraunhofer lines)

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.

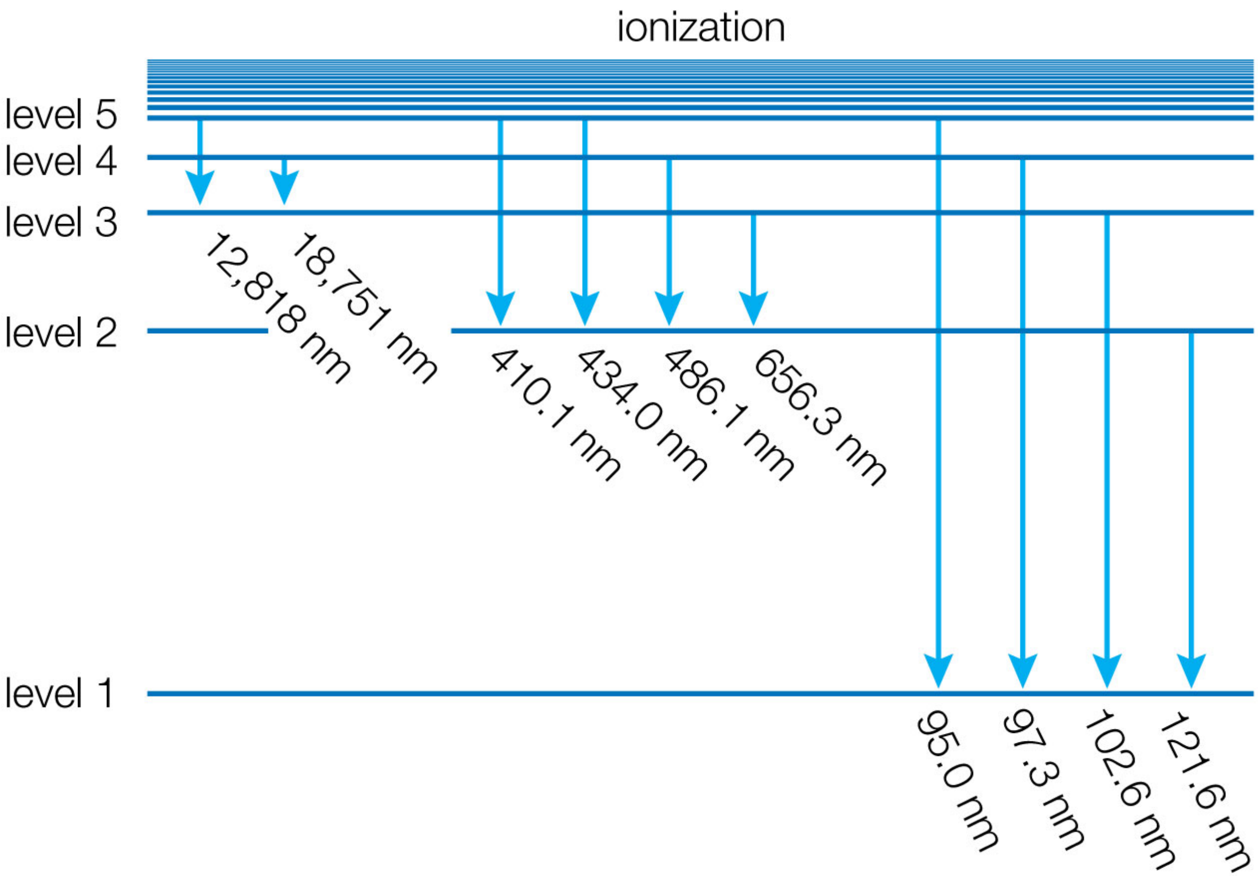
Chemical Fingerprints



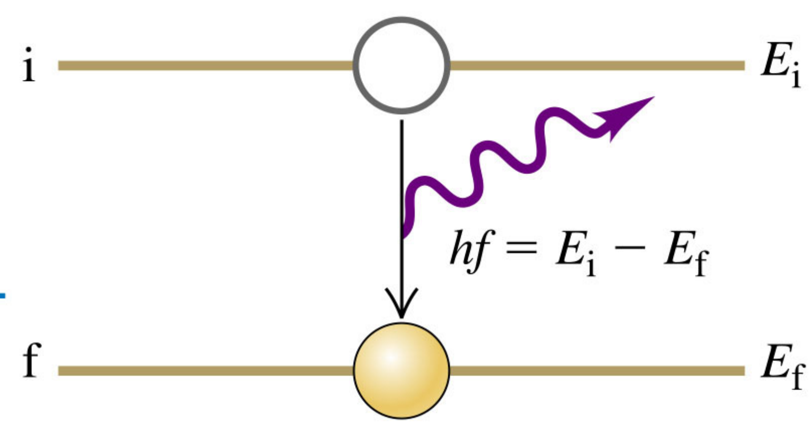
Energy levels of hydrogen

- Each type of atom has a unique set of energy levels.
- Each transition corresponds to a unique photon energy, frequency, and wavelength.

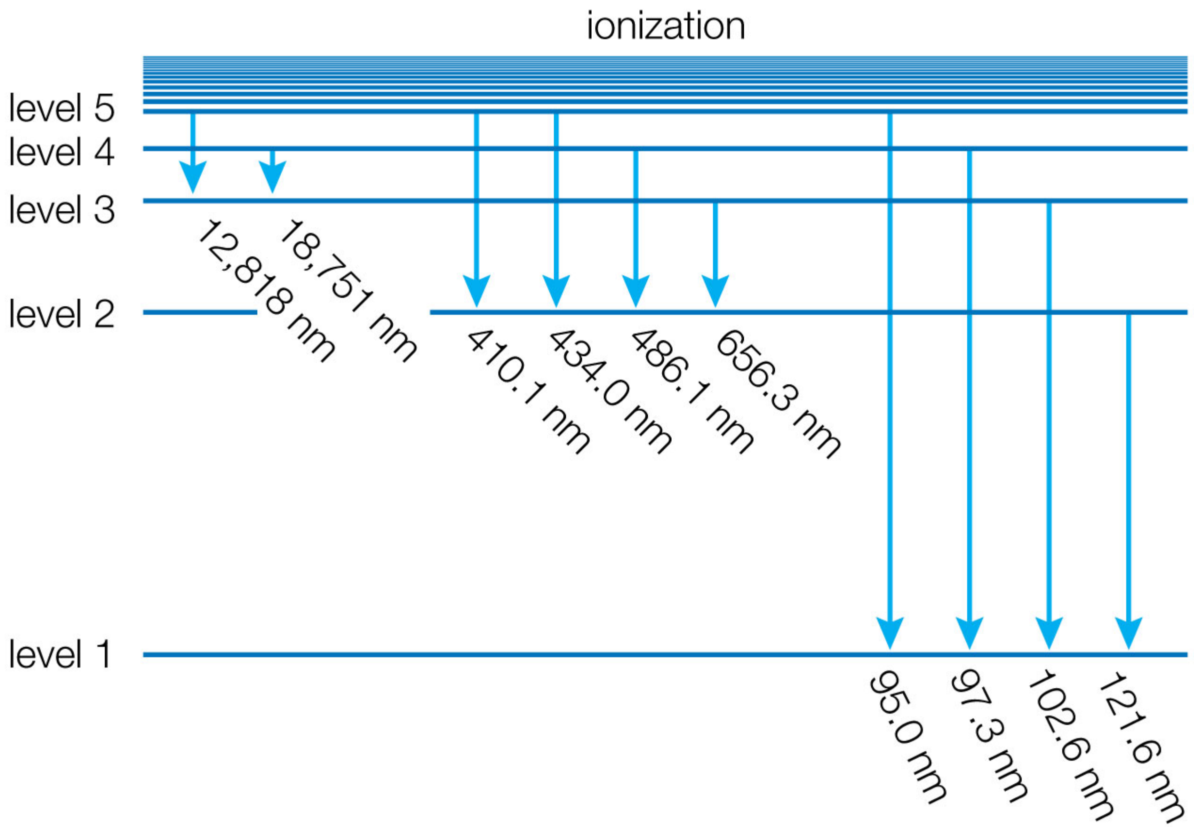
Chemical Fingerprints



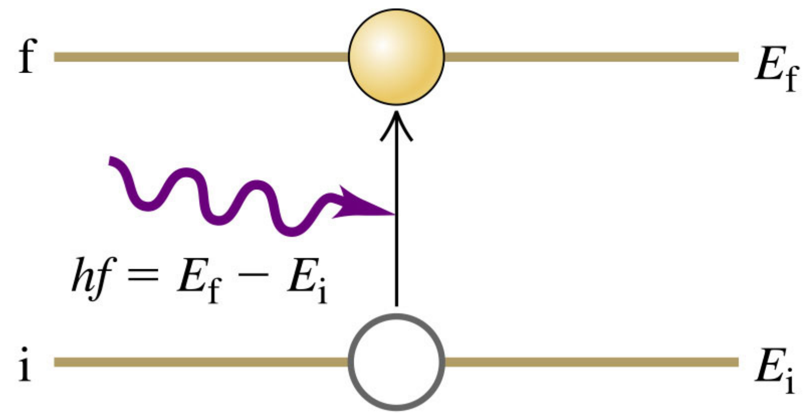
- Downward transitions produce a unique pattern of emission lines.



Chemical Fingerprints

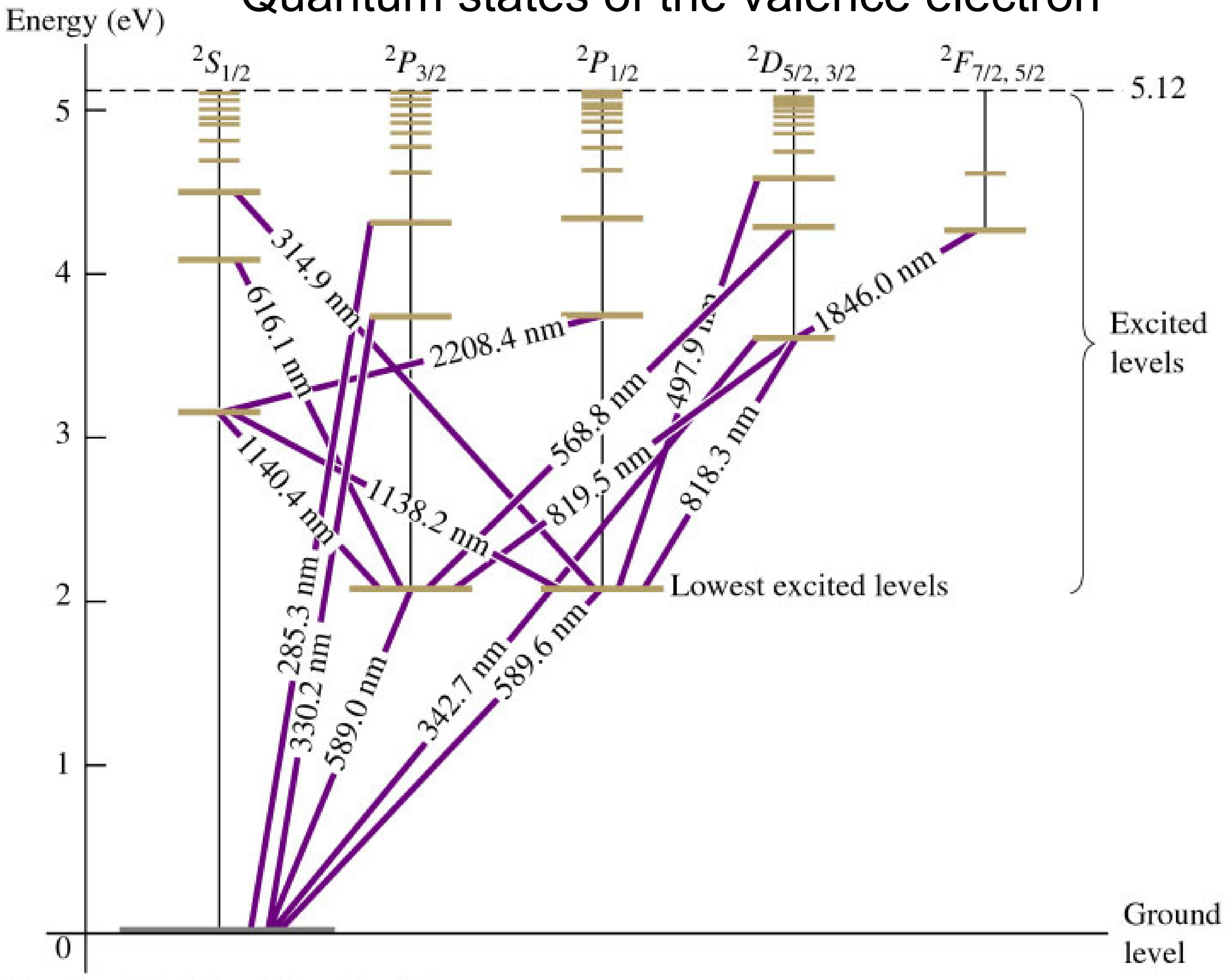


- Because those atoms can absorb photons with those same energies, upward transitions produce a pattern of absorption lines at the same wavelengths.



Energy levels and transitions of the many-electron atom: Sodium

Quantum states of the valence electron



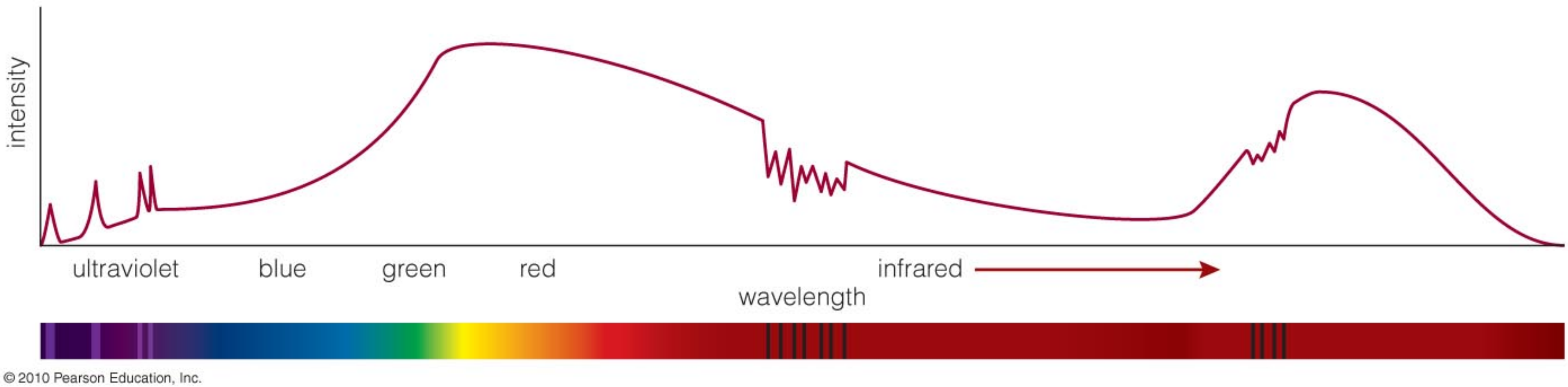
Chemical Fingerprints

- Each type of atom has a unique spectral fingerprint.
- Observing the fingerprints in a spectrum tells us which kinds of atoms are present.

Explaining Kirchoff’s laws

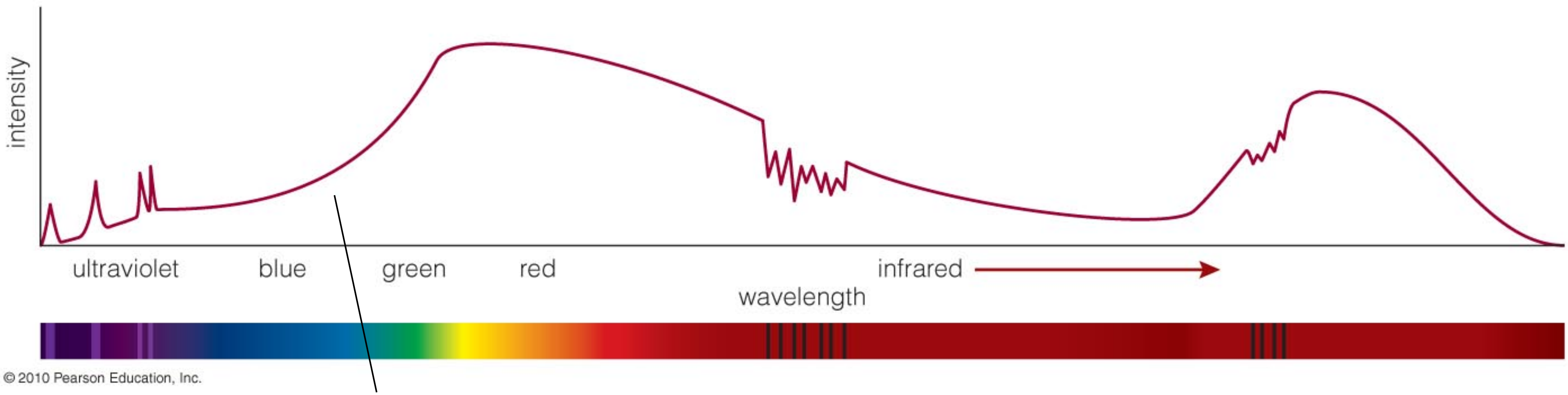
- A hot solid, liquid, or dense gas produces a continuous spectrum. **Blackbody radiation described by the Planck function and Wien's law.**
- A thin gas in front of a cooler background produces an emission line spectrum. **Downward transition of electron producing a single photon.**
- A thin gas in front of a hot source imprints absorption lines on the spectrum. This is mainly what we see from stars. **Upward transition of electron depending on energy of incident photon.**

Interpreting an Actual Spectrum



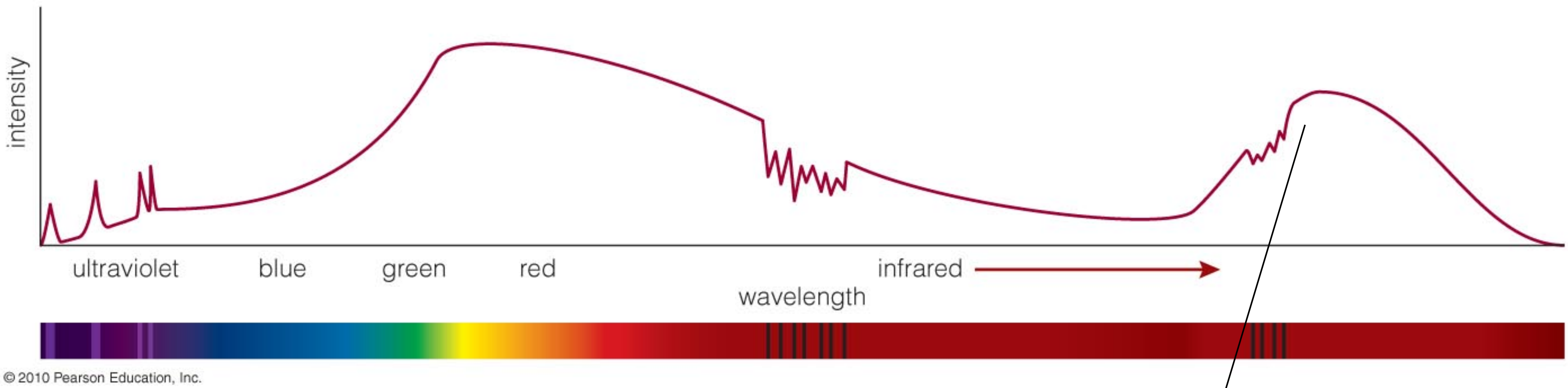
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

Interpreting an Actual Spectrum



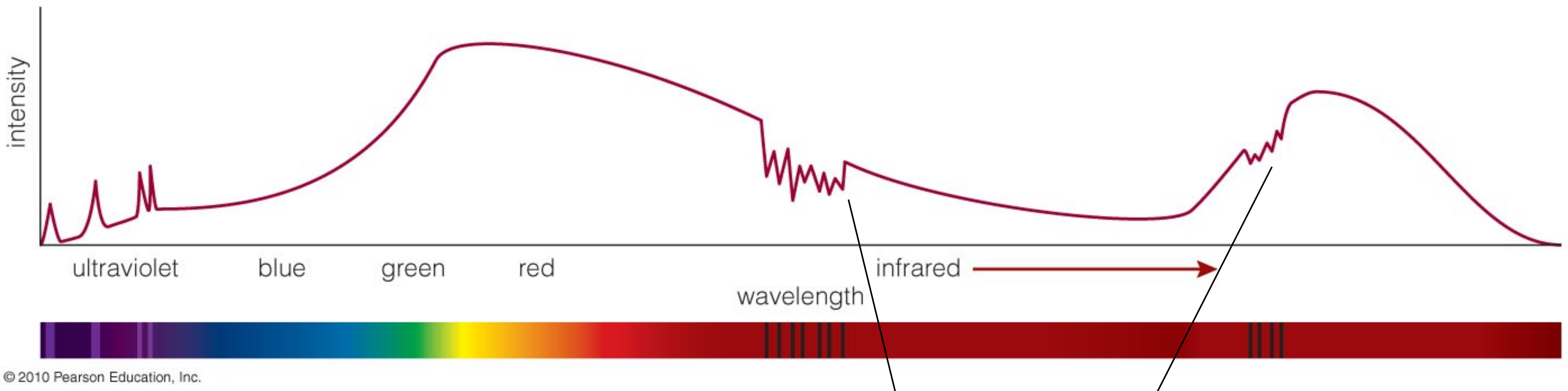
Reflected sunlight:
Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed—the object must look red.

Interpreting an Actual Spectrum



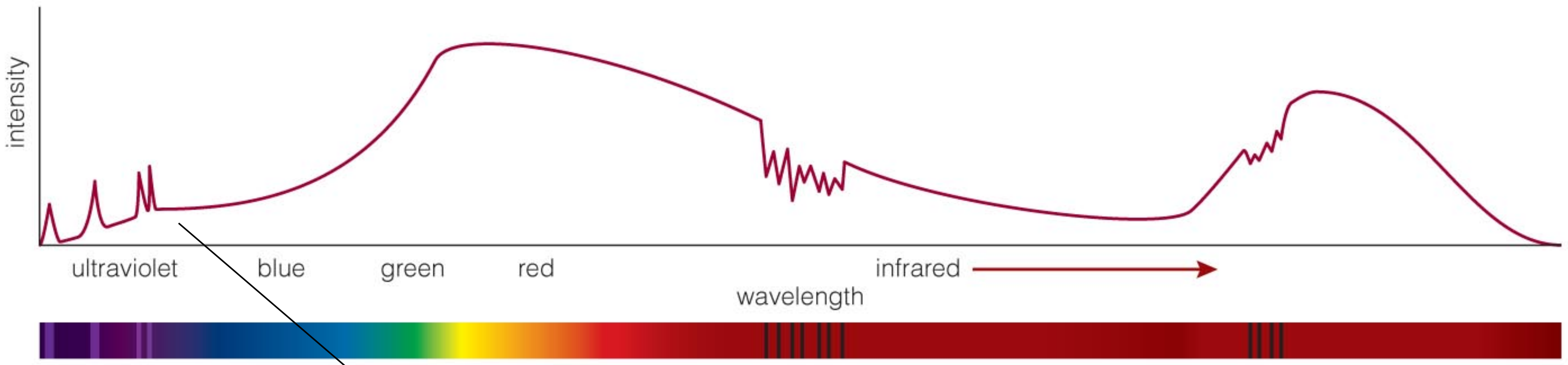
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K.

Interpreting an Actual Spectrum



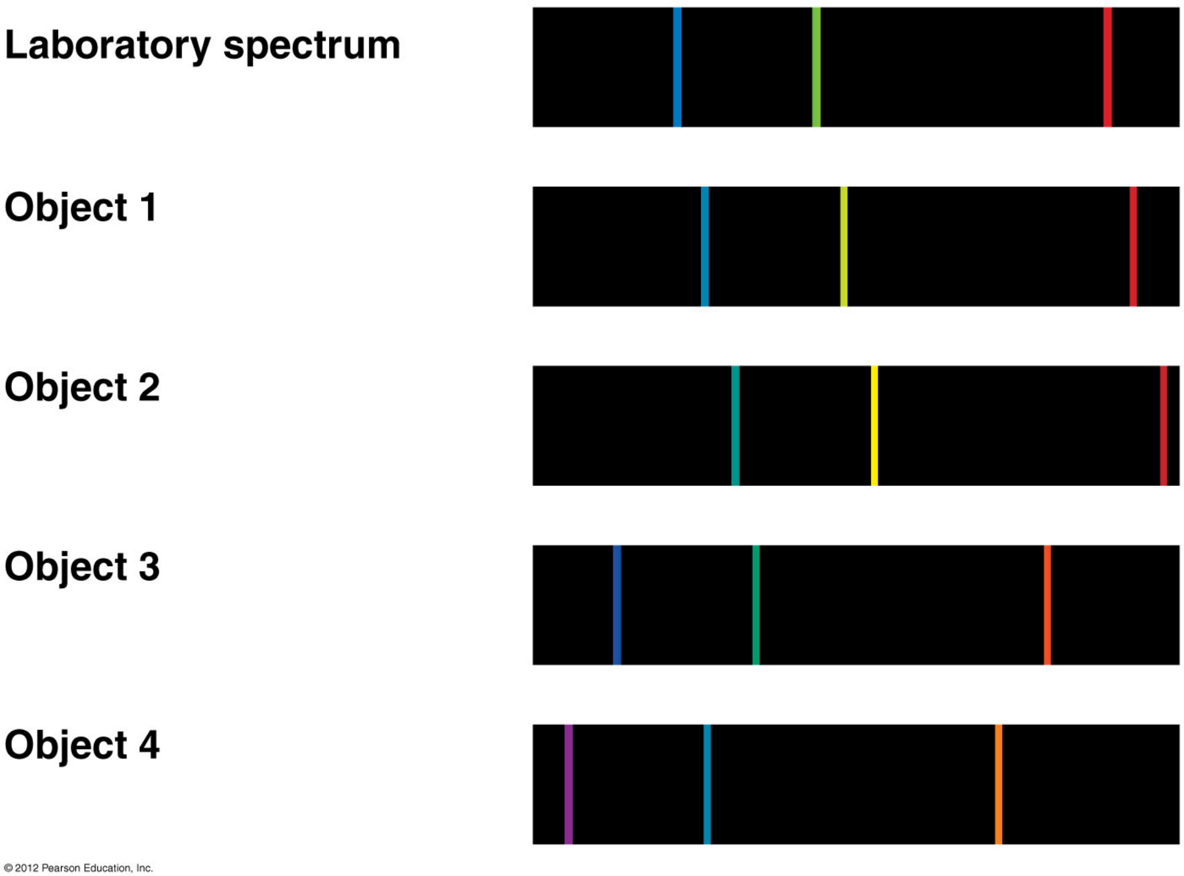
Carbon dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere.

Interpreting an Actual Spectrum



Ultraviolet emission lines:
Indicate a hot upper
atmosphere

Measuring the Shift



Stationary

Moving Away

Away Faster

Moving Toward

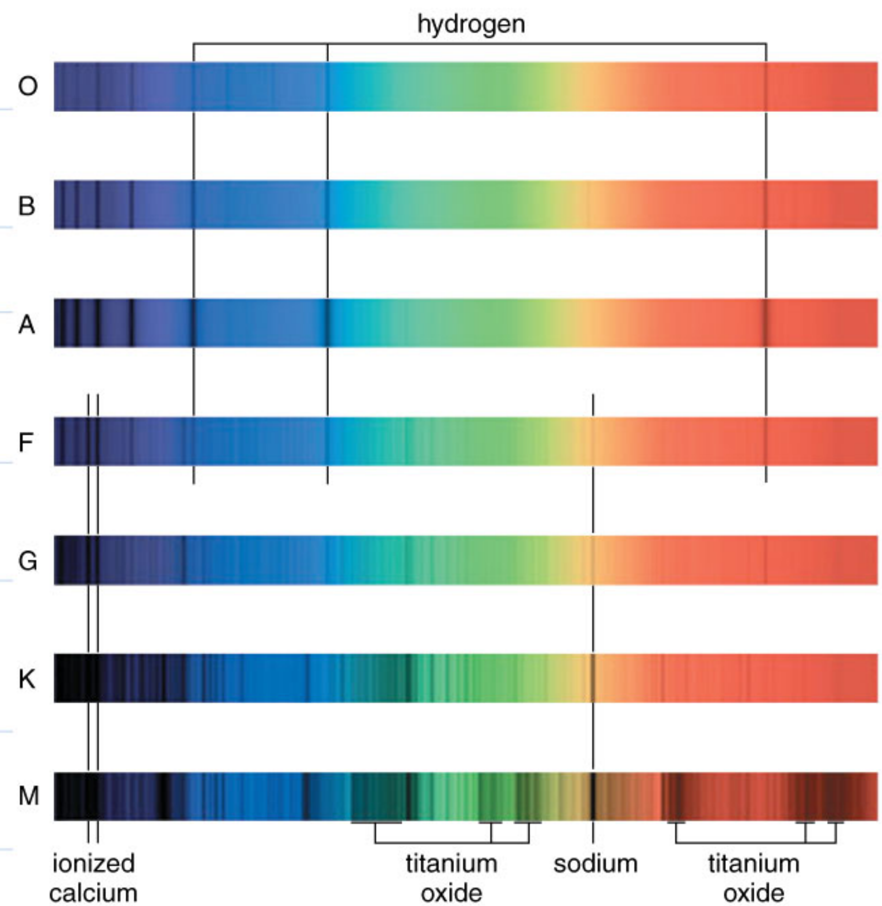
Toward Faster

- We generally measure the Doppler effect from shifts in the wavelengths of spectral lines. A **blueshift** means moving towards us. A **redshift** means moving away.

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)

Typical Spectrum

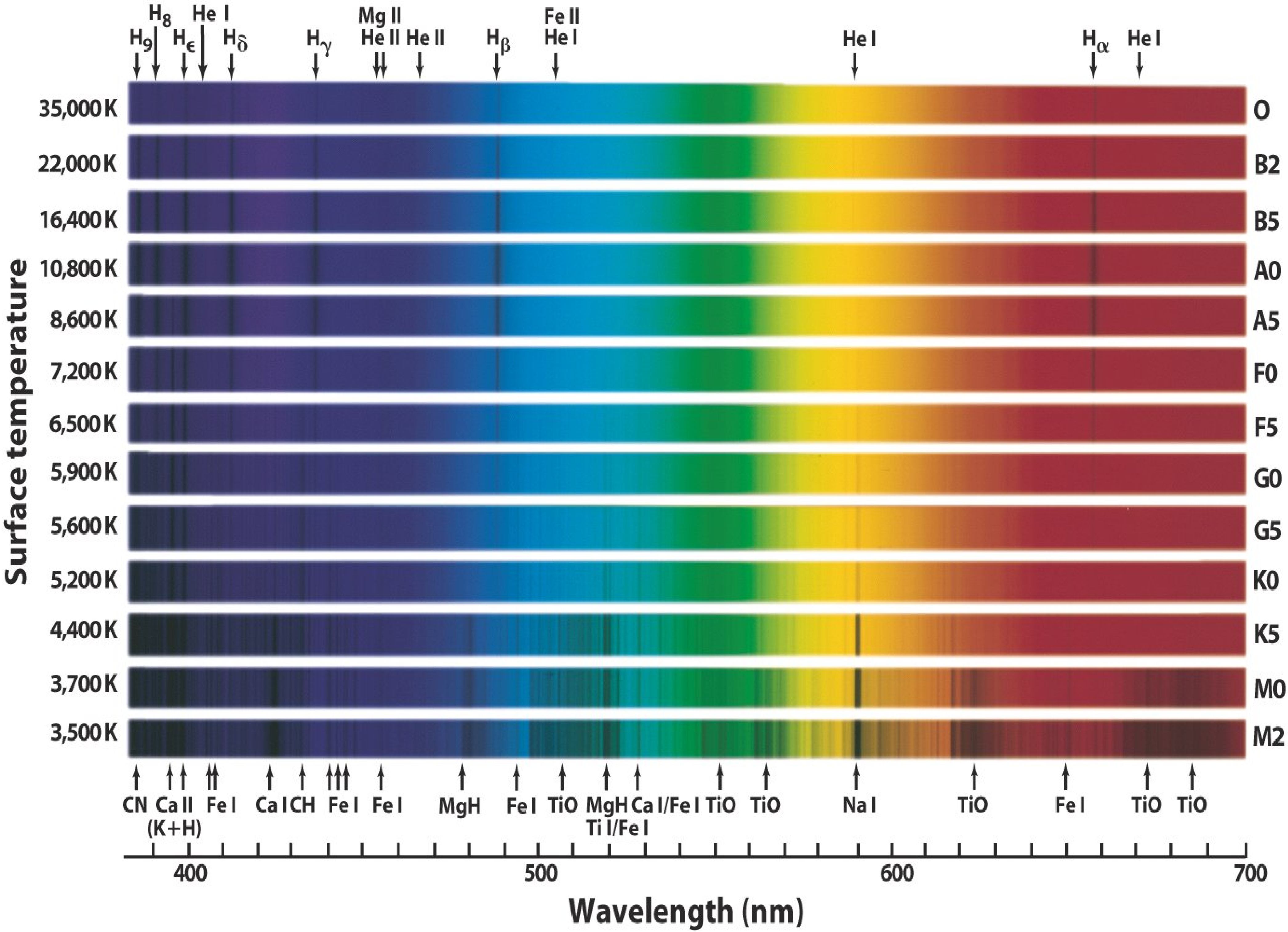


*All stars above 6000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

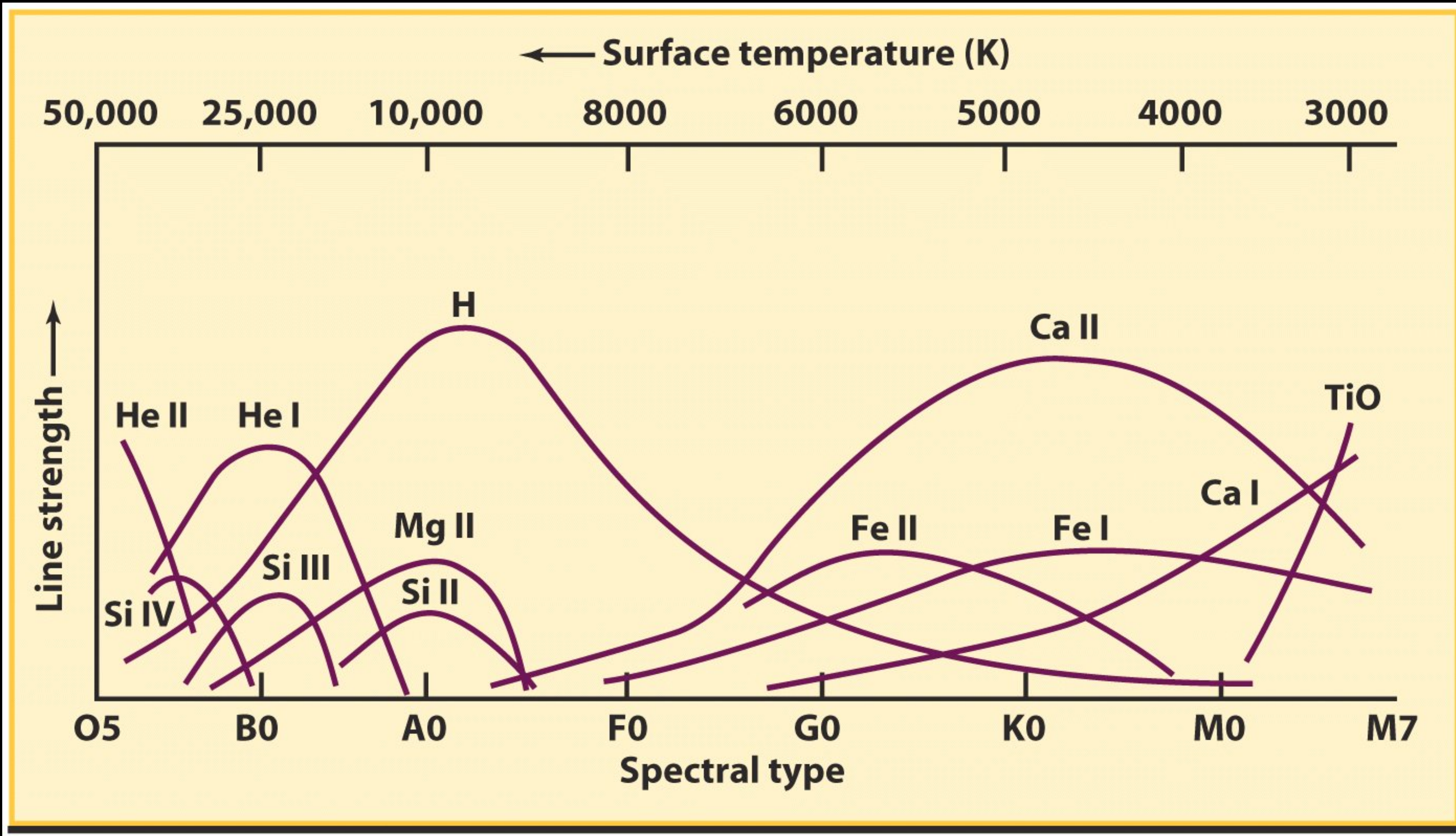
Lines in a star's spectrum correspond to a ***spectral type*** that reveals its temperature:

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

"Early type" "Late type"

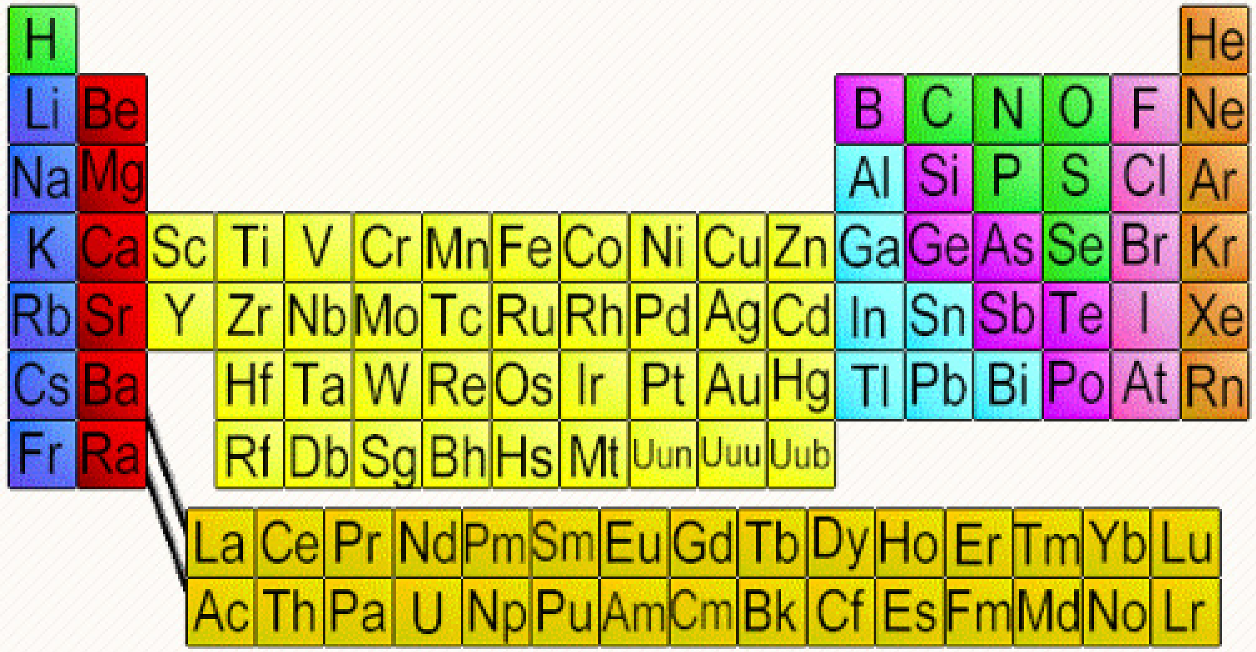


H9
H8
Hϵ
He I
Hδ
Hγ
Mg II
He II
He II
Hβ
Fe II
He I
He I
Hα
He I
Surface temperature
35,000 K
22,000 K
16,400 K
10,800 K
8,600 K
7,200 K
6,500 K
5,900 K
5,600 K
5,200 K
4,400 K
3,700 K
3,500 K
O
B2
B5
A0
A5
F0
F5
G0
G5
K0
K5
M0
M2
CN
Ca II (K+H)
Fe I
Ca I
CH
Fe I
Fe I
MgH
Fe I
TiO
MgH Ti I/Fe I
Ca I/Fe I
TiO
TiO
Na I
TiO
Fe I
TiO
TiO
400
500
600
700
Wavelength (nm)

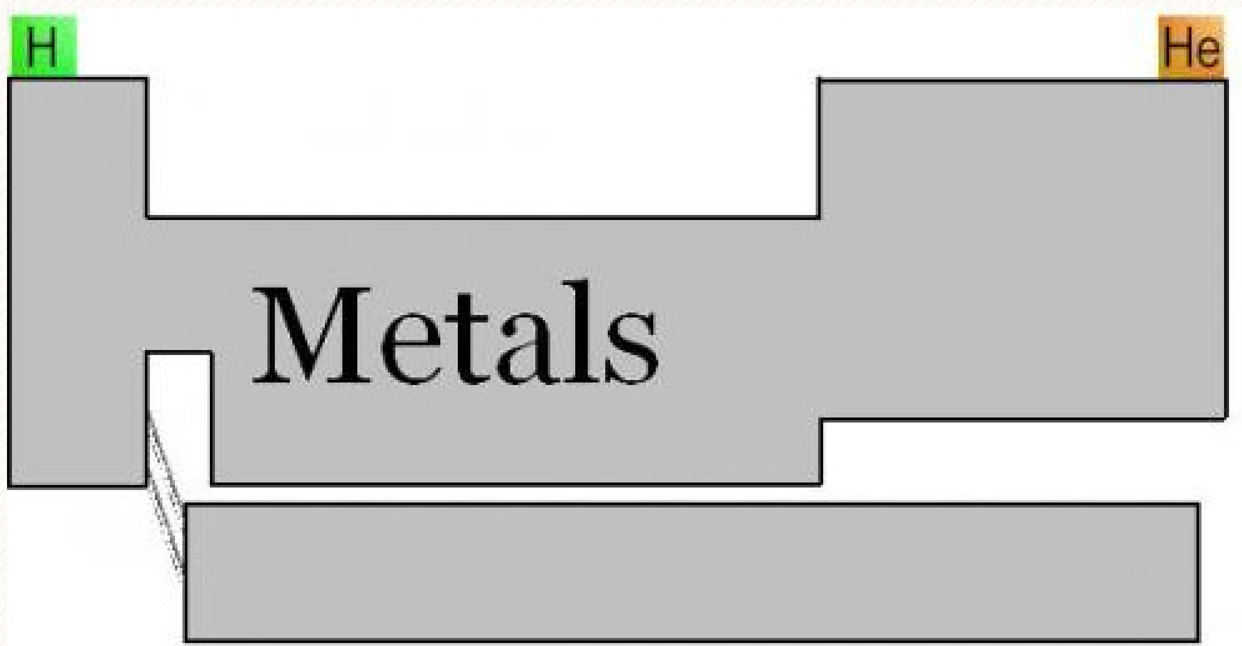


- The spectral class of a star is directly related to its surface temperature
  - O stars are the hottest
  - M stars are the coolest
  - The Saha ionization equation explains strength of hydrogen lines

What a chemist sees:



What an astronomer sees:



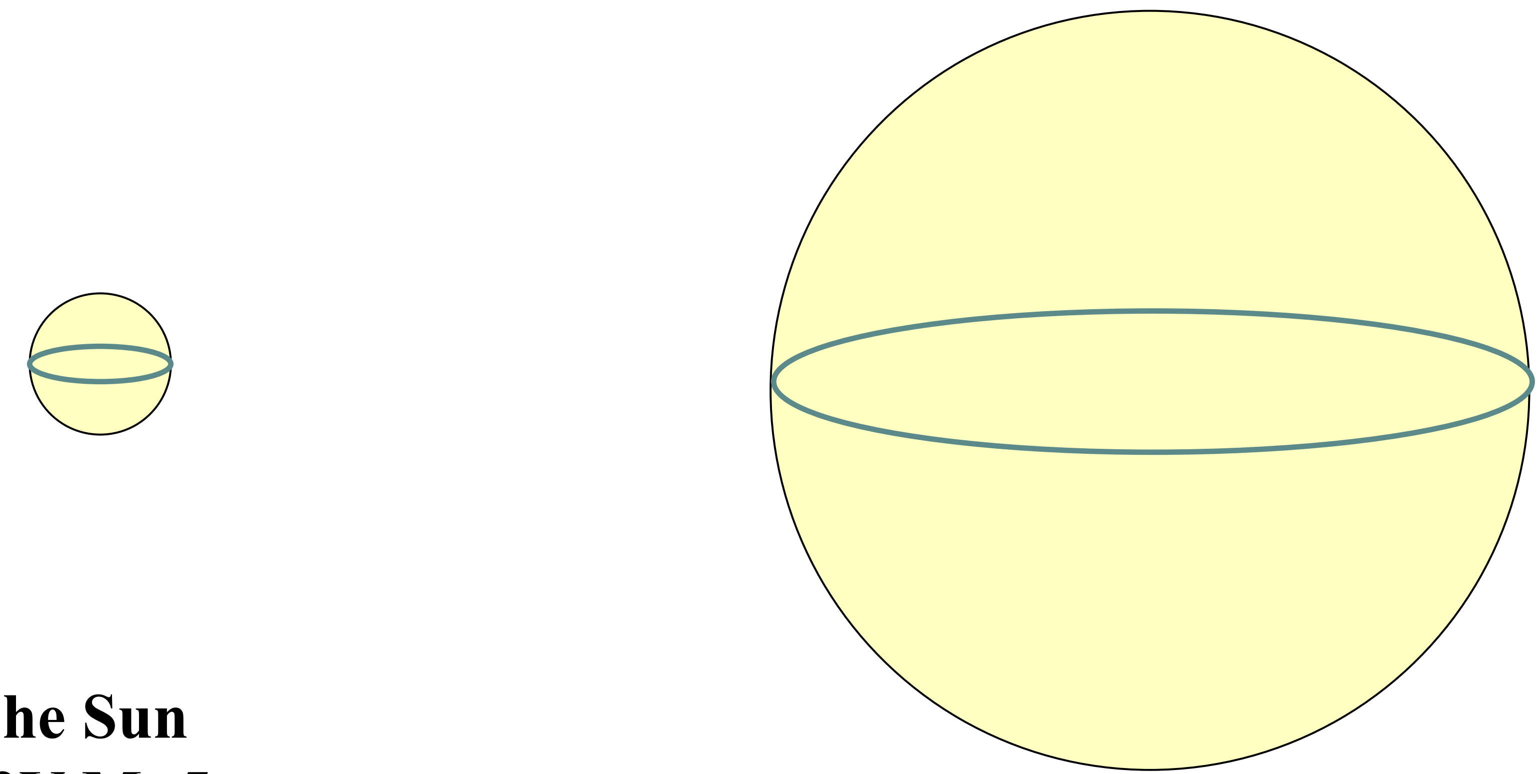
A star's full classification includes spectral type (line identities) and luminosity class (line shapes, related to the size of the star):

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



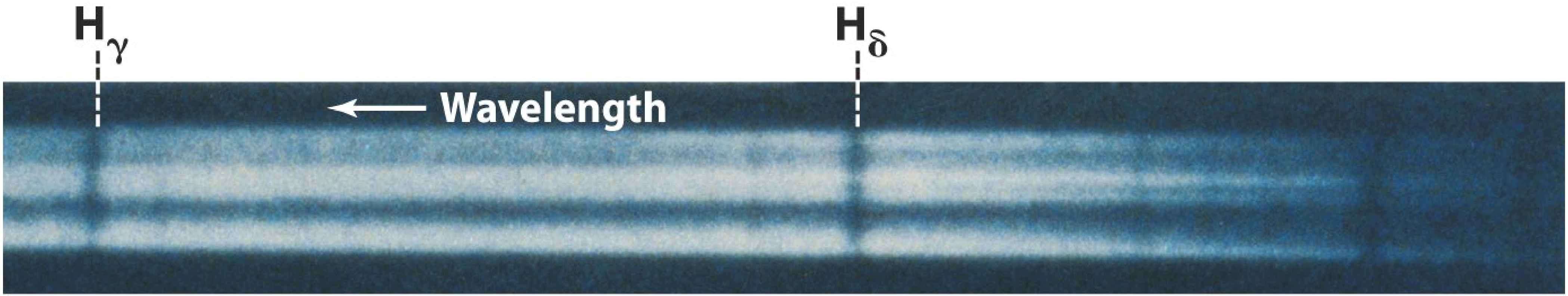
The Sun
G2V M=5

Capella
G2III M=0

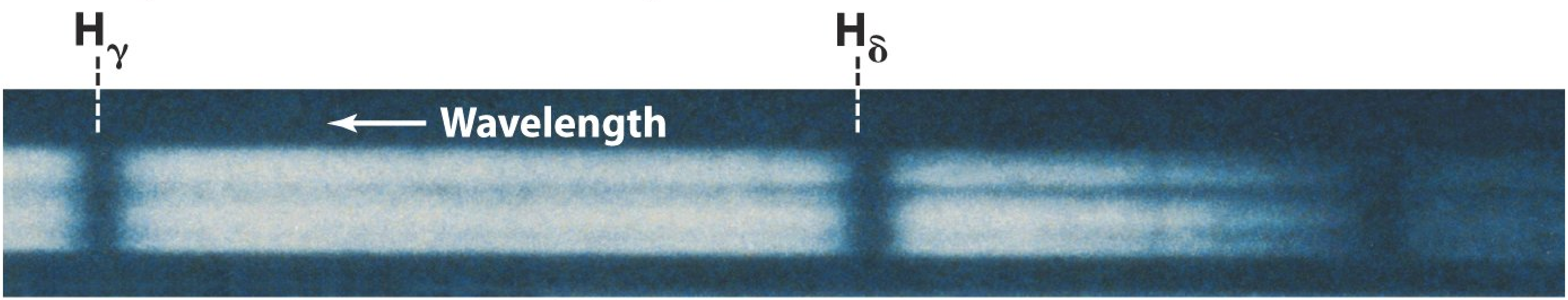
Luminosity Class Implies Size

- 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.

By carefully examining a star's spectral lines, astronomers can determine whether that star is a main-sequence star, giant, supergiant, or white dwarf



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



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

Luminosity Classes

The width of the absorption lines in a star's spectrum indicates its density. The thinner the line the less the density.

Supergiants & Giants are the least dense.

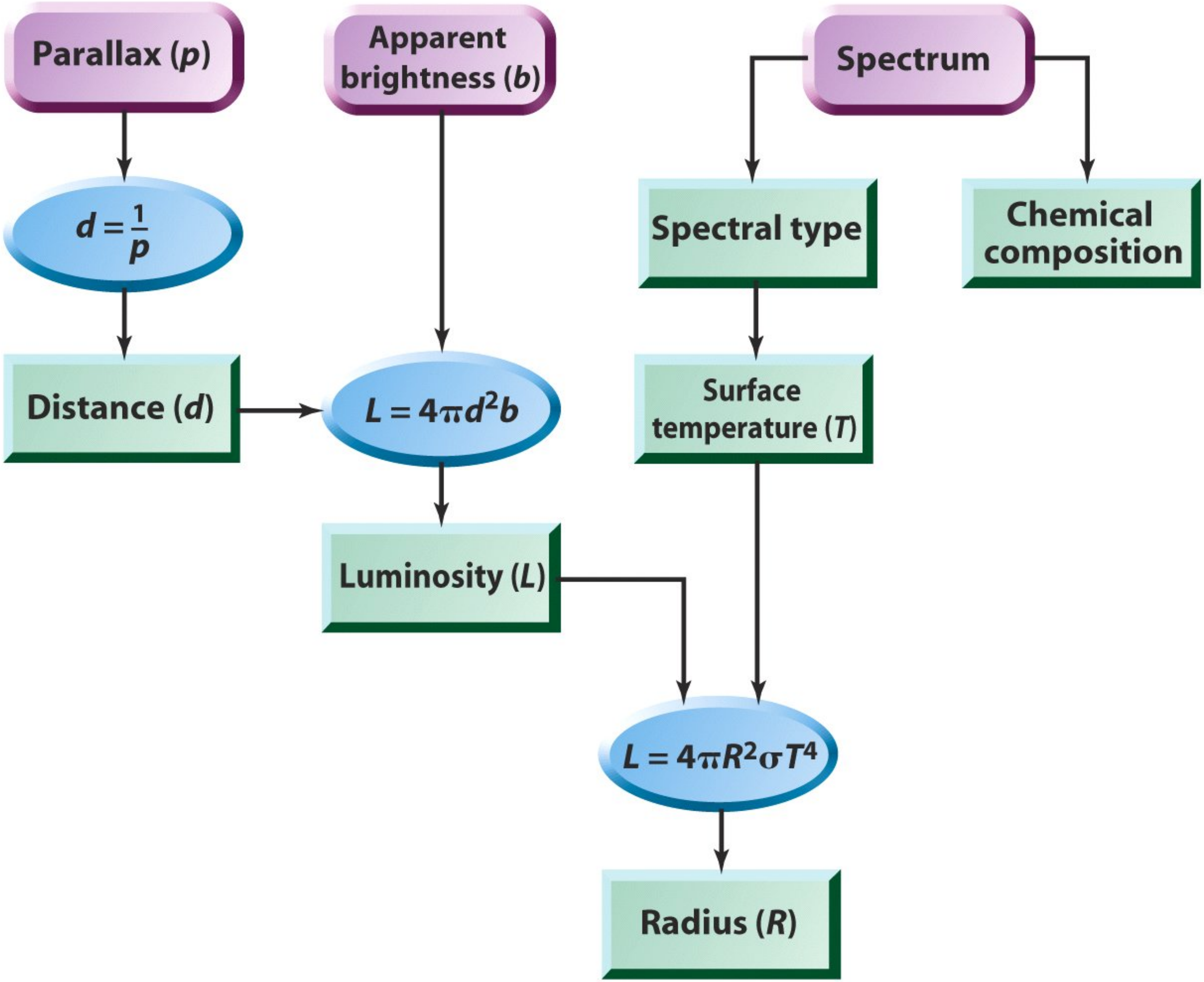
In general the less dense a star is the more luminous it will be (because it has more surface area).

Luminosity and the thickness of the absorption lines are combined to group stars into Lumniosity Classes.

Luminosity Classes are combined with spectral class to describe Stars. The Sun is Class V so …

The Sun is a "G2 V" star.

Flowchart of Key Stellar Parameters



Stellar Mass

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

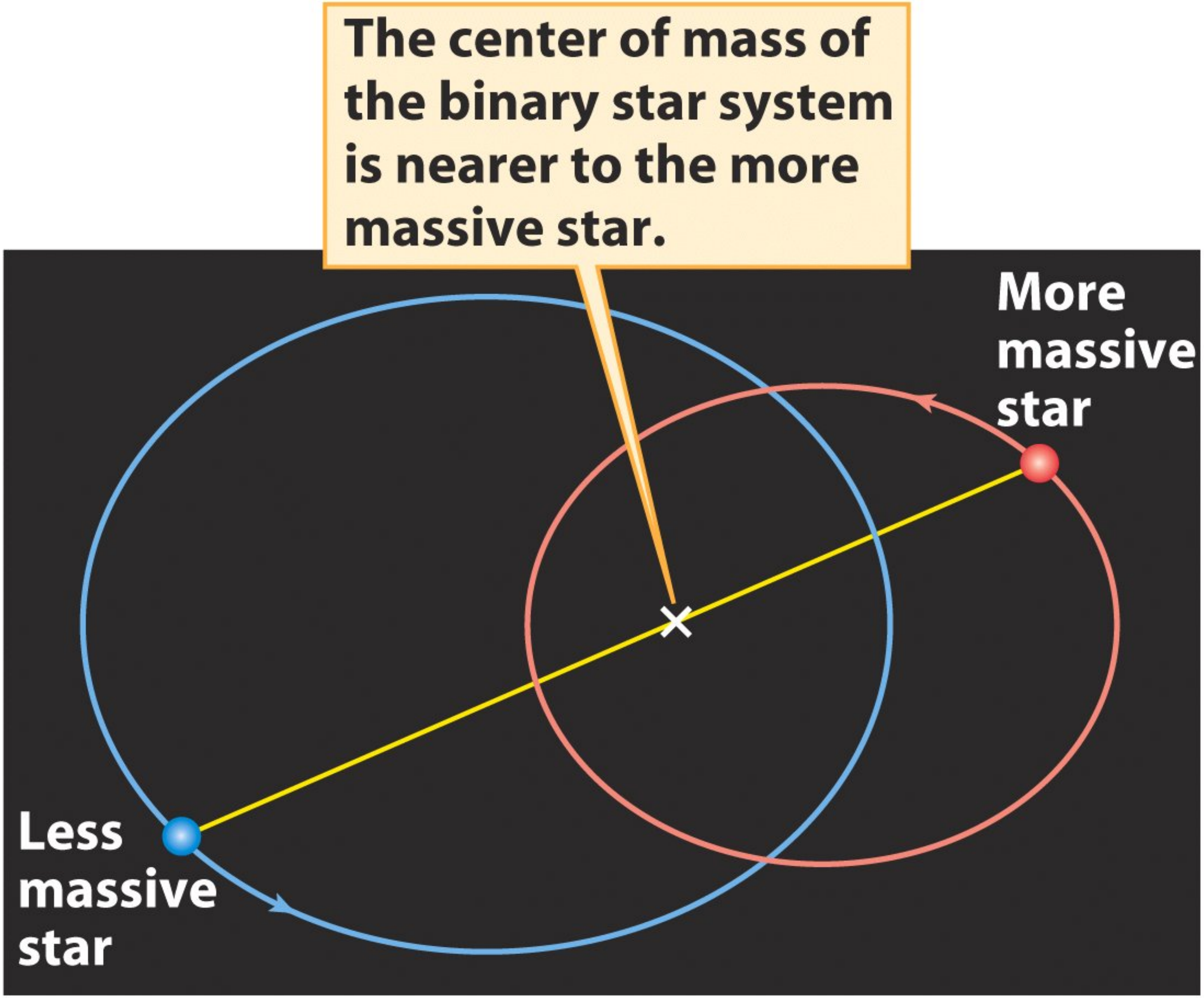
How do we measure stellar masses?

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.



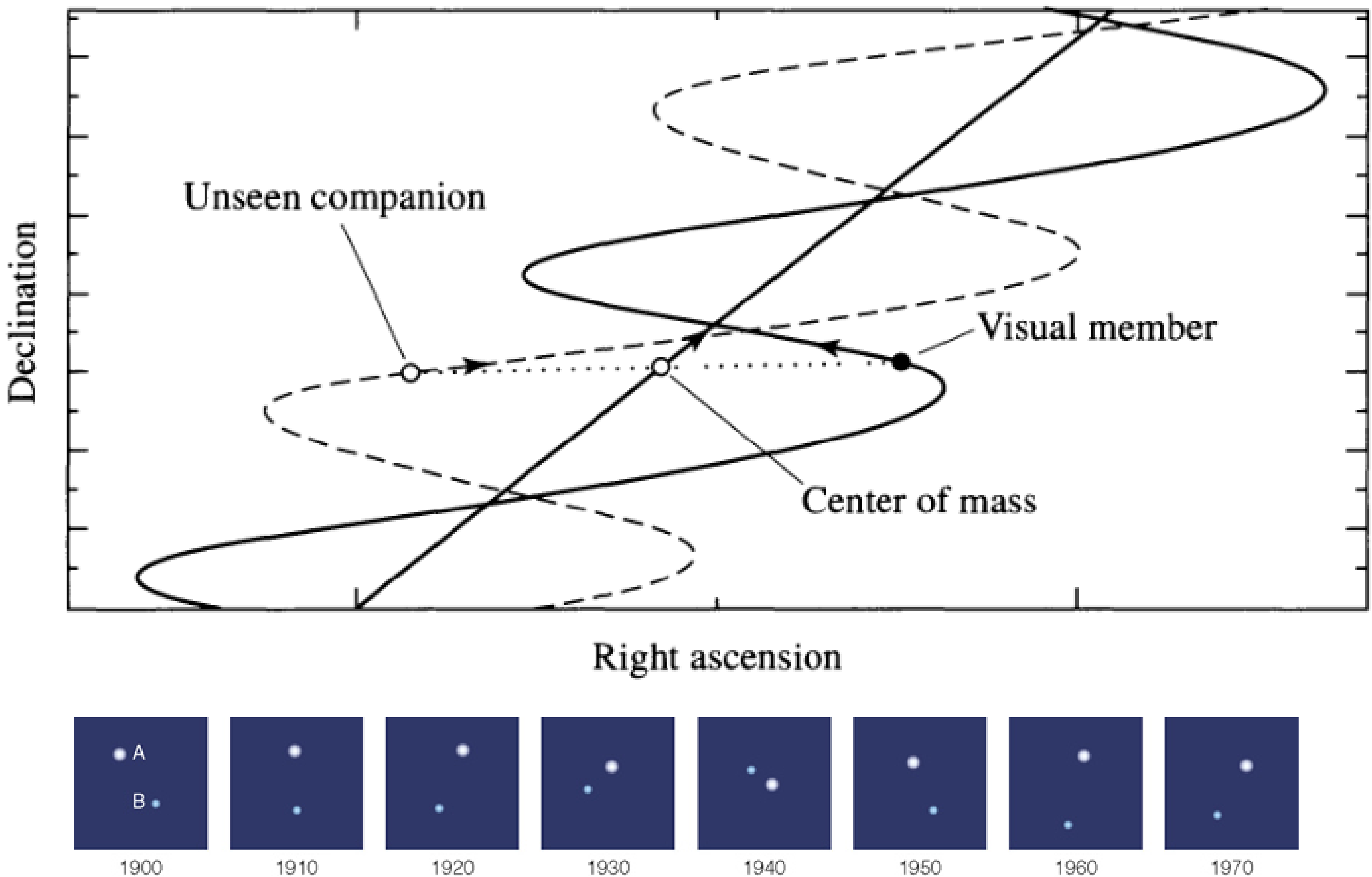
A binary star system

Types of Binary Star Systems

- Optical double
- Visual binary
- Astrometric binary
- Eclipsing binary
- Spectrum binary
- Spectroscopic binary

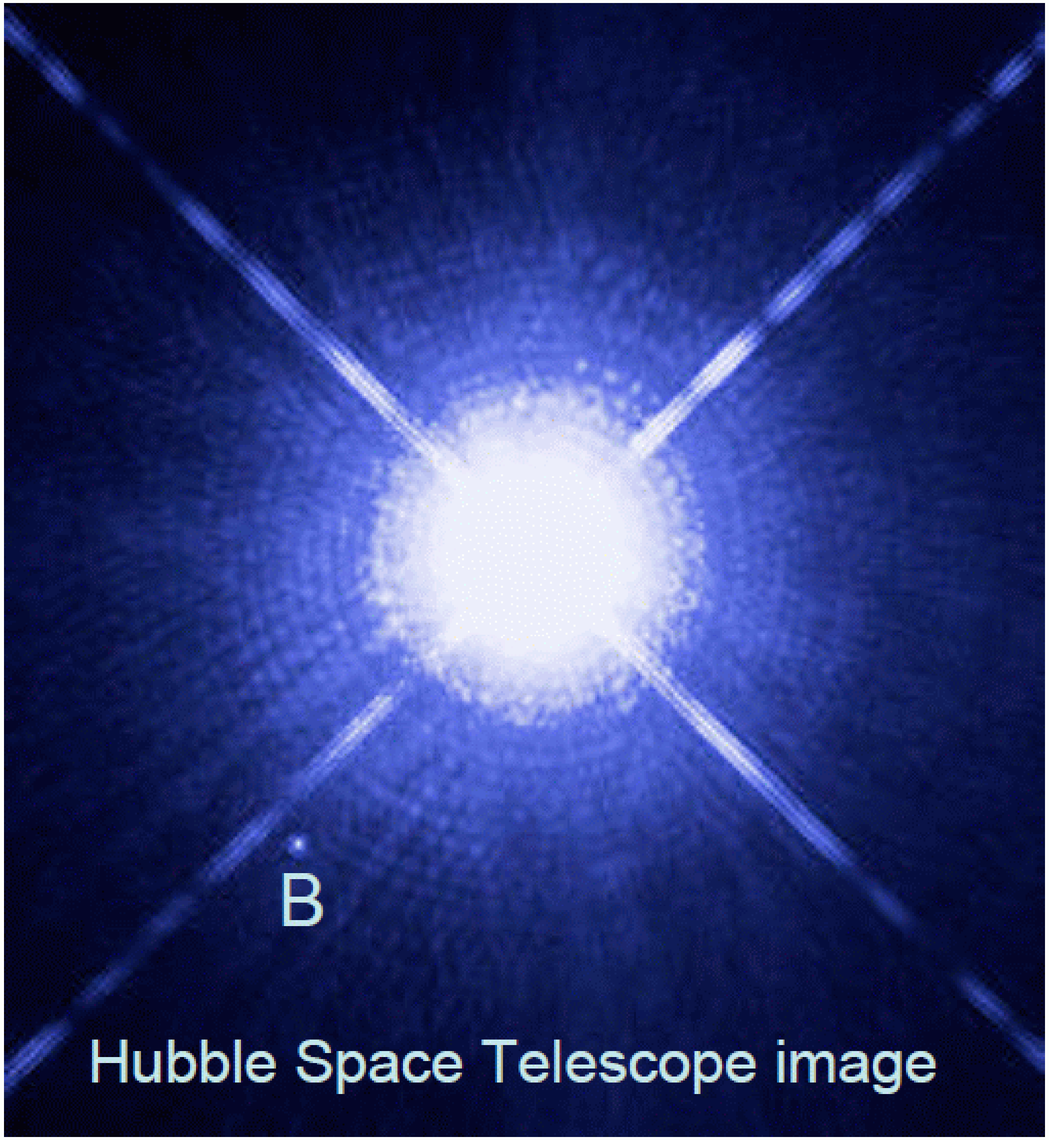
About half of all stars are in binary systems.

Astrometric Binary

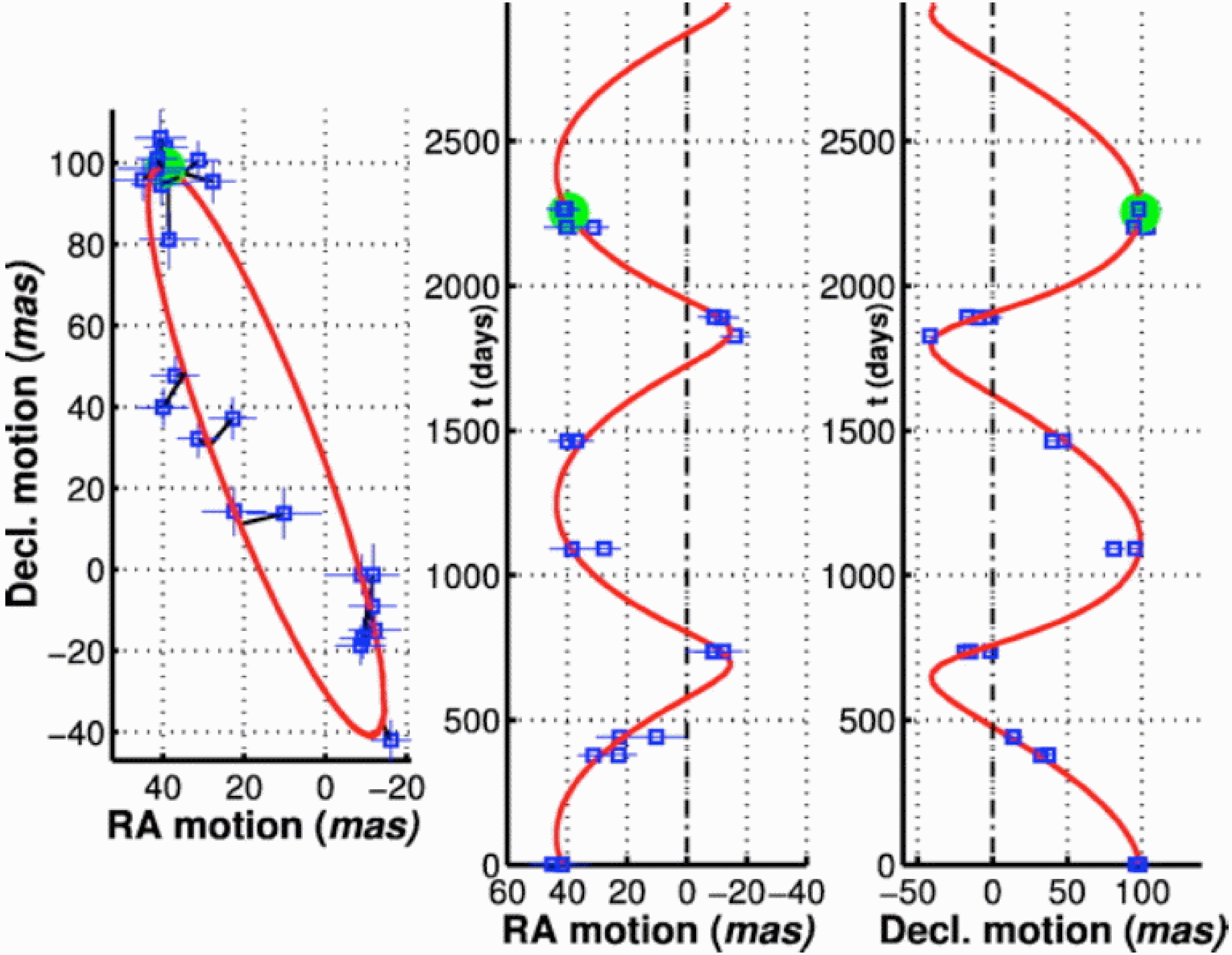


Astrometric Binary: Sirius AB

- Sirius A:
  - nearby luminous B star
  - brightest star in the sky
- ~1 M_{Sun} white dwarf companion first inferred from its large astrometric effect on primary
- now also a visual binary



Astrometric Binary: GJ 802AB

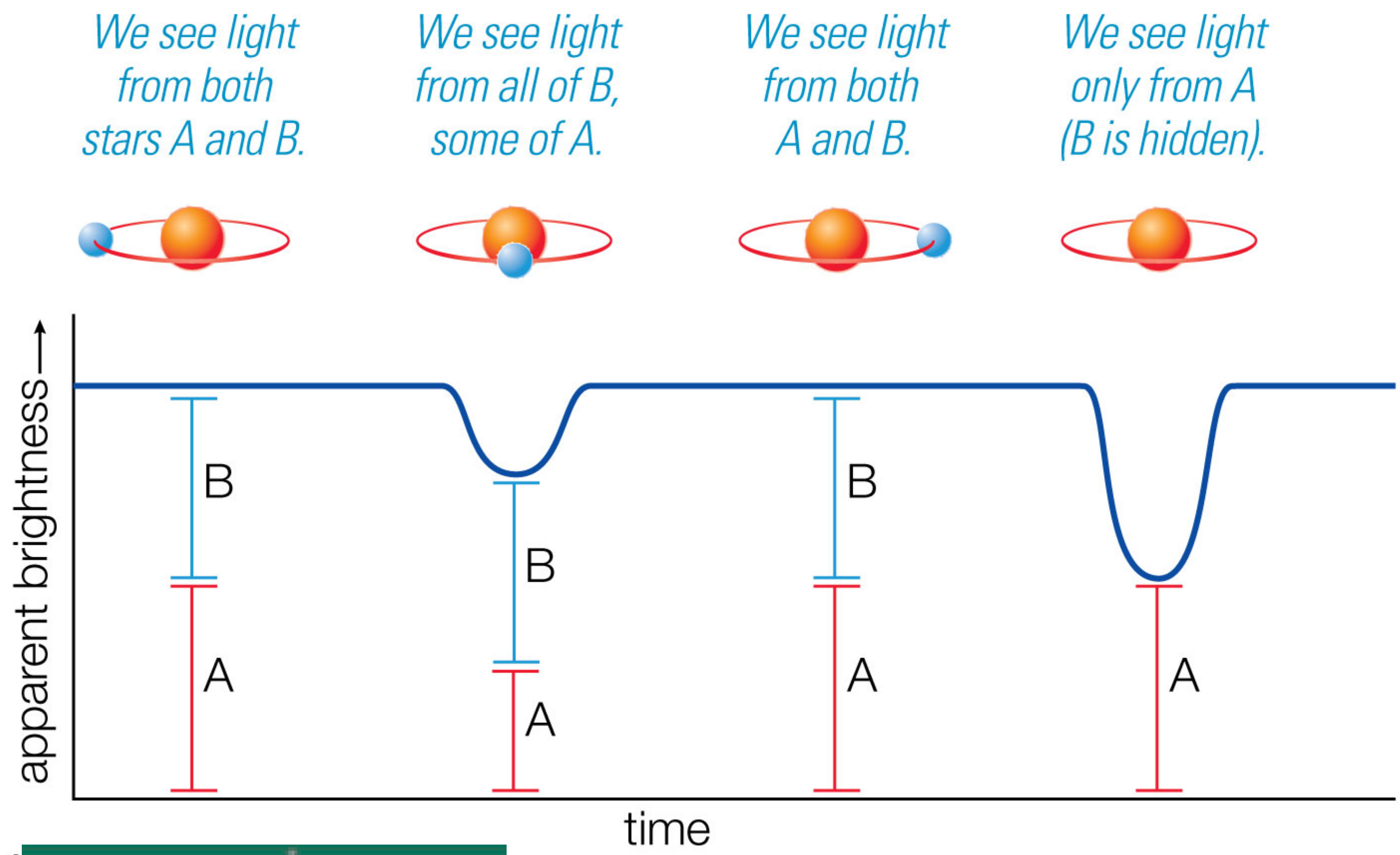


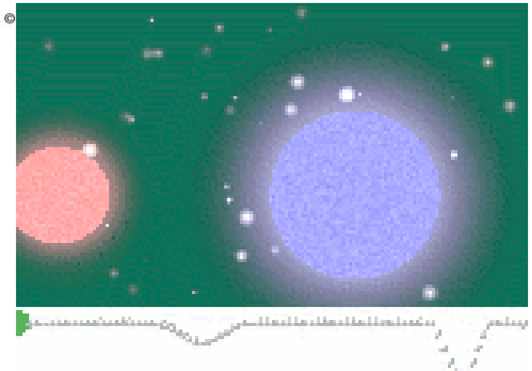
unseen brown dwarf companion

$a > 0.5–2\text{AU}$

(Pravdo et al. 2005)

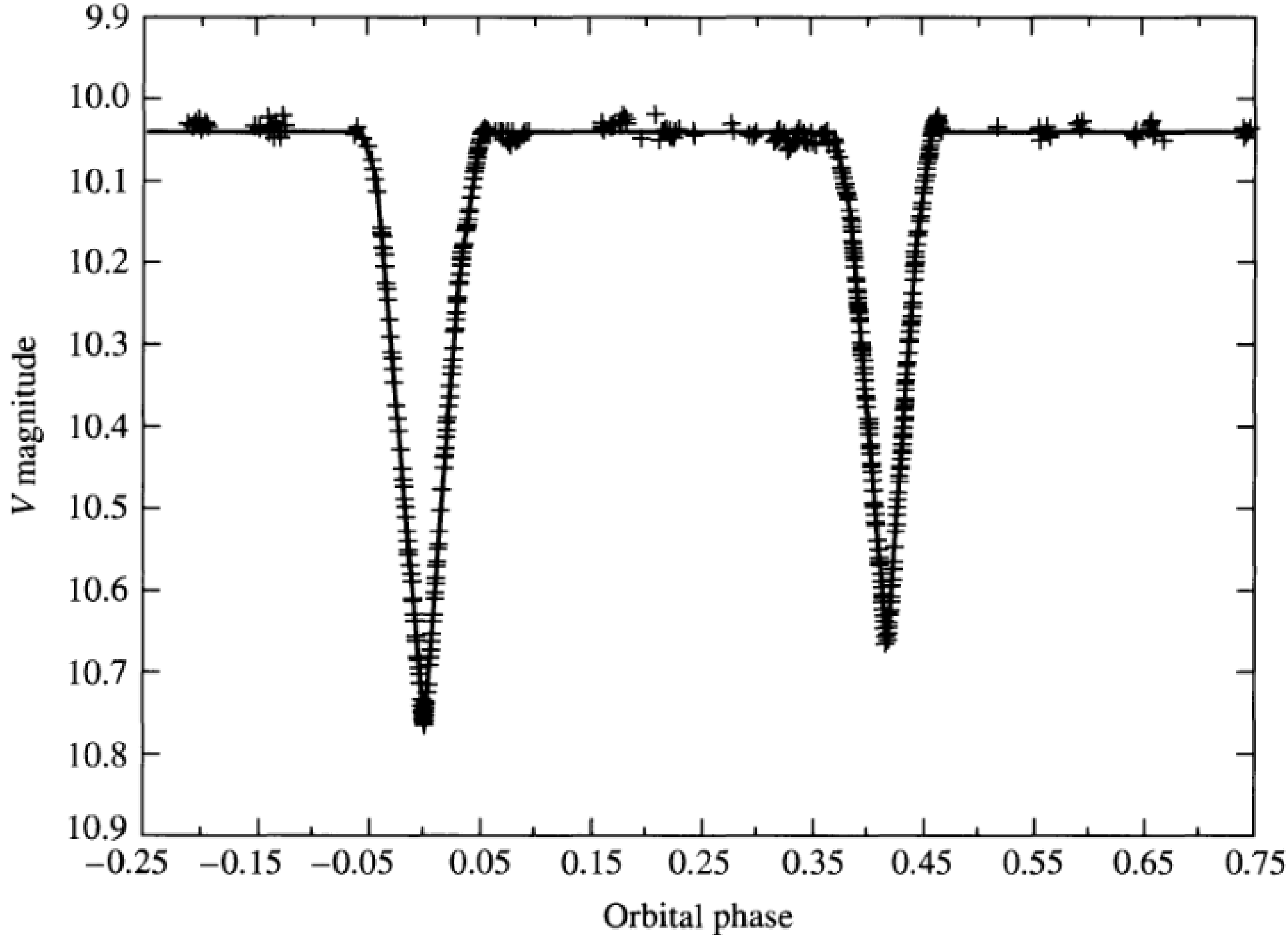
Eclipsing Binary





We can measure periodic eclipses.

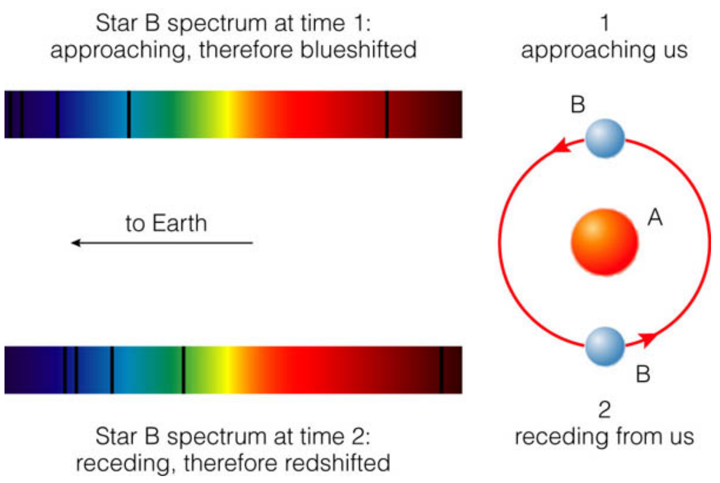
Eclipsing Binary

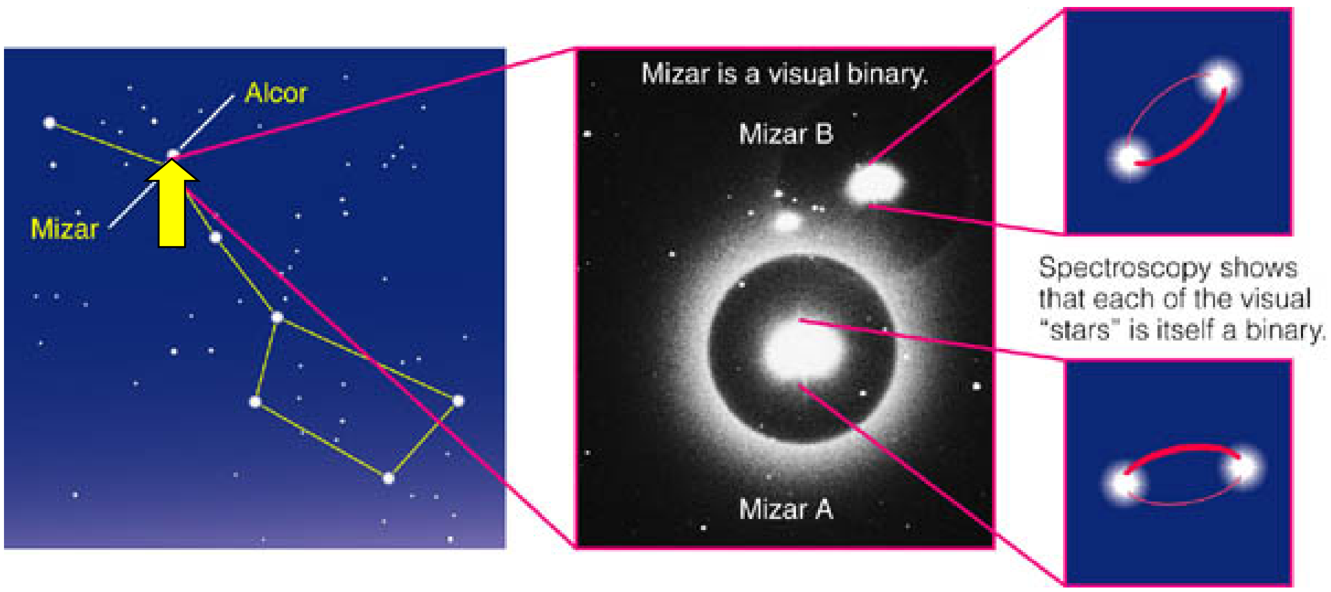


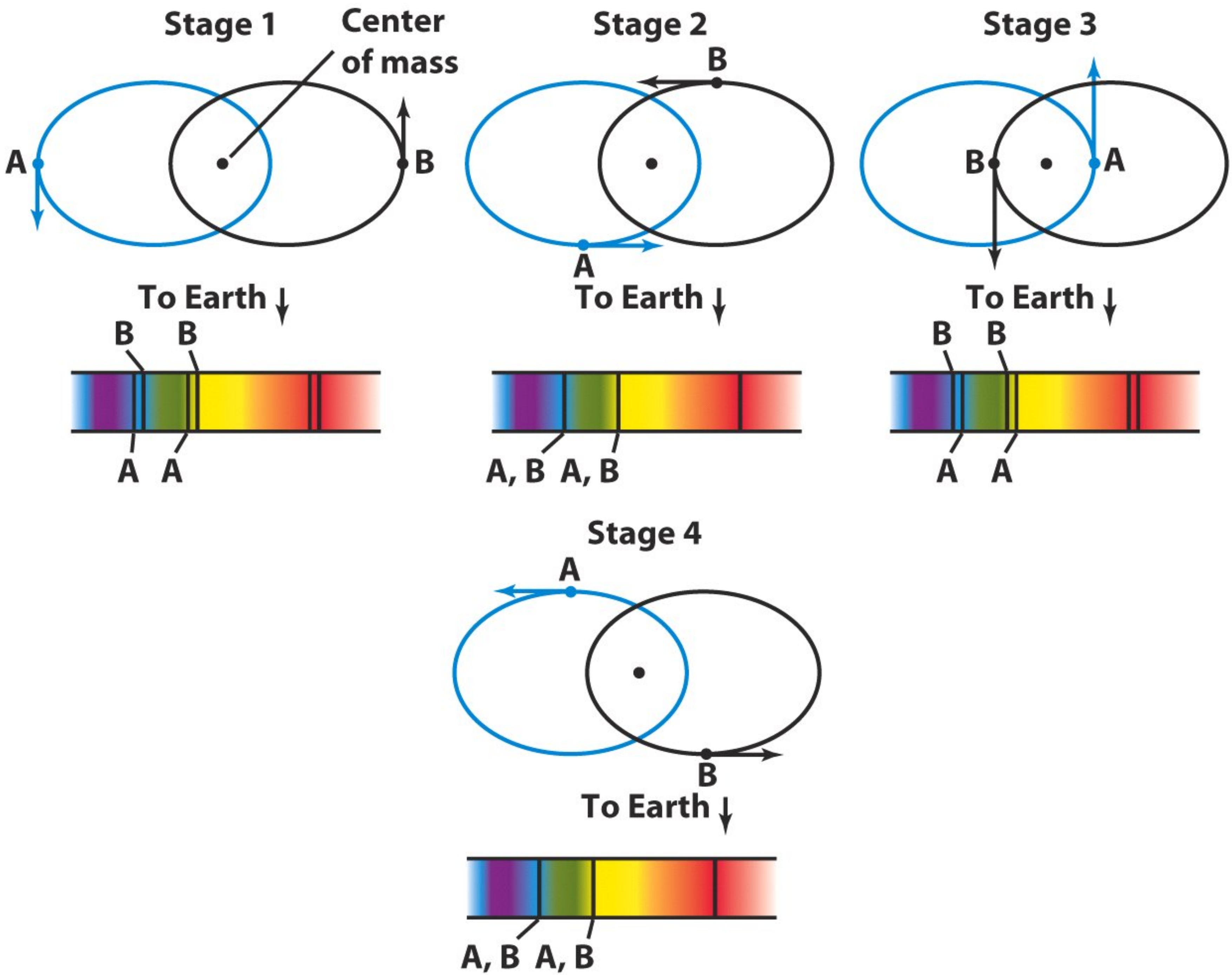
Phased lightcurve for YY Sagittarii.

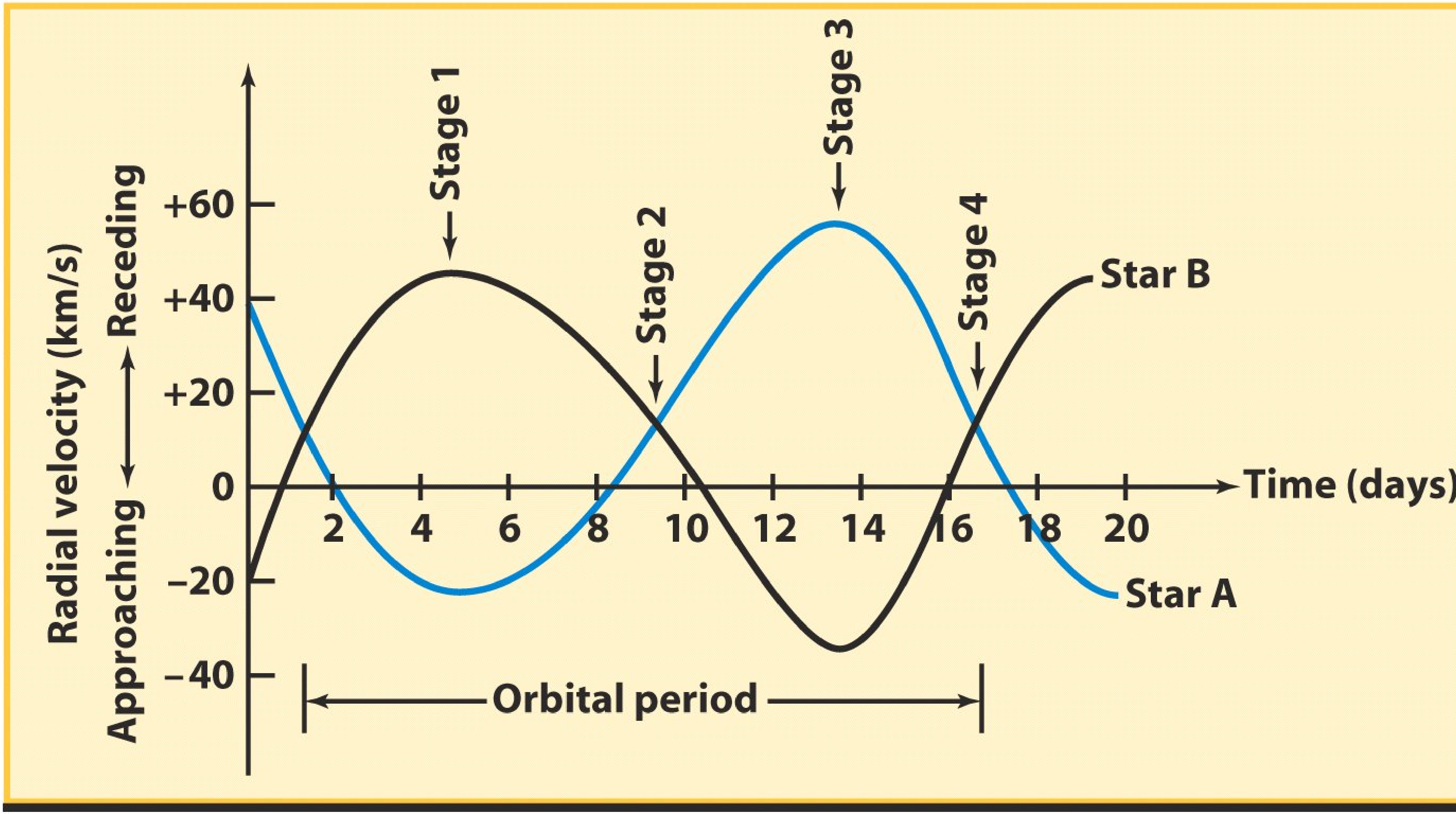
Spectroscopic Binary

- Sometimes only the spectrum from one star is seen, the other star is too dim.
- Sometimes two sets of spectra can be seen at the same time
- Sometimes more than two sets of spectra can be seen
  - ***Mizar*** is a visual binary system in the constellation of *Big Dipper.*
  - Each 'star' in the visual binary system is also a spectroscopic binary!






Stage 1
Center of mass
A
B
To Earth
B B
A A
Stage 2
B
A
To Earth
A, B A, B
Stage 3
B
A
To Earth
B B
A A
Stage 4
A
B
To Earth
A, B A, B

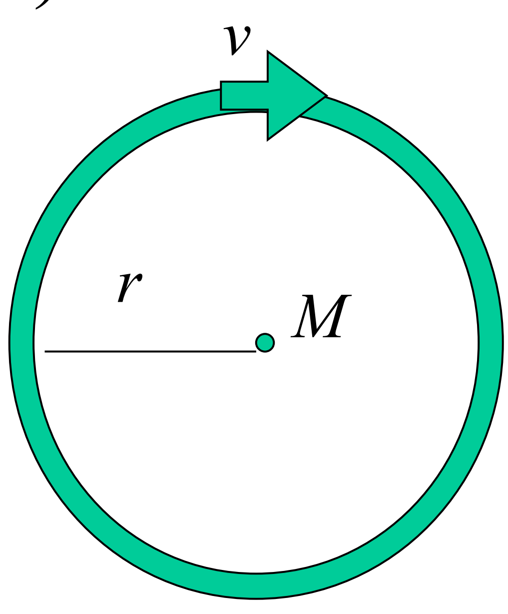


Radial velocity (km/s)
Approaching
Receding
+60
+40
+20
0
−20
−40
Stage 1
Stage 2
Stage 3
Stage 4
Star B
Star A
Time (days)
2
4
6
8
10
12
14
16
18
20
Orbital period

Need two out of three observables to measure mass:

1. Orbital period (P)
2. Orbital separation (a or r = radius)
3. Orbital velocity (v)

For circular orbits, $v = 2\pi r / P$



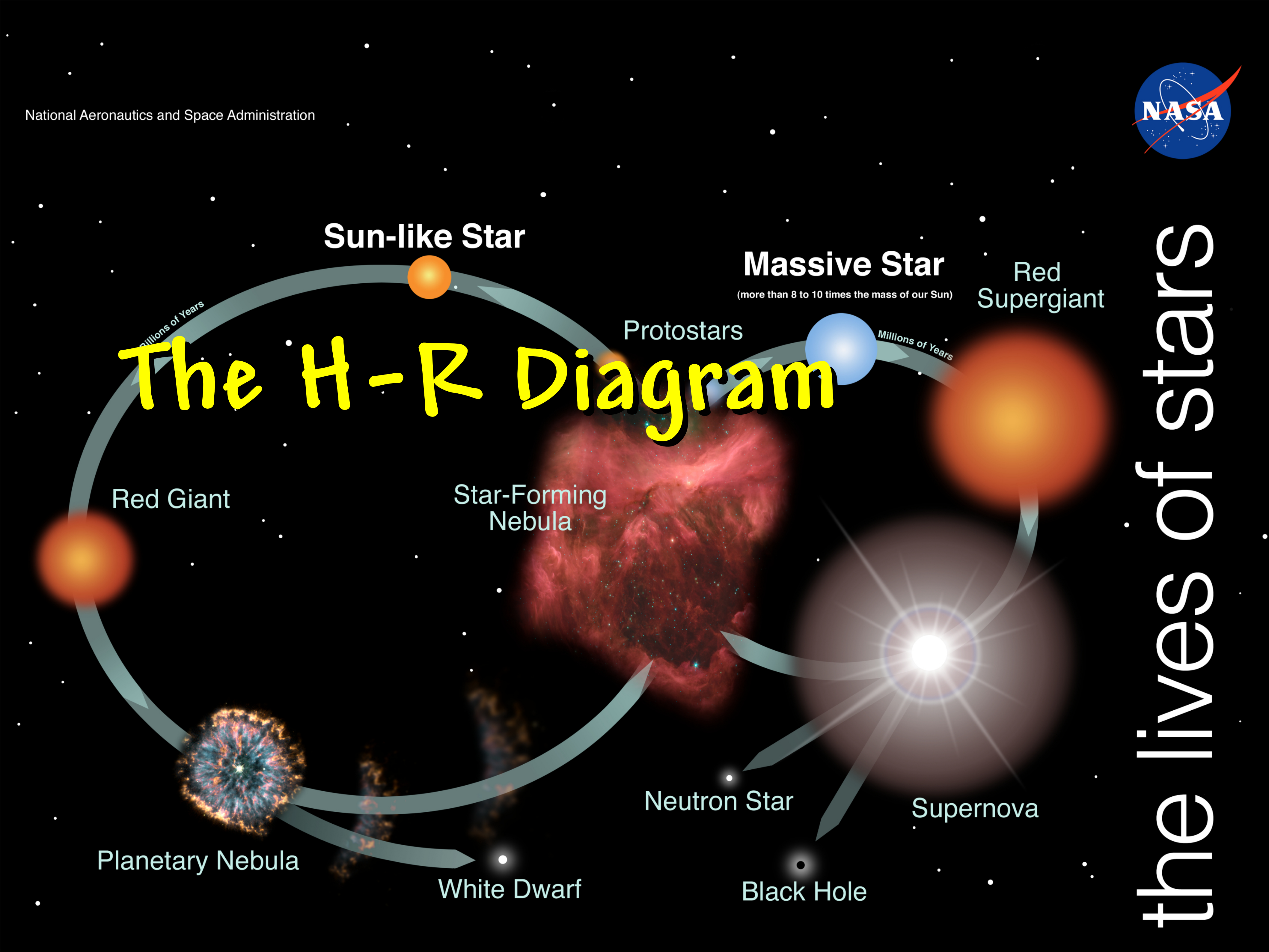
Dynamical Mass Determination

– If orbital major axes (relative to center of mass) or radial velocity amplitudes are known, so is the ratio of masses:

$$\frac{m_1}{m_2} = \frac{a_2}{a_1} = \frac{v_{2r}}{v_{1r}}$$

– If the period, P, and the sum of semi-major axis lengths, $a = a_1 + a_2$, are known, Kepler's third law can give masses separately:

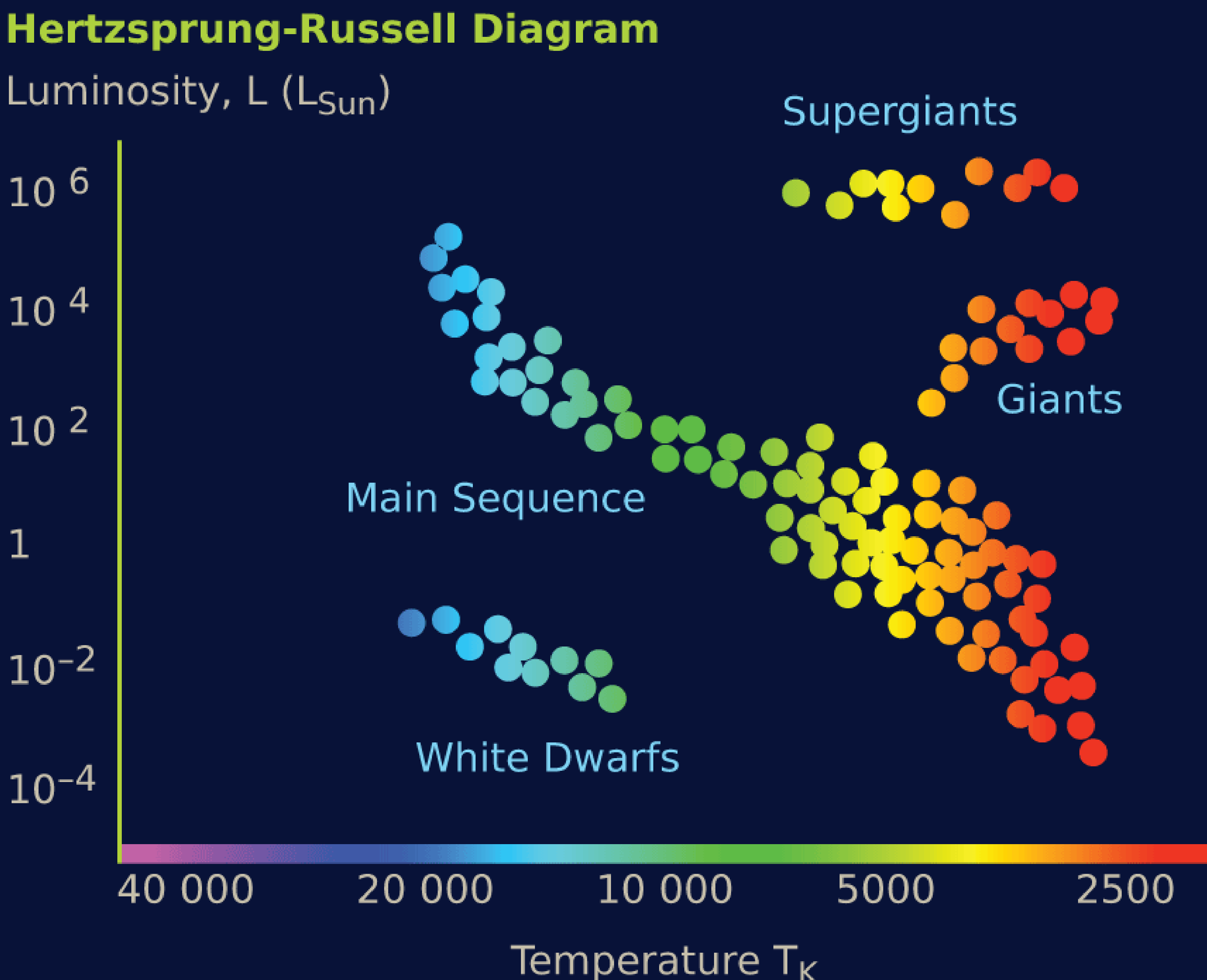
$$P = \left(\frac{4\pi^2}{G(m_1 + m_2)} a^3 \right)^{1/2}$$


National Aeronautics and Space Administration
NASA
The H-R Diagram
Sun-like Star
Millions of Years
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Millions of Years
Red Giant
Star-Forming Nebula
Planetary Nebula
White Dwarf
Neutron Star
Supernova
Black Hole
the lives of stars

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
Luminosity, L (L_{Sun})
Supergiants
Giants
Main Sequence
White Dwarfs
10^6
10^4
10^2
1
10^{-2}
10^{-4}
40 000
20 000
10 000
5000
2500
Temperature T_K