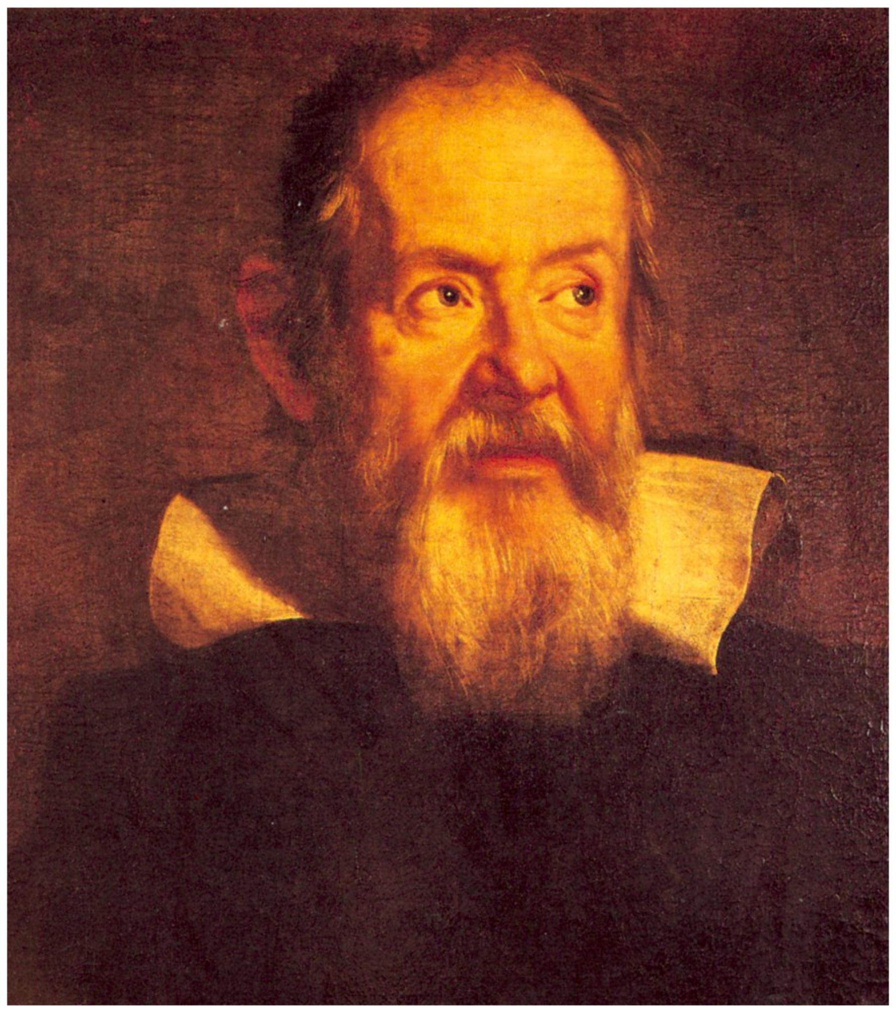
Light and Telescopes

Chapter Three

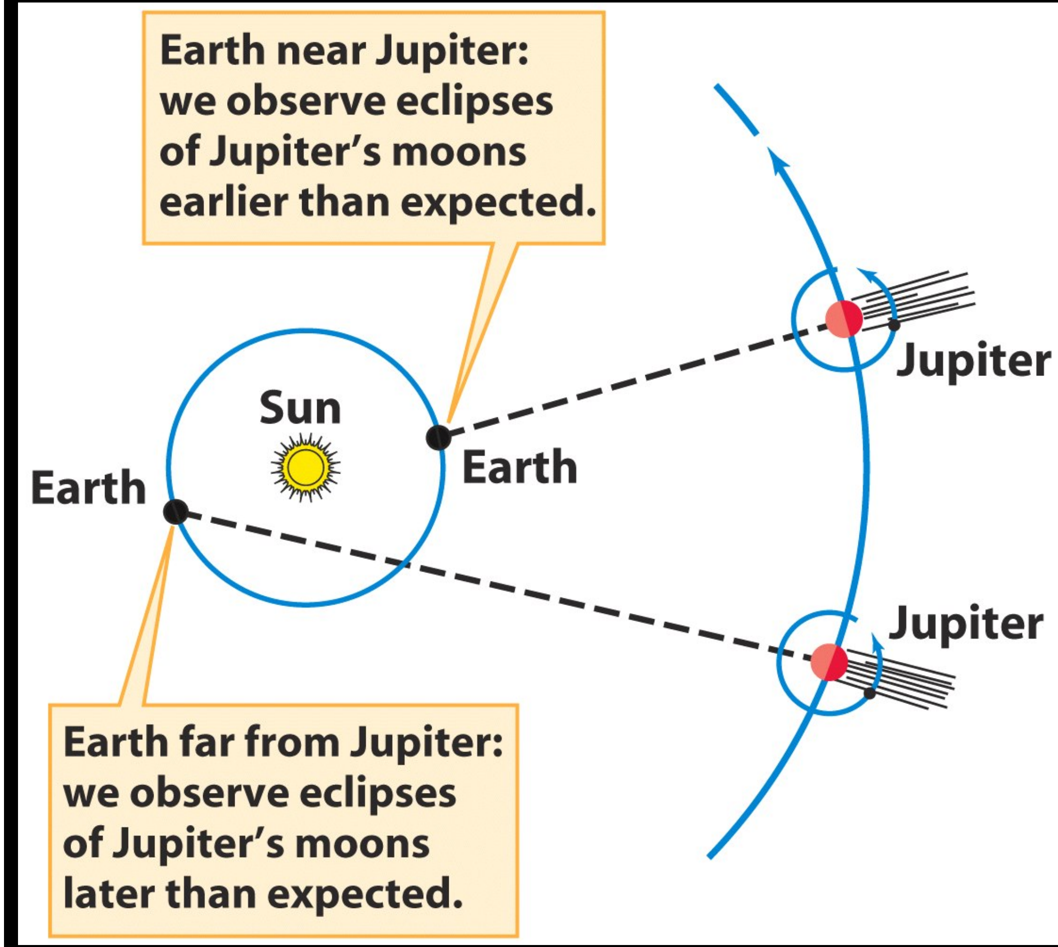
Determining the Speed of Light

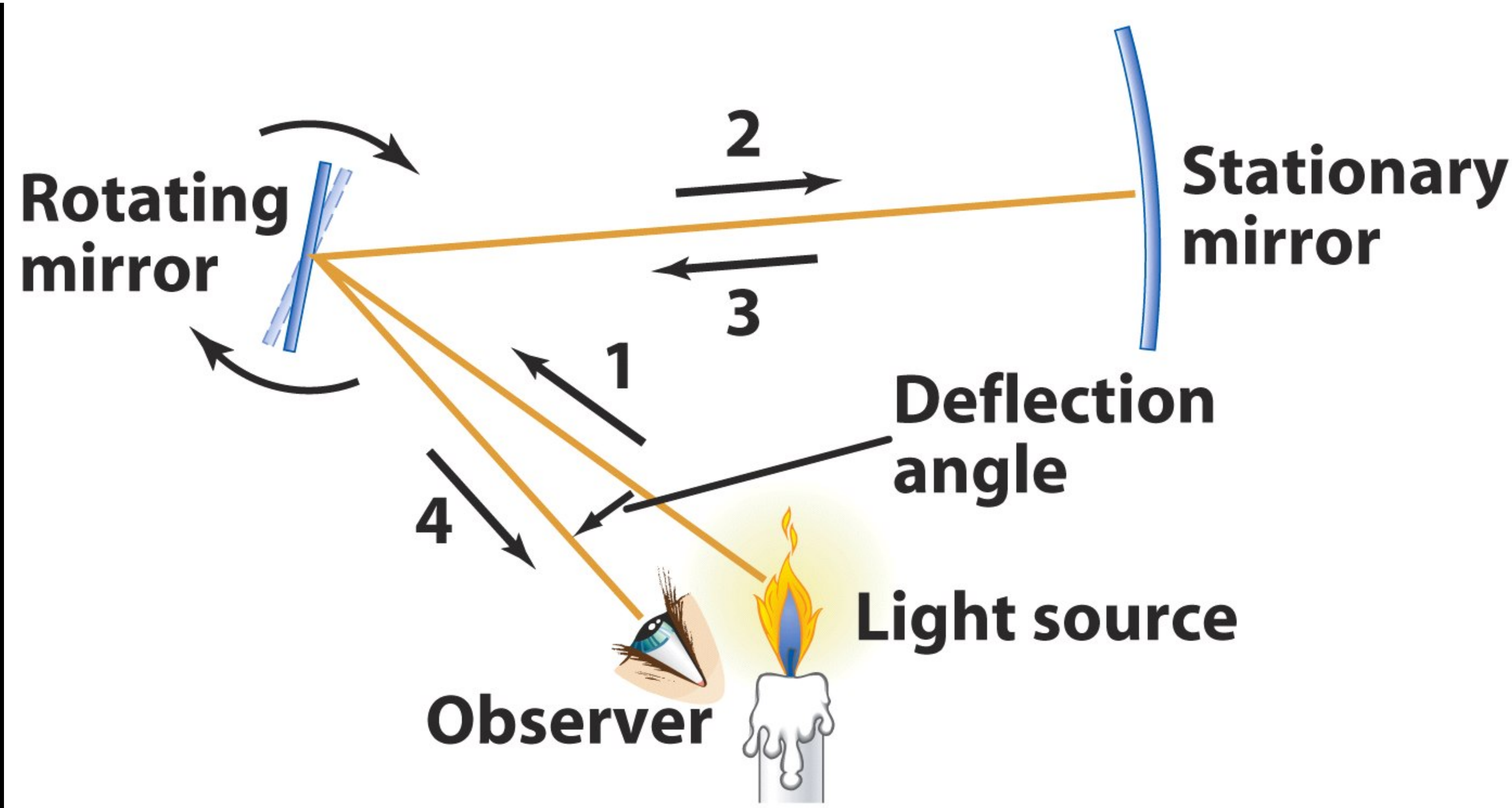
- Galileo tried unsuccessfully to determine the speed of light using an assistant with a lantern on a distant hilltop



Light travels through empty space at a speed of 300,000 km/s

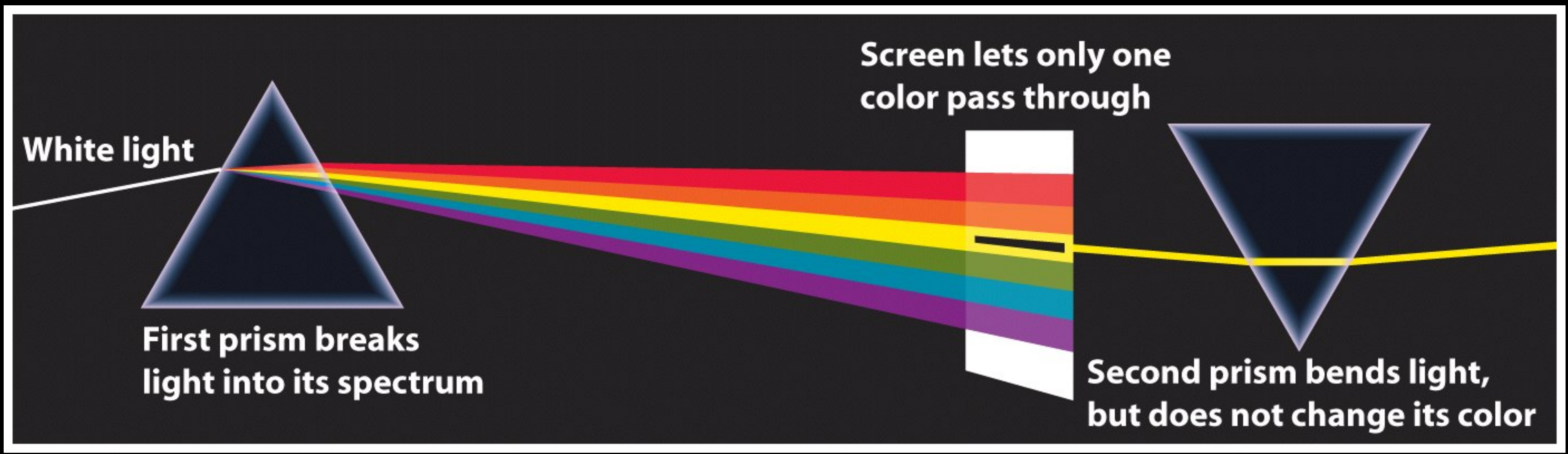
- In 1676, Danish astronomer Olaus Rømer discovered that the exact time of eclipses of Jupiter's moons depended on the distance of Jupiter to Earth
- This happens because it takes varying times for light to travel the varying distance between Earth and Jupiter
- Using v=d/t with a known distance, d, and a measured time, t, gave the speed, v, of the light



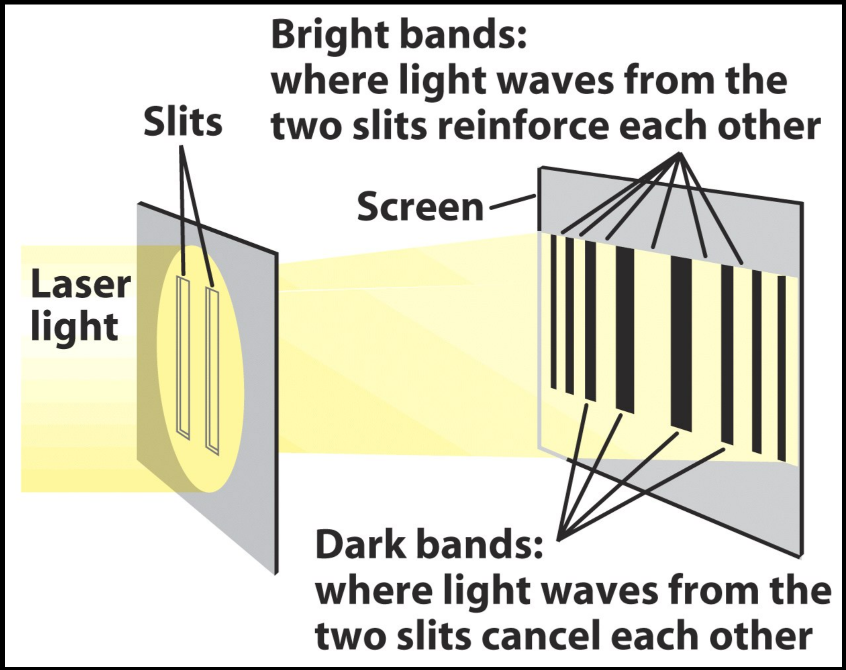


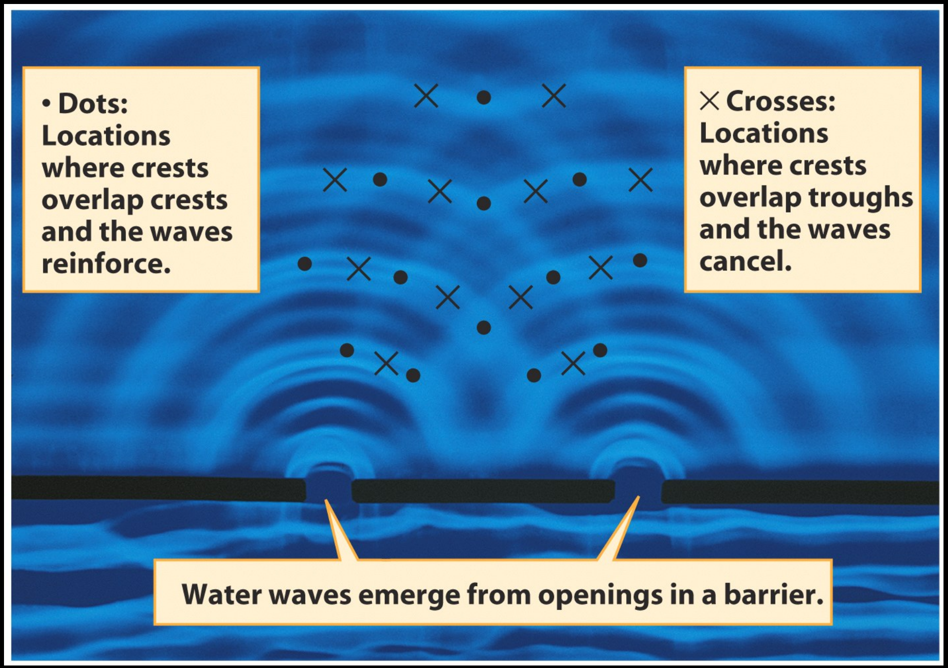
- In 1850 Fizeau and Foucalt also experimented with light by bouncing it off a rotating mirror and measuring time
- The light returned to its source at a slightly different position because the mirror has moved during the time light was traveling
- => c

Light is electromagnetic radiation and is characterized by its wavelength (λ)



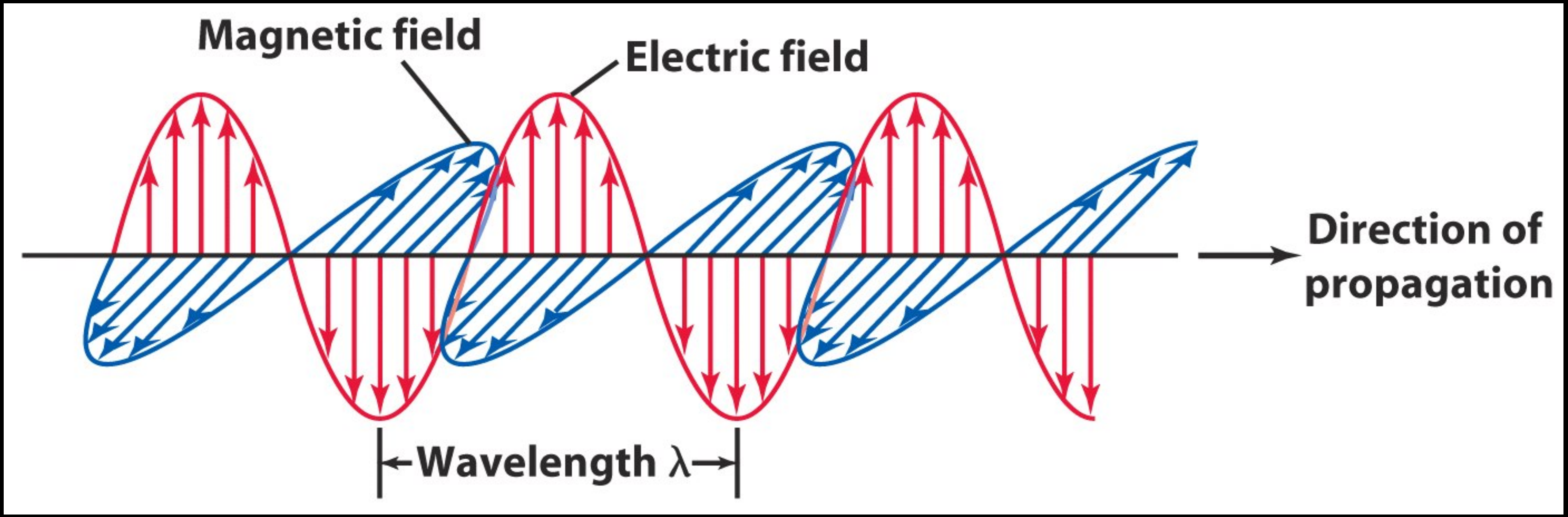
Light has properties of both waves and particles





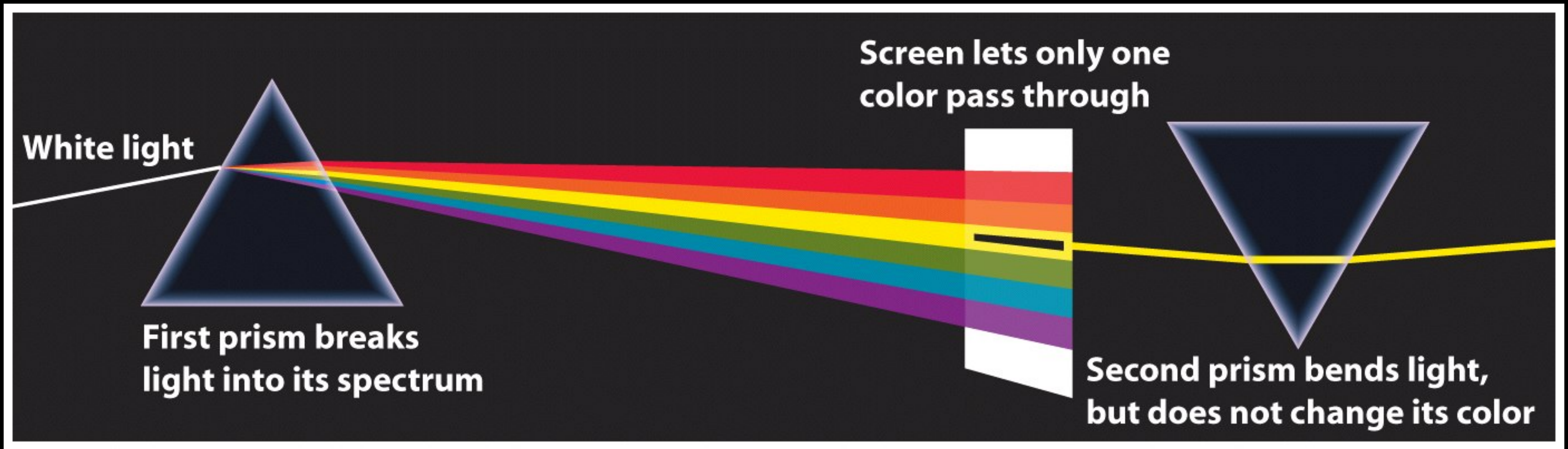
- Newton thought light was in the form of little packets of energy called photons and subsequent experiments with blackbody radiation indicate it has particle-like properties
- Young's Double-Slit Experiment indicated light behaved as a wave
- Light has a dual personality; it behaves as a stream of particle like photons, but each photon has wavelike properties

The Nature of Light



- In the 1860s, the Scottish mathematician and physicist James Clerk Maxwell succeeded in describing all the basic properties of electricity and magnetism in four equations
- This mathematical achievement demonstrated that electric and magnetic forces are really two aspects of the same phenomenon, which we now call **electromagnetism**
- http://www-groups.dcs.st-and.ac.uk/~history/PictDisplay/Maxwell.html

Wavelength and Frequency



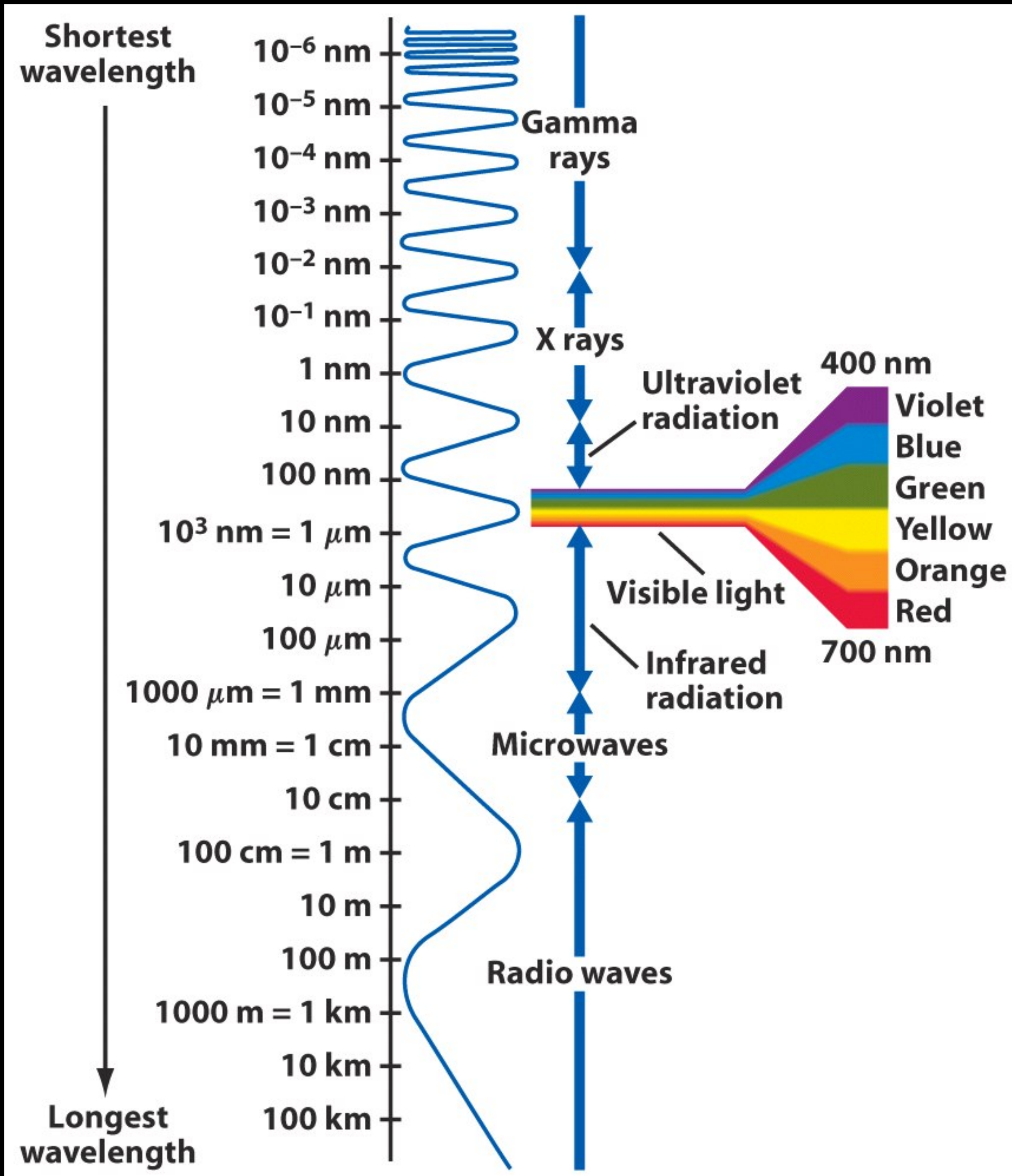
Frequency and wavelength of an electromagnetic wave

$$\nu = \frac{c}{\lambda}$$

ν = frequency of an electromagnetic wave (in Hz)

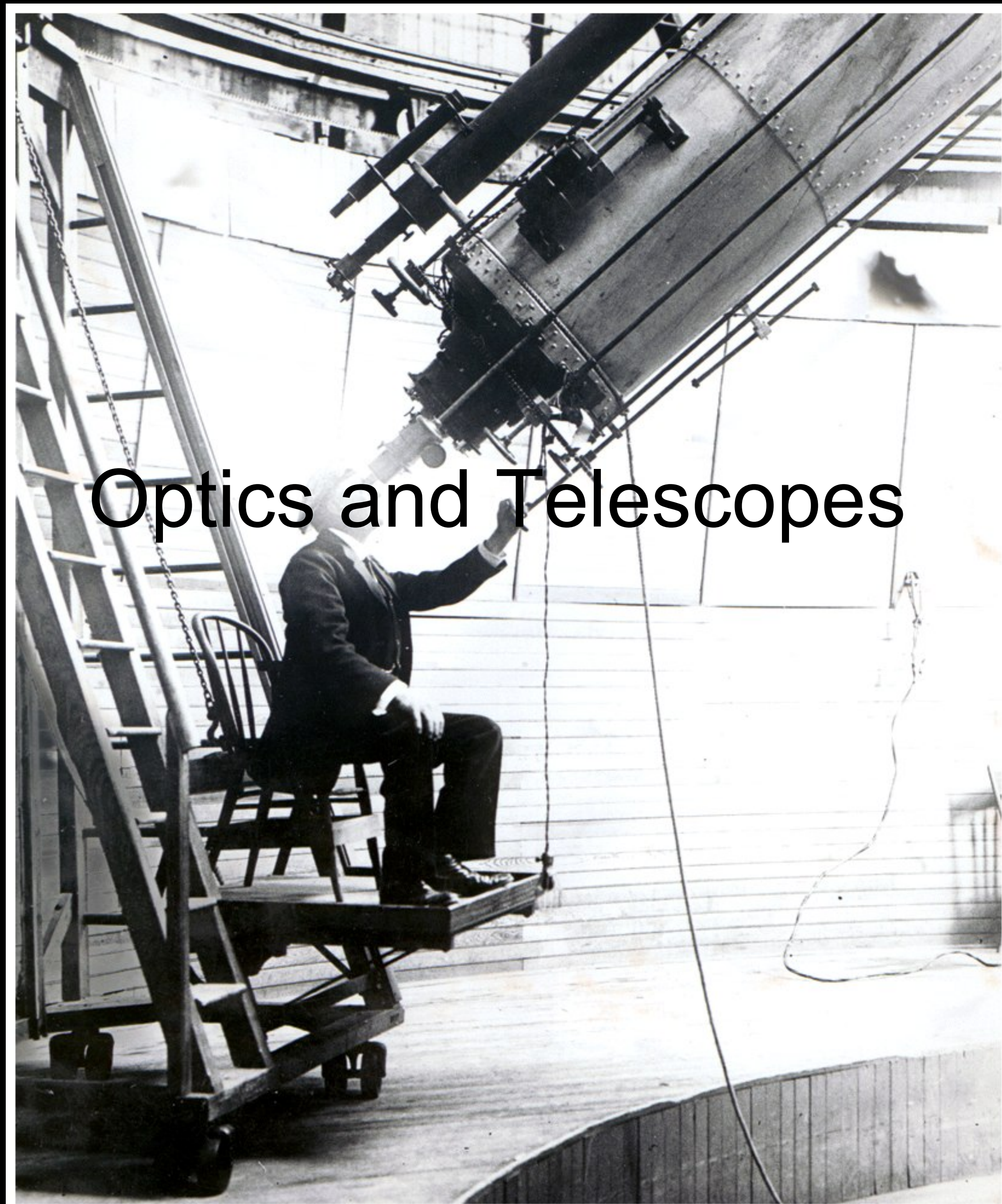
c = speed of light = 3×10^8 m/s

λ = wavelength of the wave (in meters)



- Photon energy
- $E=hc/\lambda = h\nu$
- $h=6.67 \cdot 10^{-34}$ Js (Planck's constant)

- Visible light falls in the 400 to 700 nm range

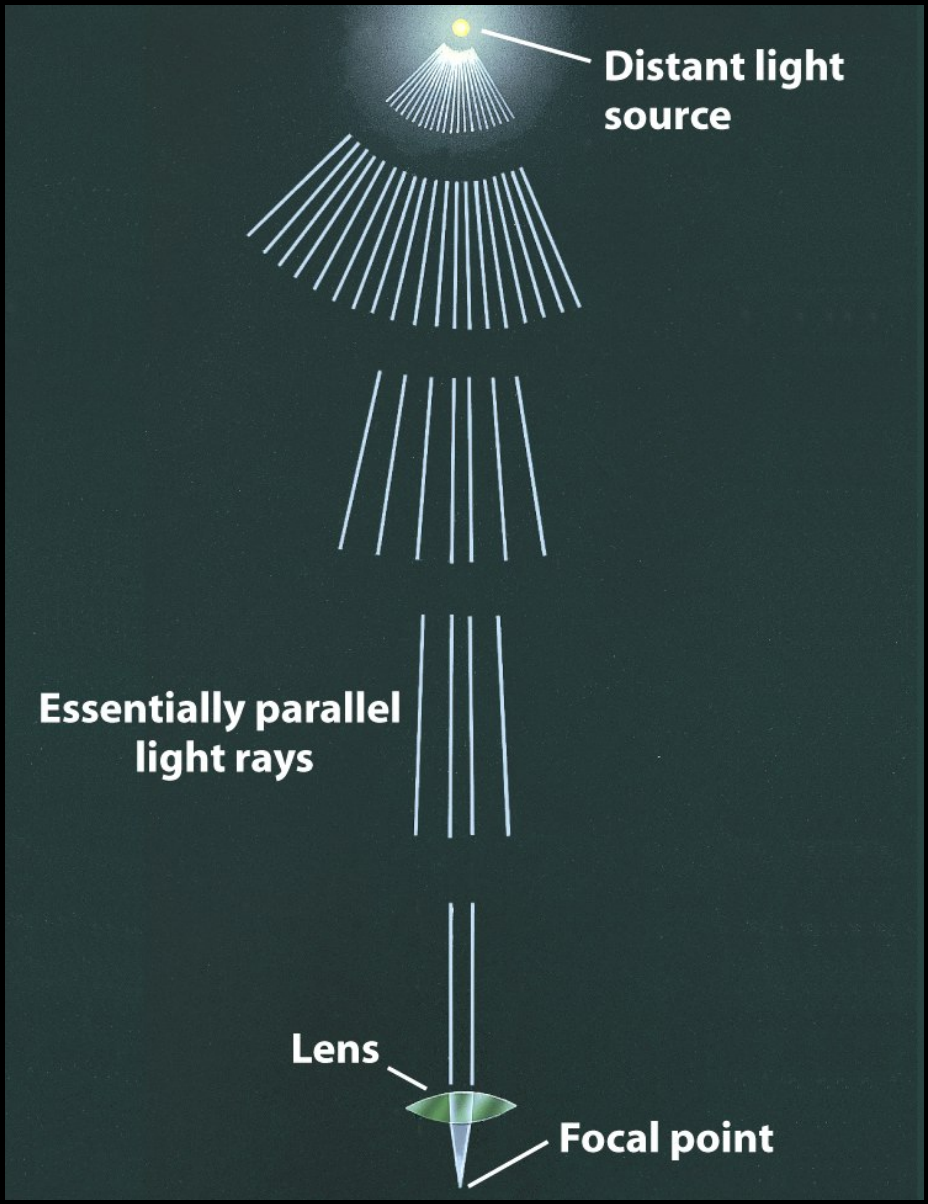


Optics and Telescopes

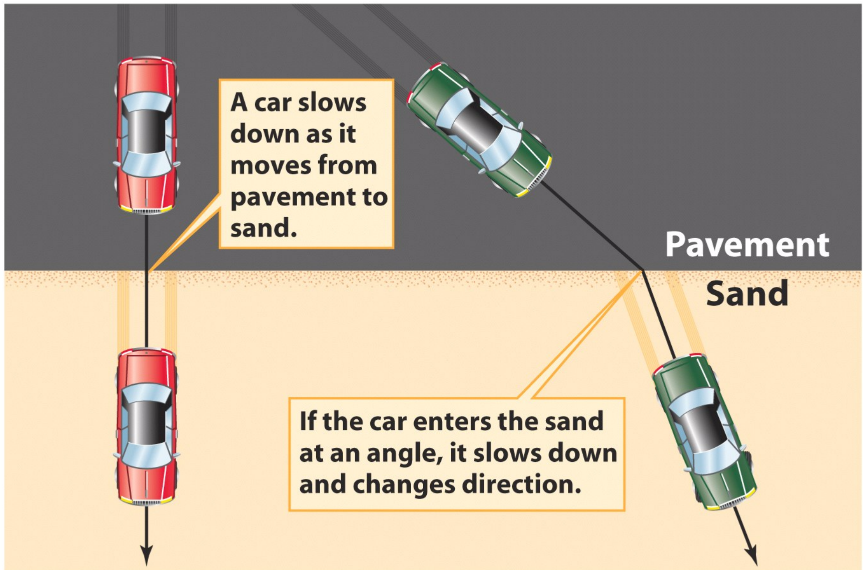
Telescopes

- The fundamental purpose of any telescope is to gather more light than the naked eye can
- In many cases telescopes are used to produce images far brighter and sharper than the eye alone could ever record

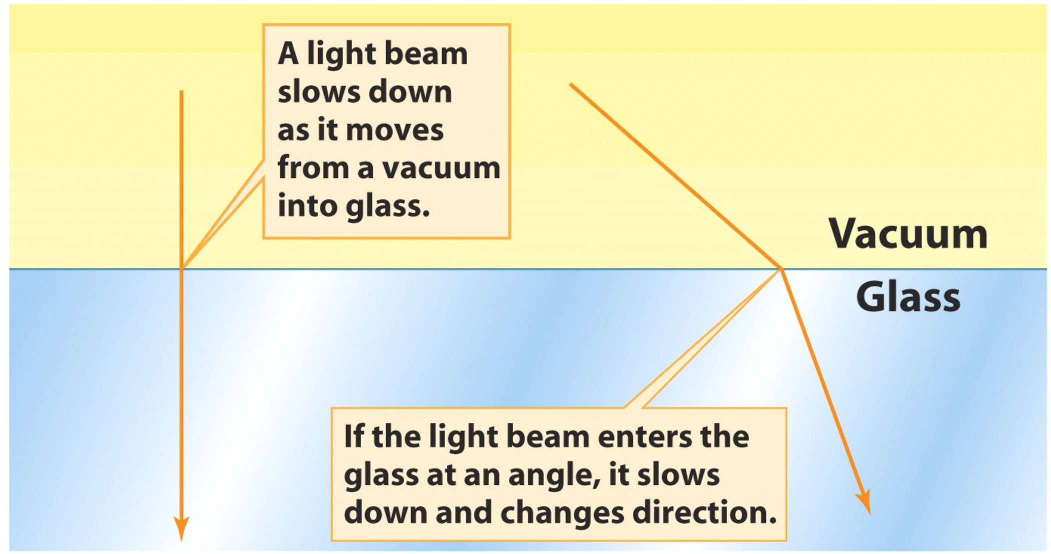
A refracting telescope uses a lens to concentrate incoming light at a focus



How Light Beams Behave

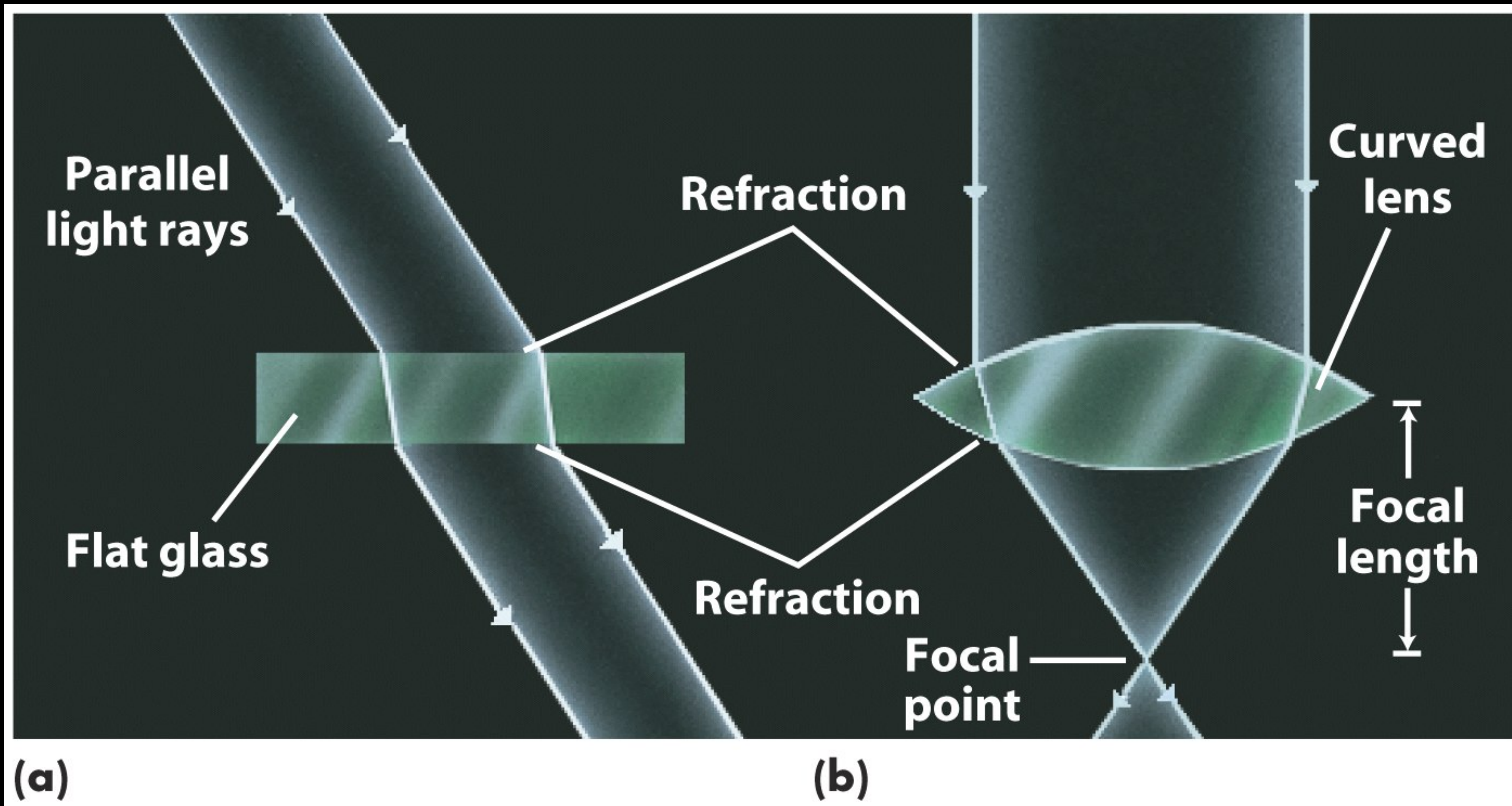


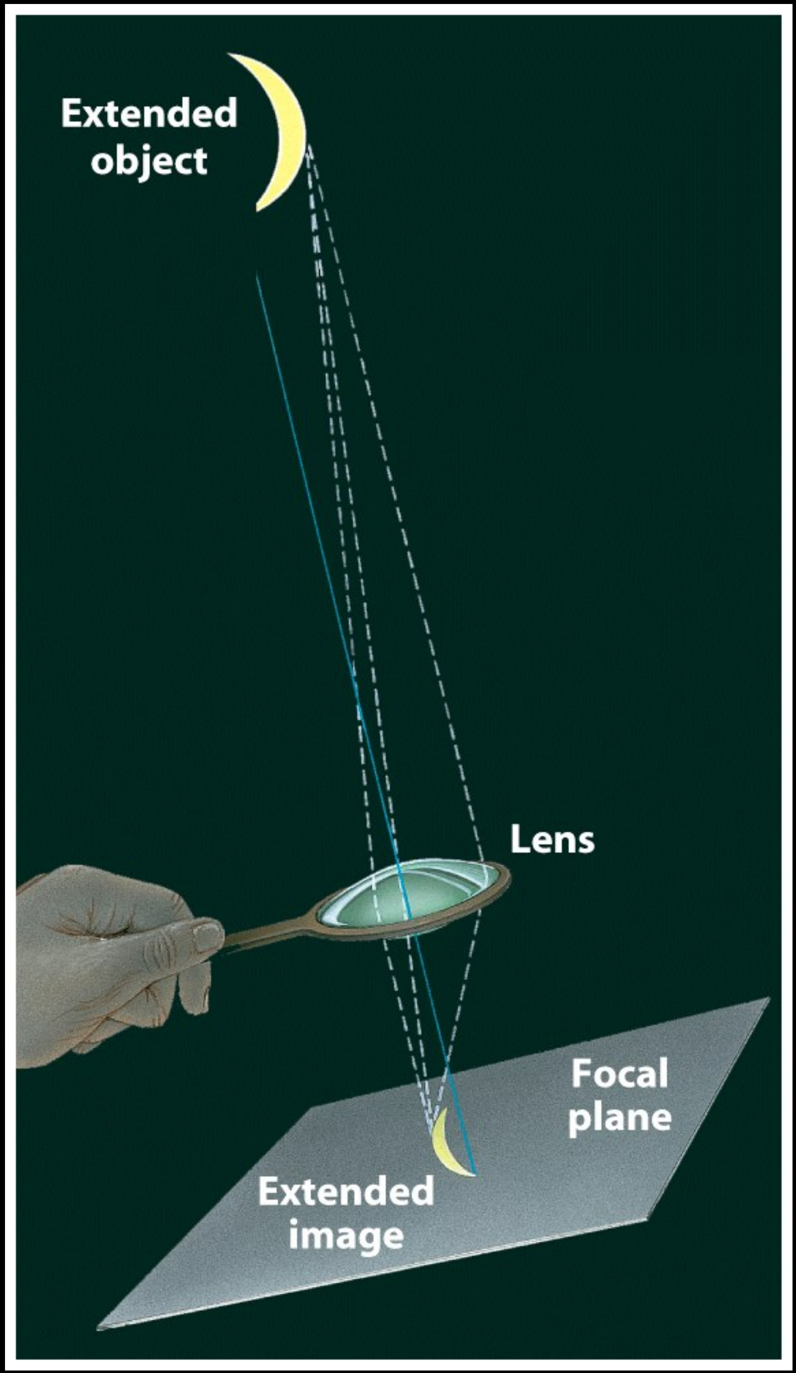
(a) How cars behave



(b) How light beams behave

- As a beam of light passes from one transparent medium into another—say, from air into glass, or from glass back into air—the direction of the light can change
- This phenomenon, called **refraction,** is caused by the change in the speed of light


Parallel
light rays
Refraction
Curved
lens
Flat glass
Refraction
Focal
length
Focal
point
(a)
(b)


Extended
object
Lens
Focal
plane
Extended
image

Powers of telescopes

- Magnification
- Ligth gathering power
- Resolving power

Refracting Telescope and Magnification

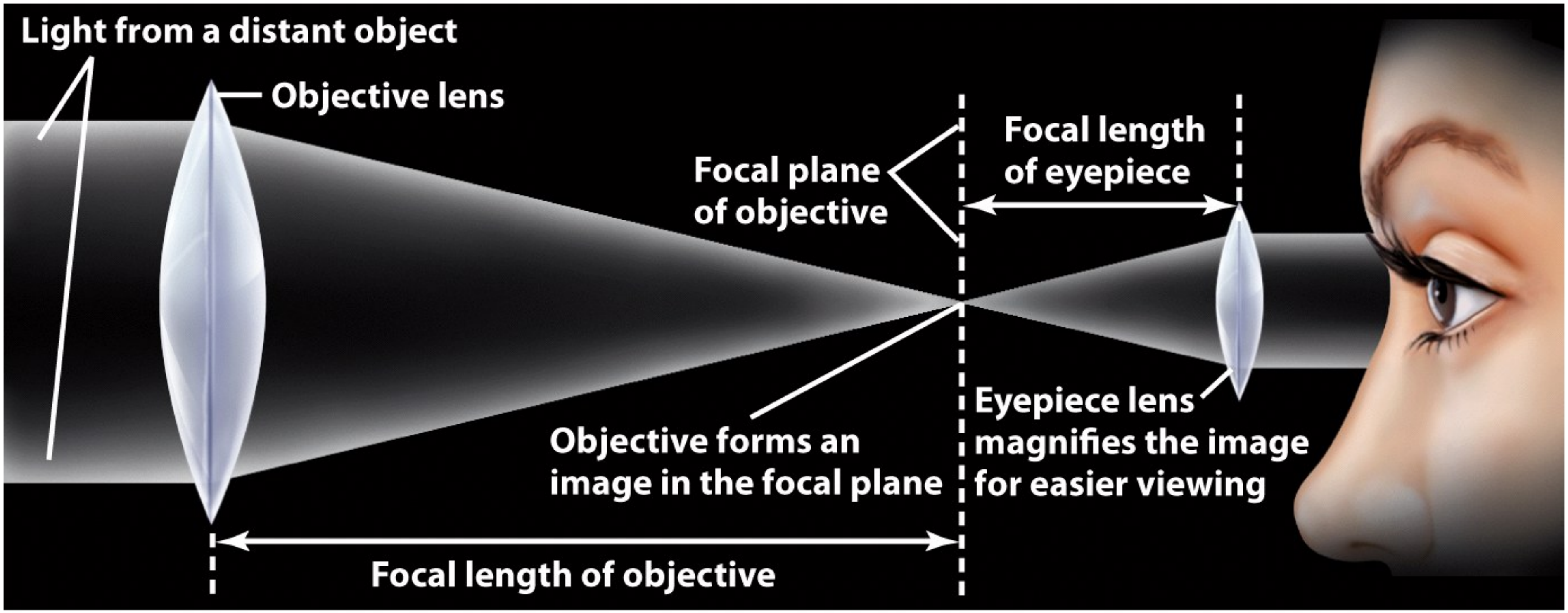


Figure 3-19
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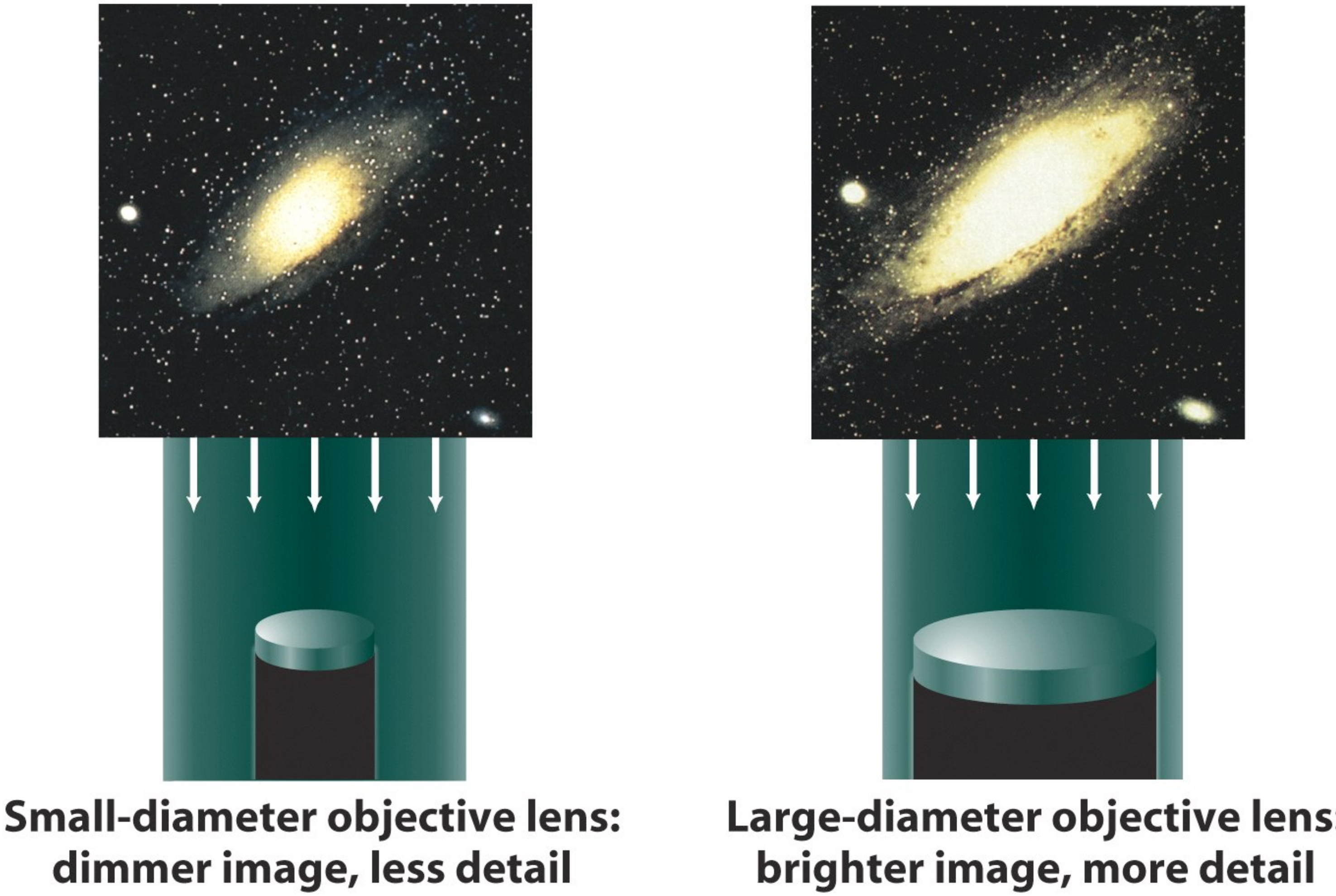
Magnification, m, is given by the ratio between the focal length of objective, f_0, and the eyepiece focal length, f_e.

$m = f_0 / f_e$

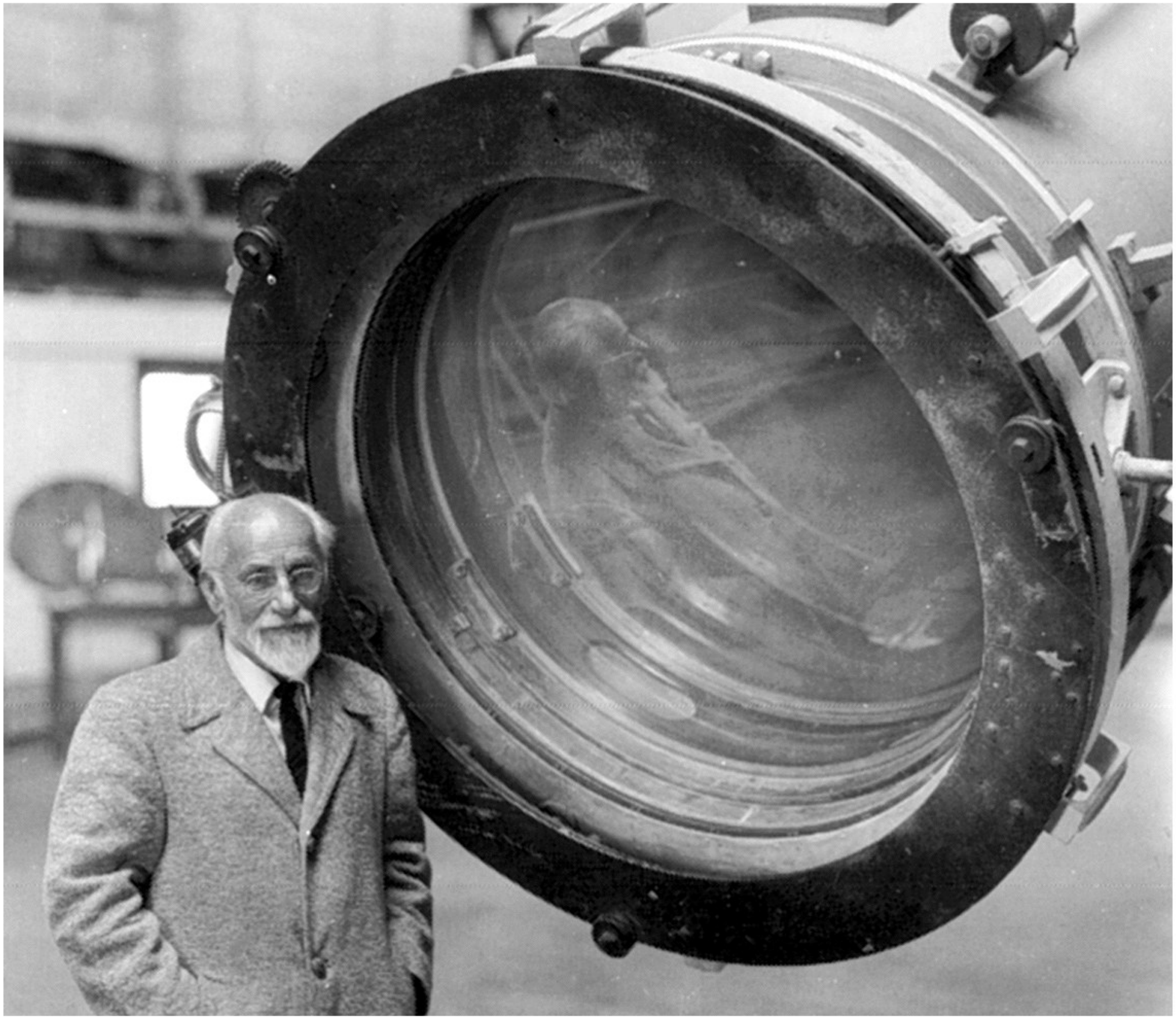
Example: $f_0 = 4$ m , $f_e = 1$ cm => m=400

Light Gathering Power



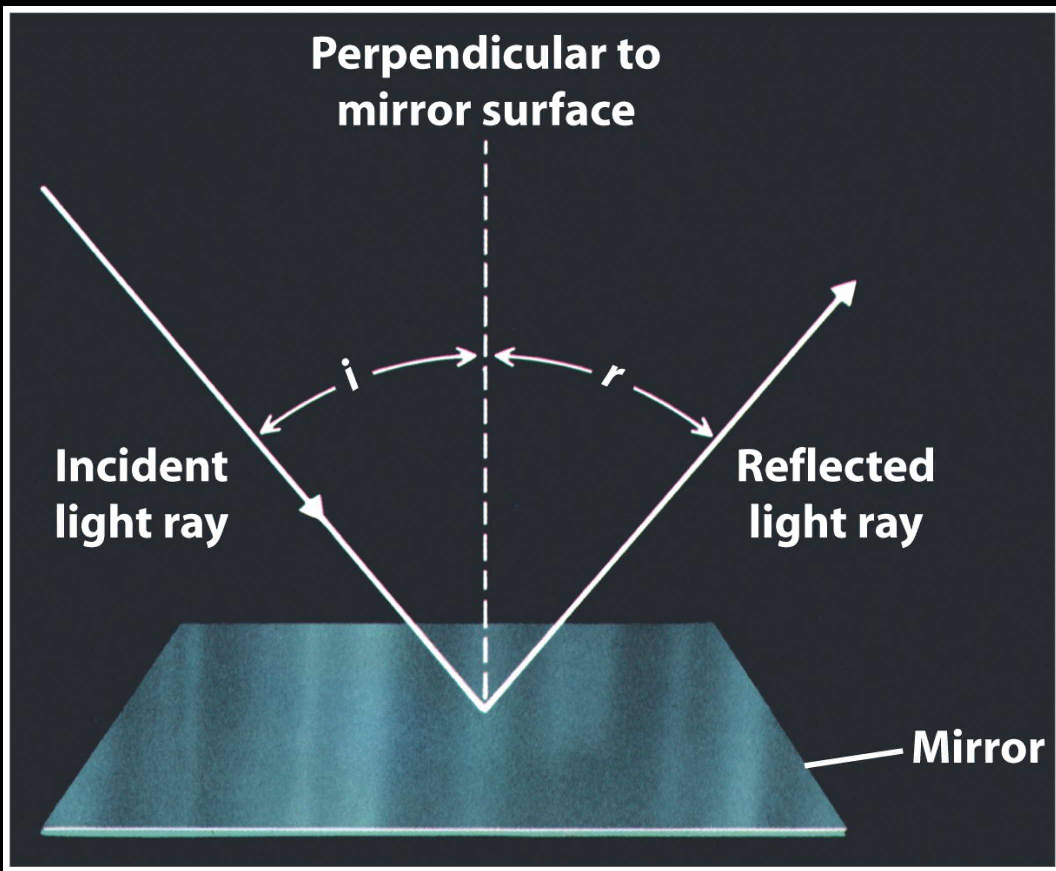
The **light-gathering power** of a telescope is directly proportional to the area of the objective lens, which in turn is proportional to the square of the lens diameter

Yerkes Observatory Refractor

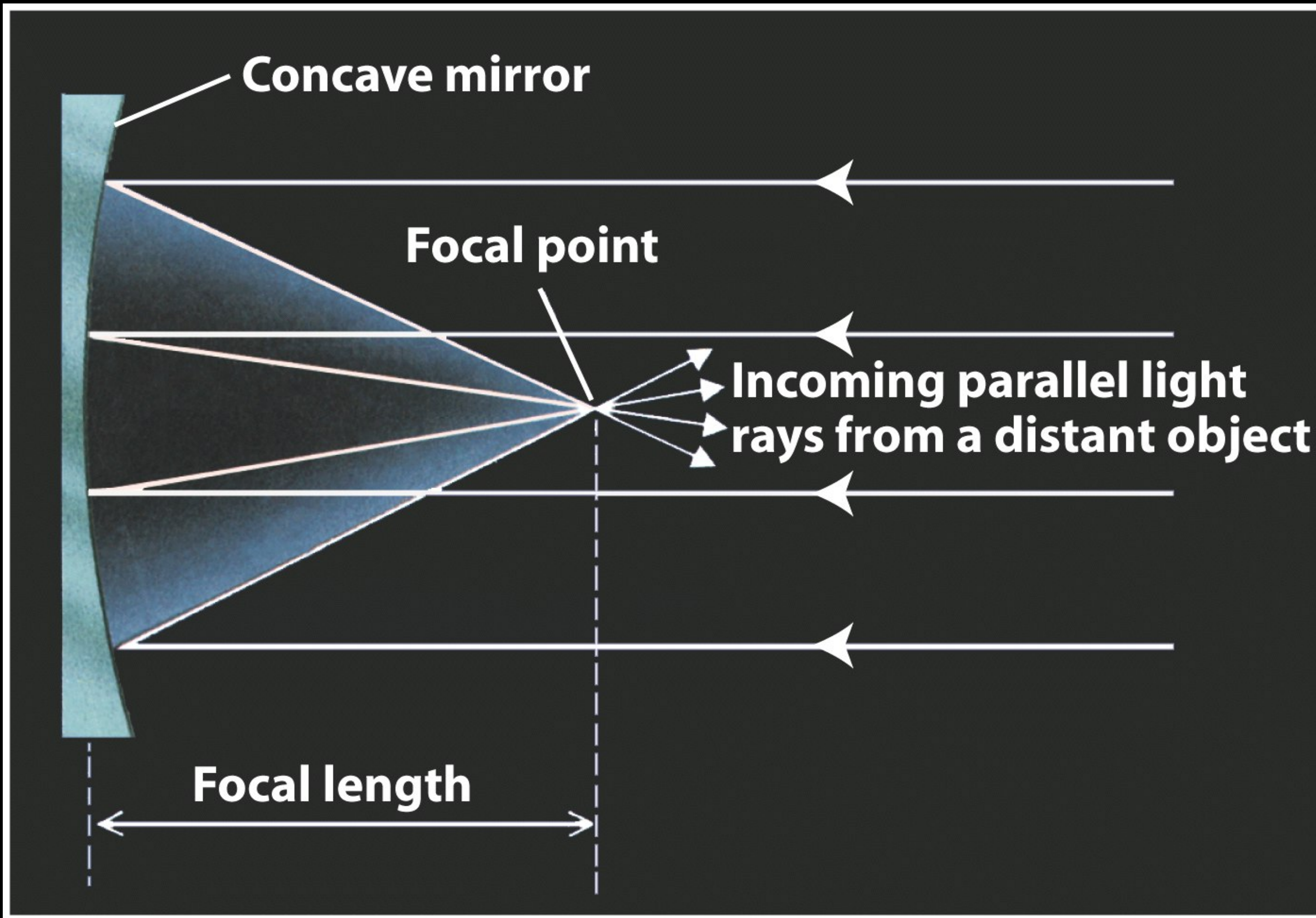


Glass impurities, chromatic aberration, opacity to certain wavelengths, and structural difficulties make it inadvisable to build extremely large refractors

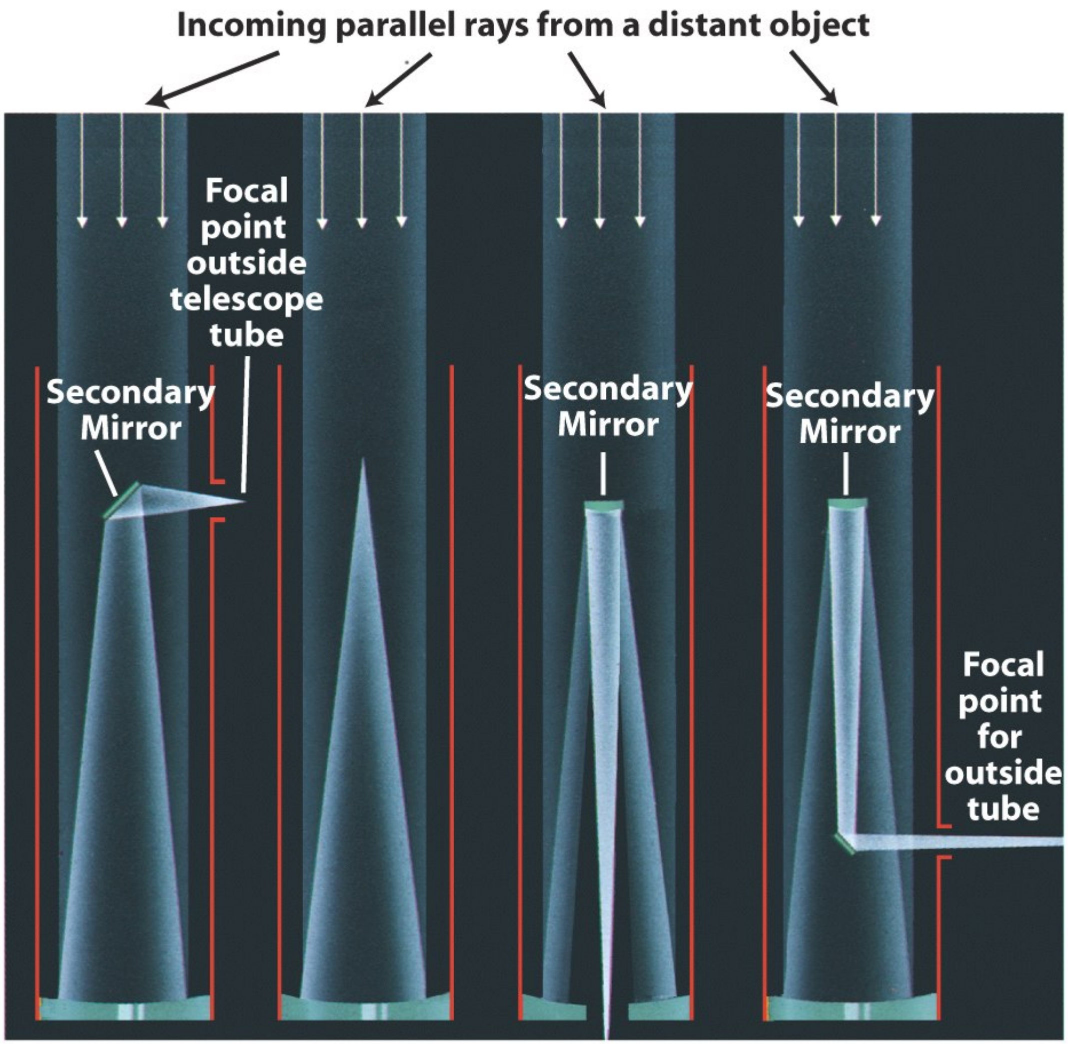
A reflecting telescope uses a mirror to concentrate incoming light at a focus



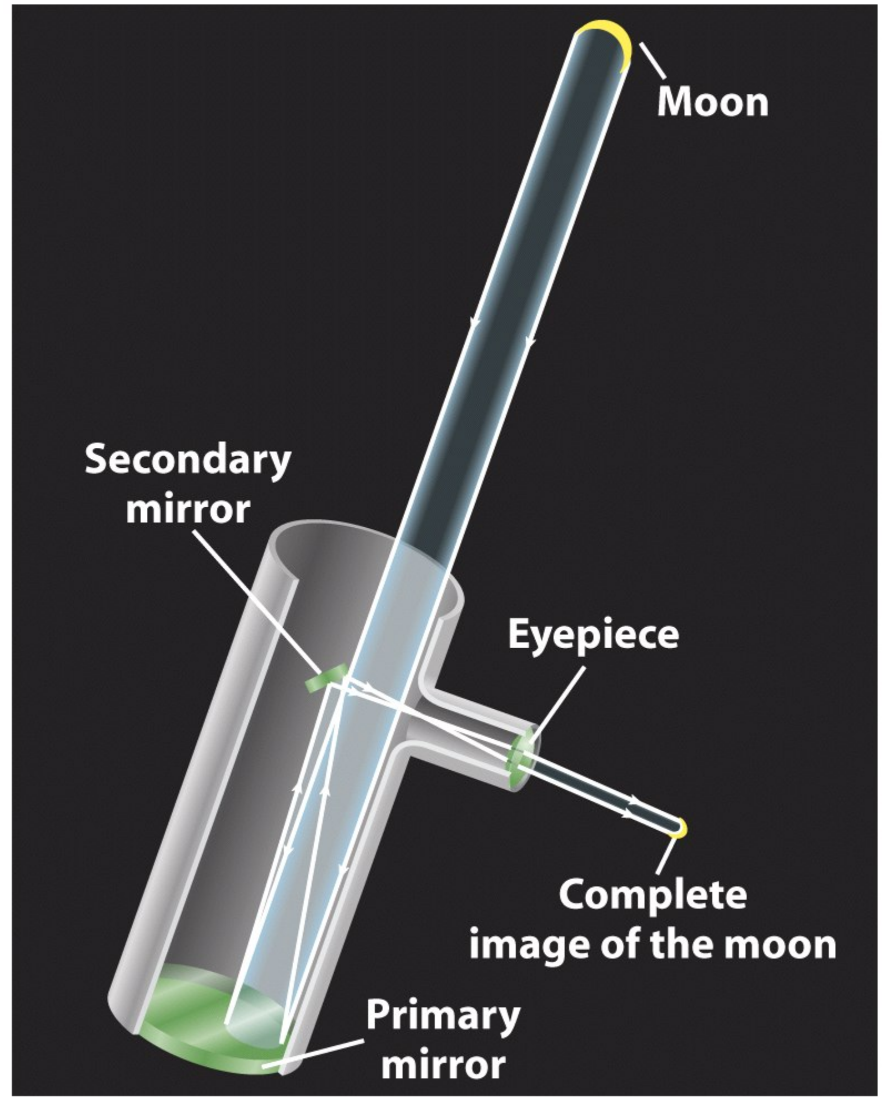
- Reflecting telescopes, or reflectors, produce images by reflecting light rays to a focus point from curved mirrors.
- Reflectors are not subject to most of the problems that limit the useful size of refractors.


Concave mirror
Focal point
Incoming parallel light rays from a distant object
Focal length

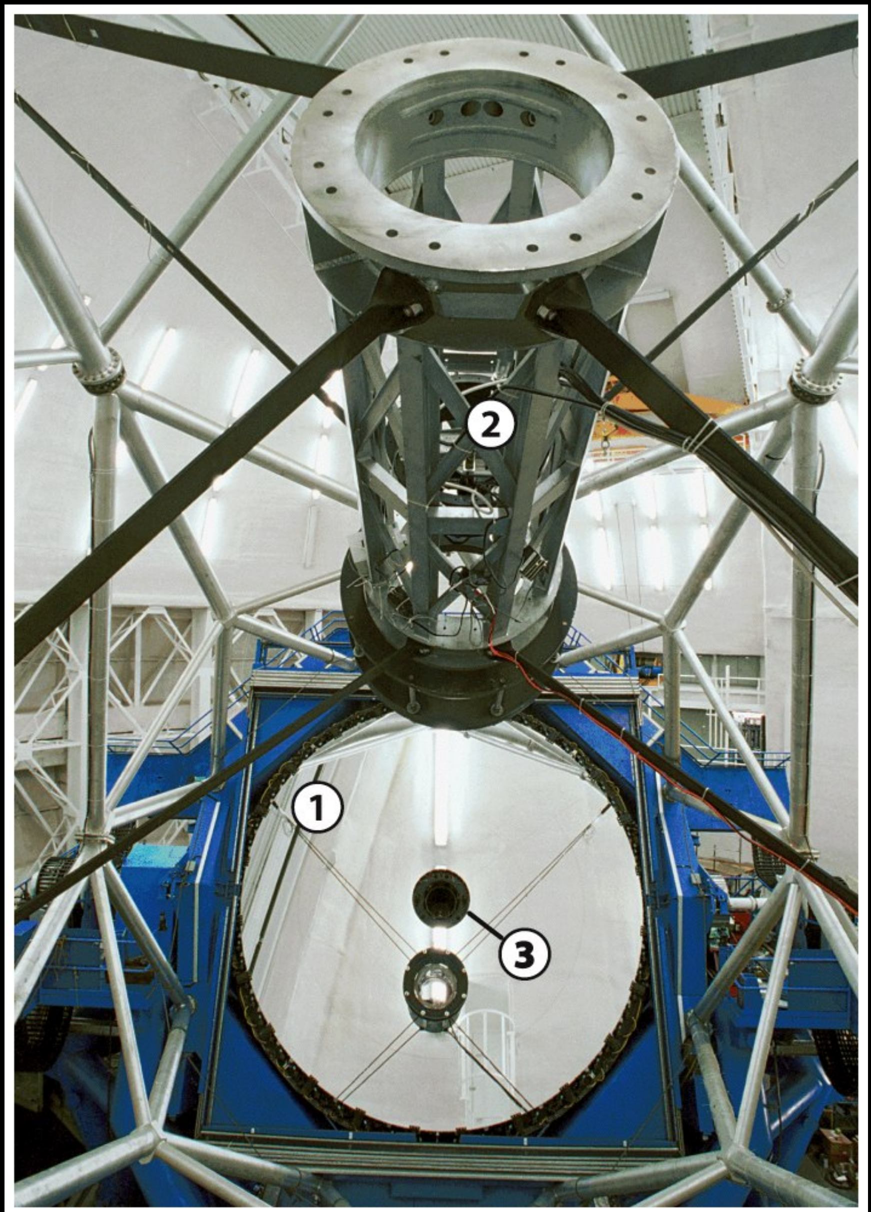
Reflecting Telescopes



(a) Newtonian focus (b) Prime focus (c) Cassegrain focus (d) Coudé focus



Gemini North Telescope



1. The 8.1-meter objective mirror
2. The 1.0-meter secondary mirror
3. The objective mirror

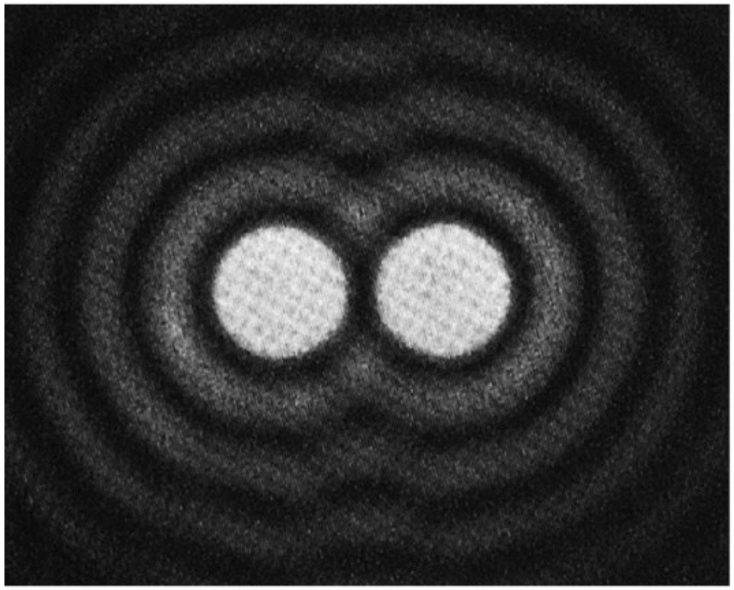
table 6-1 The World's Largest Optical Telescopes

Telescope	Location	Year of completion	Mirror diameter (m)
Gran Telescopio Canarias	La Palma, Canary Islands, Spain	2004	10.4
Keck II	Mauna Kea, Hawaii	1996	10.0
Keck I	Mauna Kea, Hawaii	1993	10.0
Hobby-Eberly Telescope	McDonald Observatory, Texas	1998	11.0*
South African Large Telescope	Sutherland, South Africa	2004	9.2
Large Binocular Telescope	Mount Graham, Arizona	2004–05	Two 8.4
Subaru	Mauna Kea, Hawaii	1999	8.3
VLT UT 1–Antu	Cerro Paranal, Chile	1998	8.2
VLT UT 2–Kueyen	Cerro Paranal, Chile	1999	8.2
VLT UT 3–Melipal	Cerro Paranal, Chile	2000	8.2
VLT UT 4–Yepun	Cerro Paranal, Chile	2000	8.2
Gemini North (Gillett)	Mauna Kea, Hawaii	1999	8.1
Gemini South	Cerro Pachón, Chile	2000	8.1

Note: *The objective mirror of the Hobby-Eberly Telescope is 11.0 m in diameter, but in operation only an area of 9.2 m in diameter is used to collect light.*

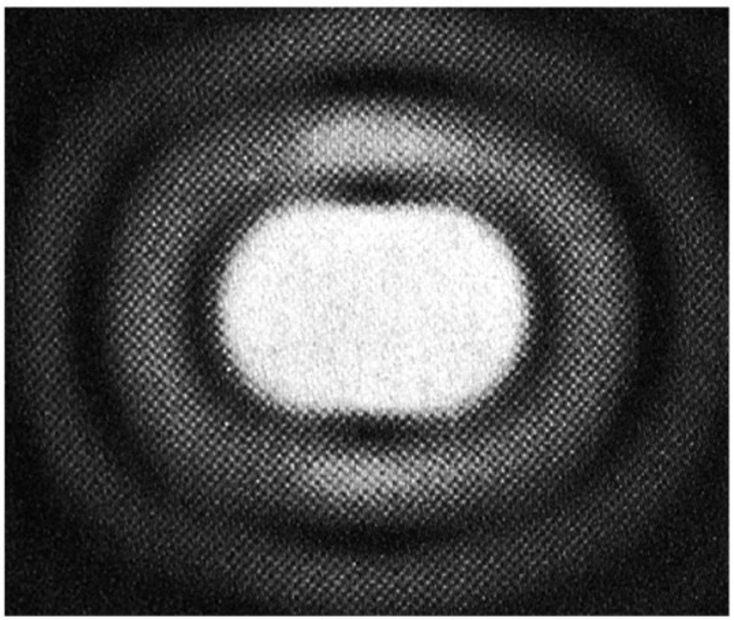
Telescope images are degraded by the blurring effects of the atmosphere and by light pollution

- **Angular Resolution**: A telescope's angular resolution, which indicates ability to see fine details, is limited by many factors.
- Diffraction is an intrinsic property of light waves.
- Its effects can be minimized by using a larger objective lens or mirror and/or a smaller wavelength of observed light.



Two light sources with angular separation greater than angular resolution of telescope: Two sources easily distinguished

(a)



Light sources moved closer so that angular separation equals angular resolution of telescope: Just barely possible to tell that there are two sources

(b)

Diffraction limited angular resolution

$$\Theta = 2.5 \times 10^5 \lambda / D$$

where Θ is the angular resolution in seconds of arc

λ is the wavelength of light in metres

D is the diameter (of mirror or lens) in metres

What is the diffraction-limited angular resolution of our 1-m telescope?

Planewave Instruments

What is the diffraction-limited angular resolution of our 1-m telescope?

Planewave Instruments

$\Theta = 2.5 \times 10^5 \lambda / D$

$= 2.5 \times 10^5\ 500 \times 10^{-9}/1$

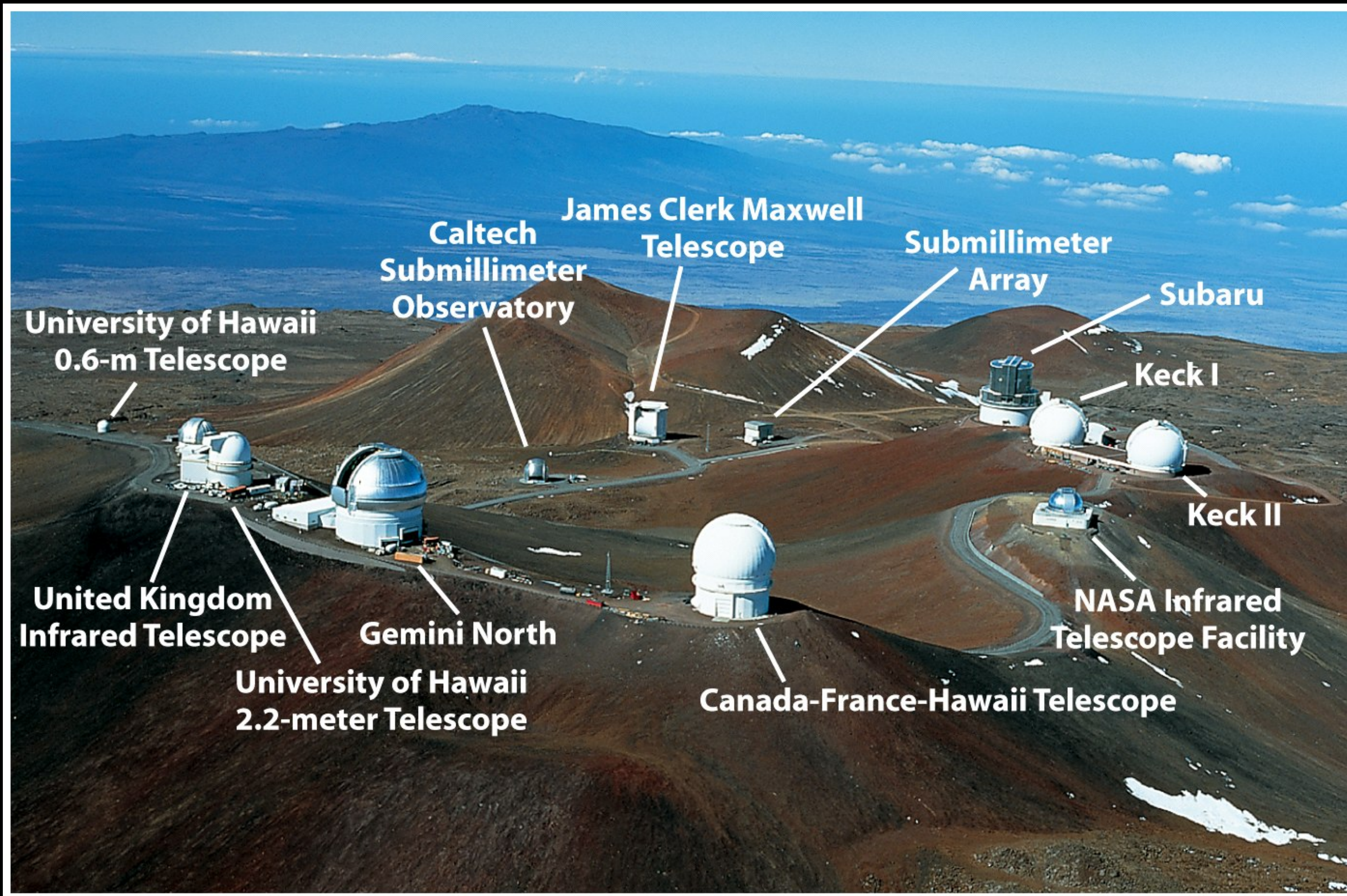
$= 0.125$ arcsec

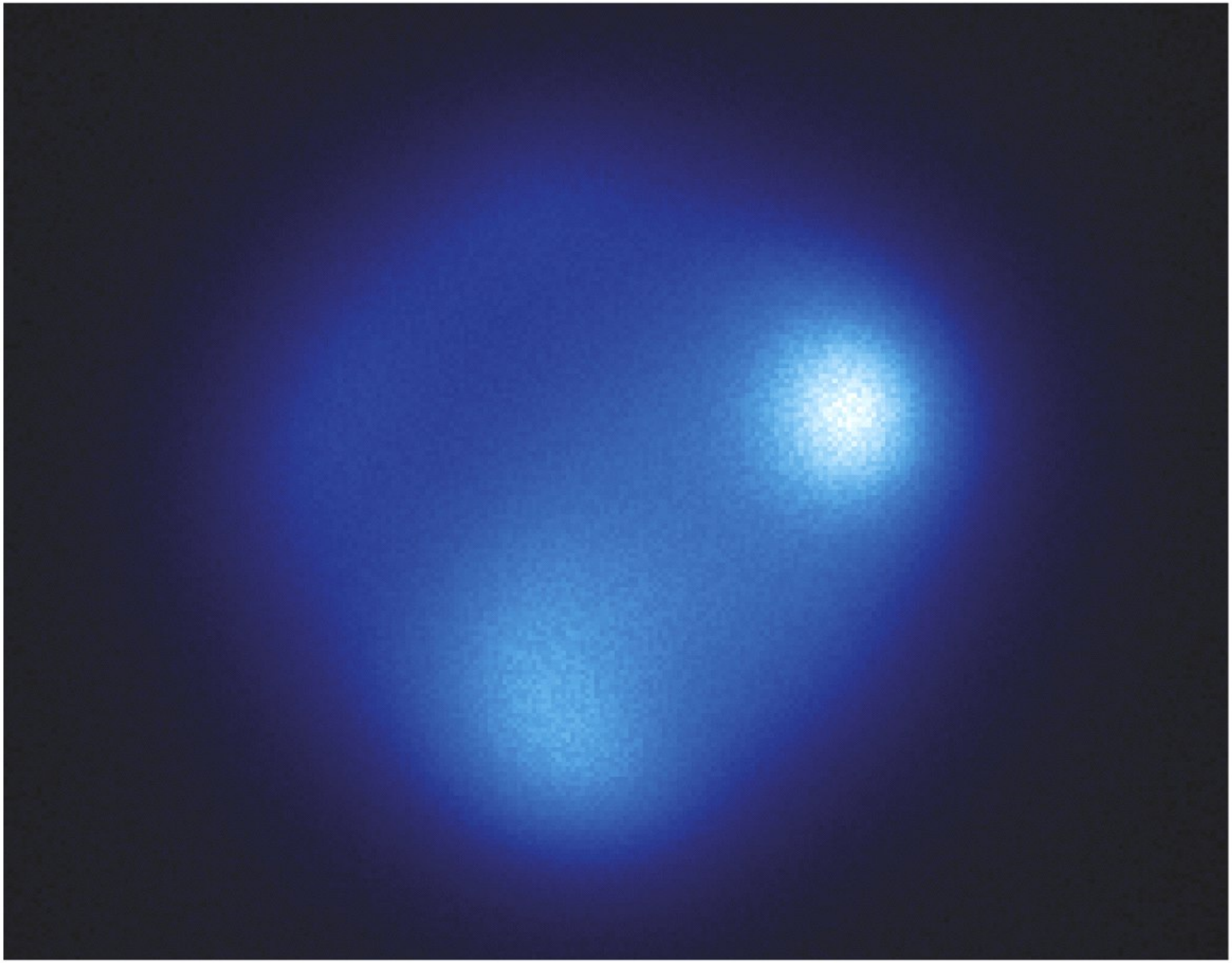
Powers of telescopes

- Magnification $m = f_0/f_e$
- Light gathering power $LGP \propto D^2$
- Resolving power $\Theta = 2.5 \times 10^5 \lambda / D$

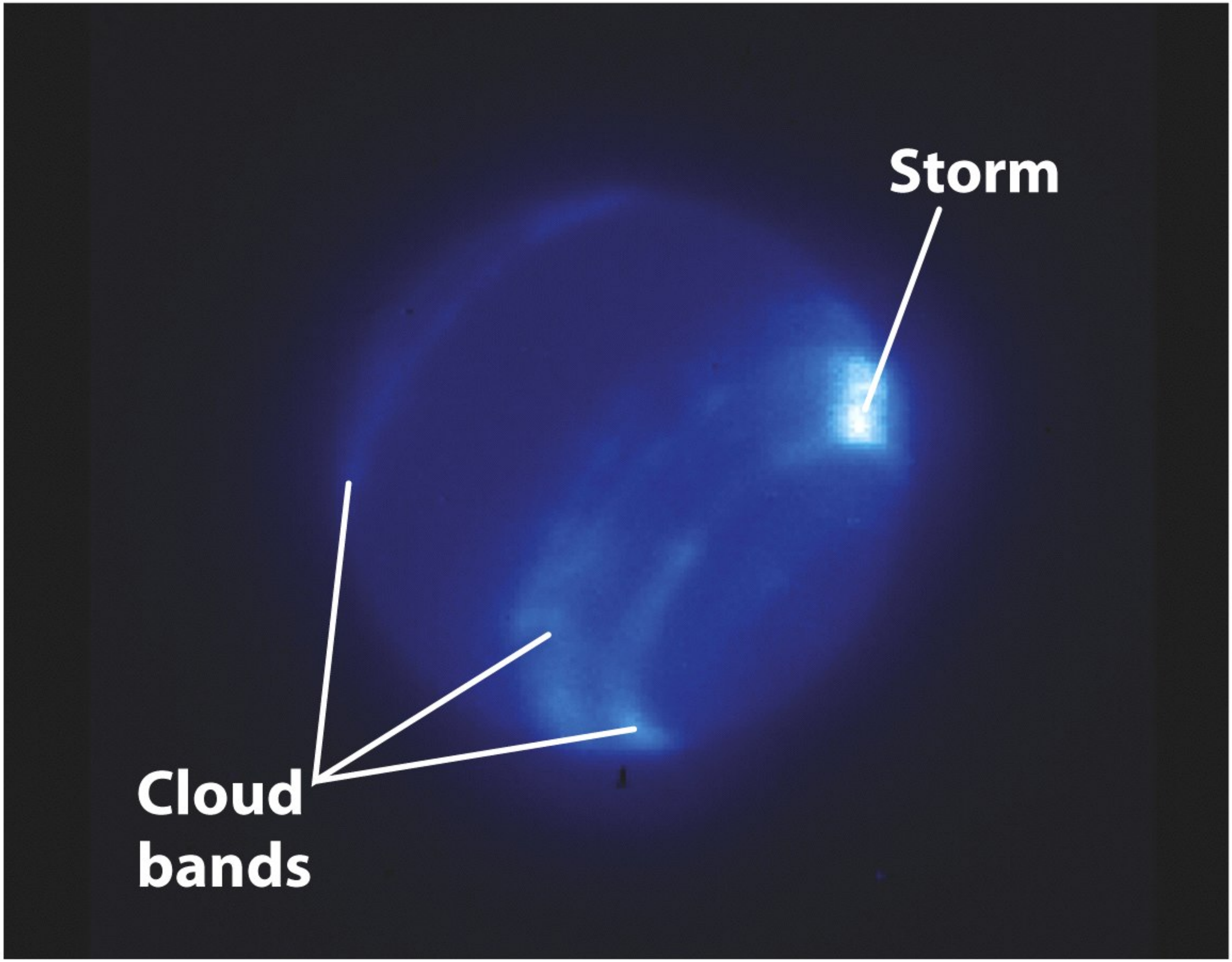
Telescope images (continued)

- The blurring effects (seeing) of atmospheric turbulence can be minimized by placing the telescope atop a tall mountain with very smooth air.
- They can be dramatically reduced by the use of adaptive optics and can be eliminated entirely by placing the telescope in orbit


James Clerk Maxwell Telescope
Caltech Submillimeter Observatory
Submillimeter Array
Subaru
University of Hawaii 0.6-m Telescope
Keck I
Keck II
United Kingdom Infrared Telescope
Gemini North
University of Hawaii 2.2-meter Telescope
NASA Infrared Telescope Facility
Canada-France-Hawaii Telescope

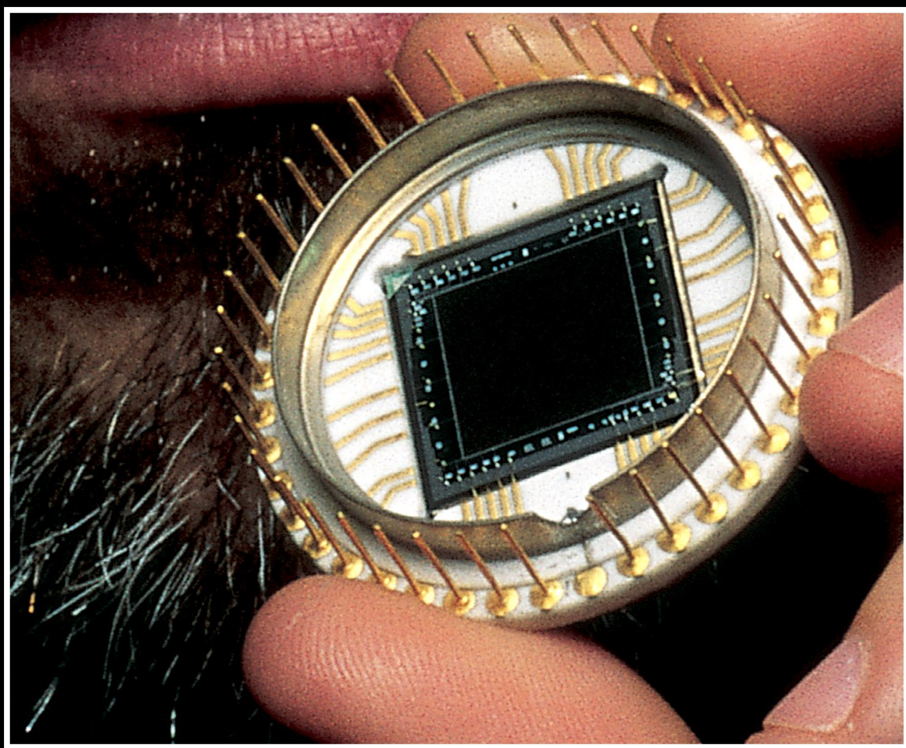


(a) Neptune viewed without adaptive optics

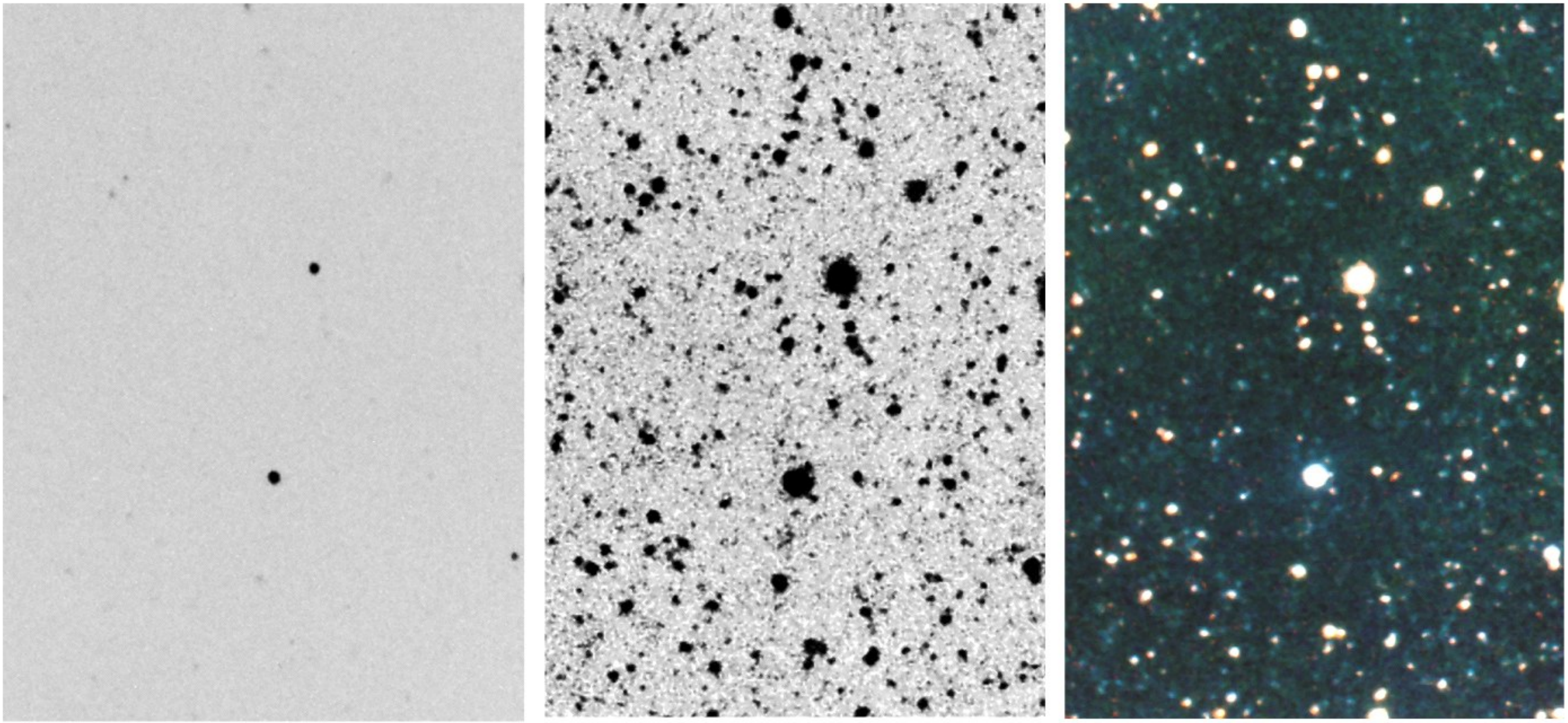


(b) Neptune viewed with adaptive optics

An electronic device is commonly used to record the image at a telescope's focus

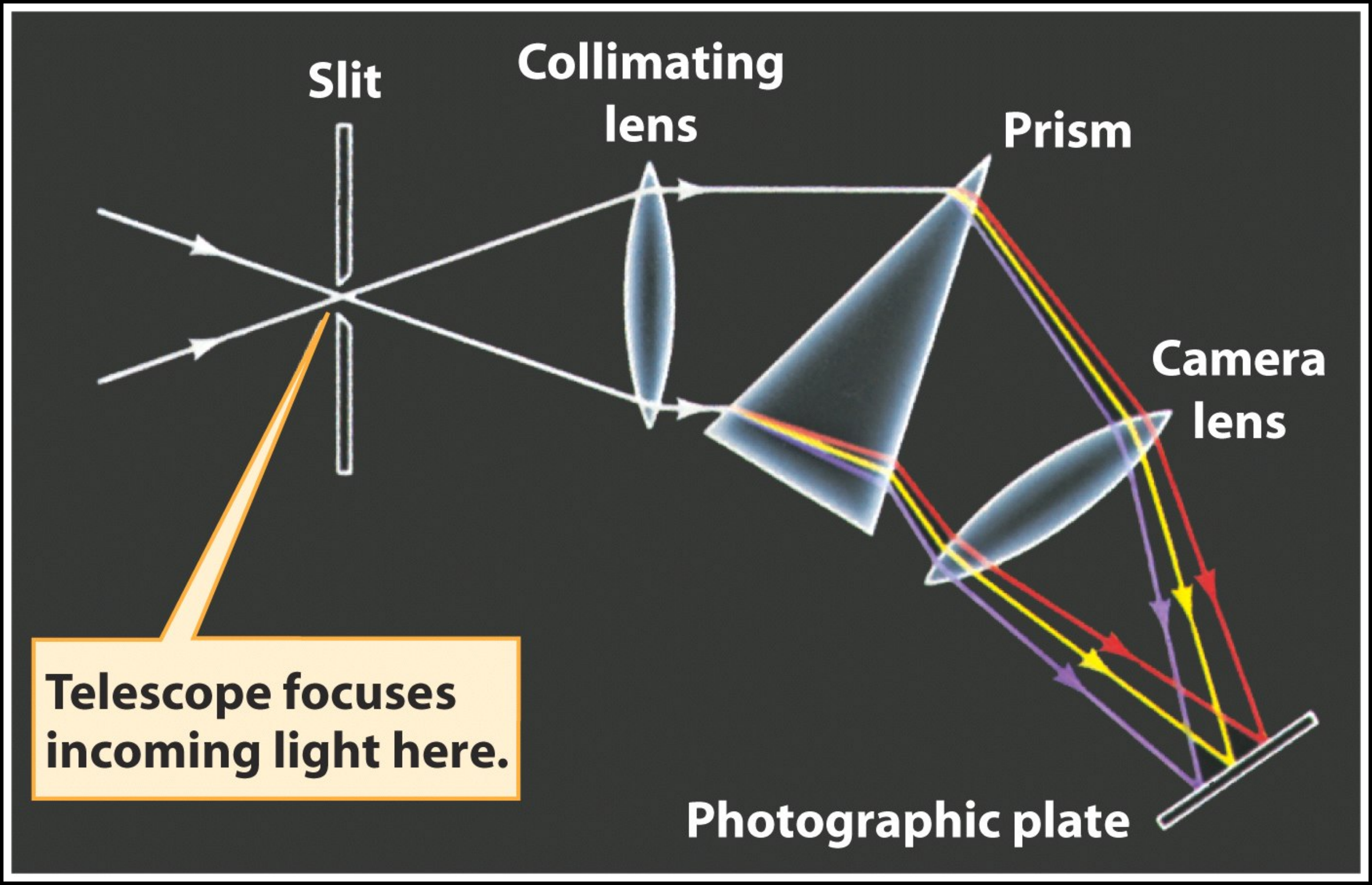


- Sensitive light detectors called charge coupled devices (CCDs) are often used at a telescope's focus to record faint images.

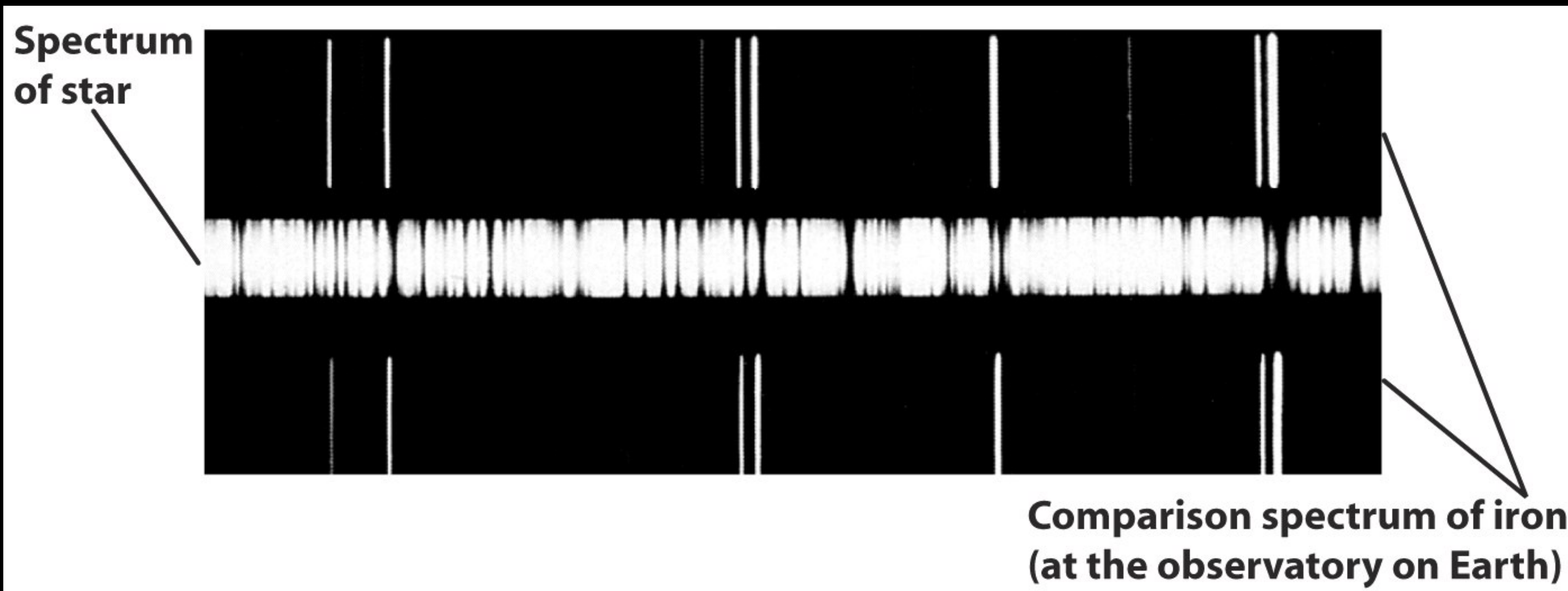


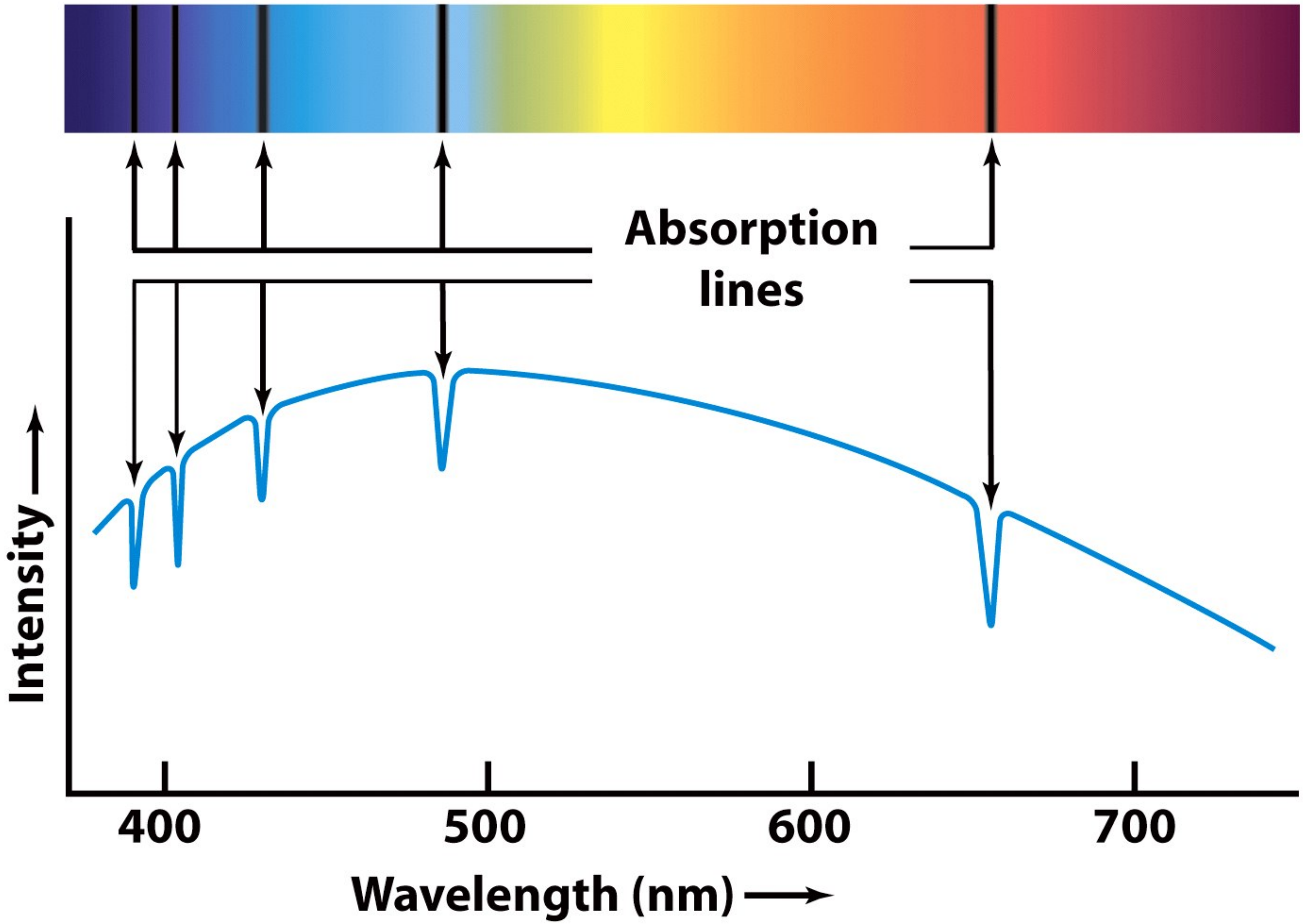
(a) Using photographic film (b) Using a CCD (c) Combined CCD image

Spectrographs record the spectra of astronomical objects

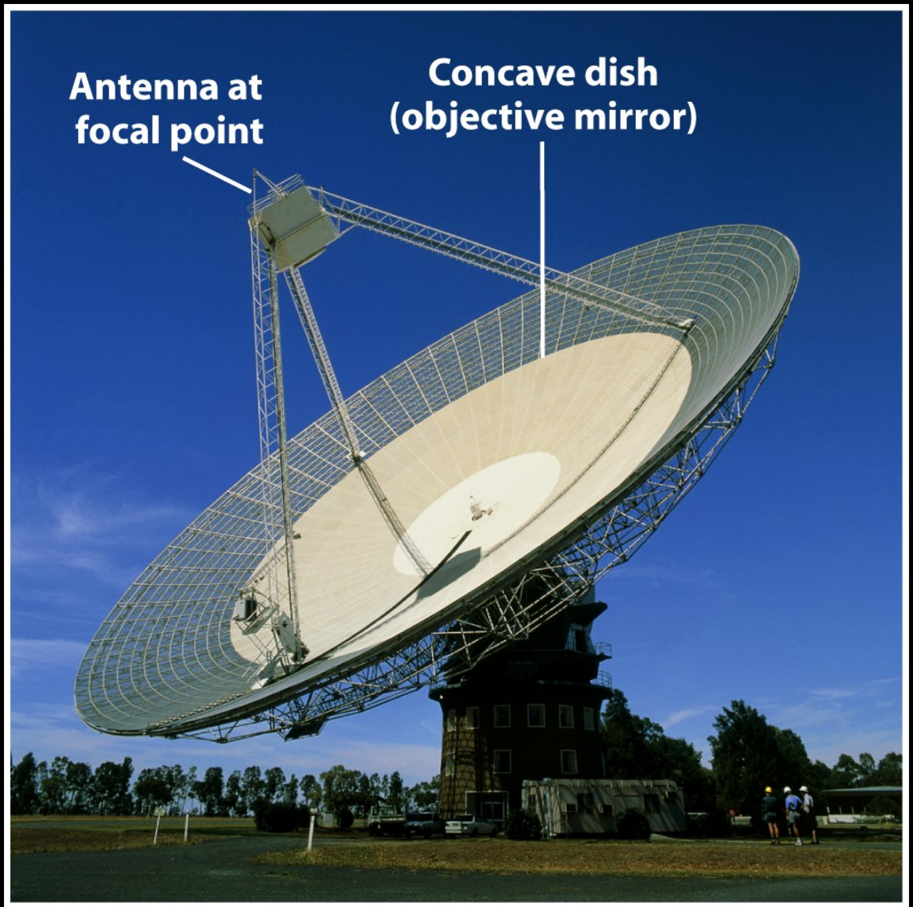


A spectrograph uses a diffraction grating and lenses to form the spectrum of an astronomical object


Spectrum of star
Comparison spectrum of iron (at the observatory on Earth)


Absorption lines
Intensity
400
500
600
700
Wavelength (nm)

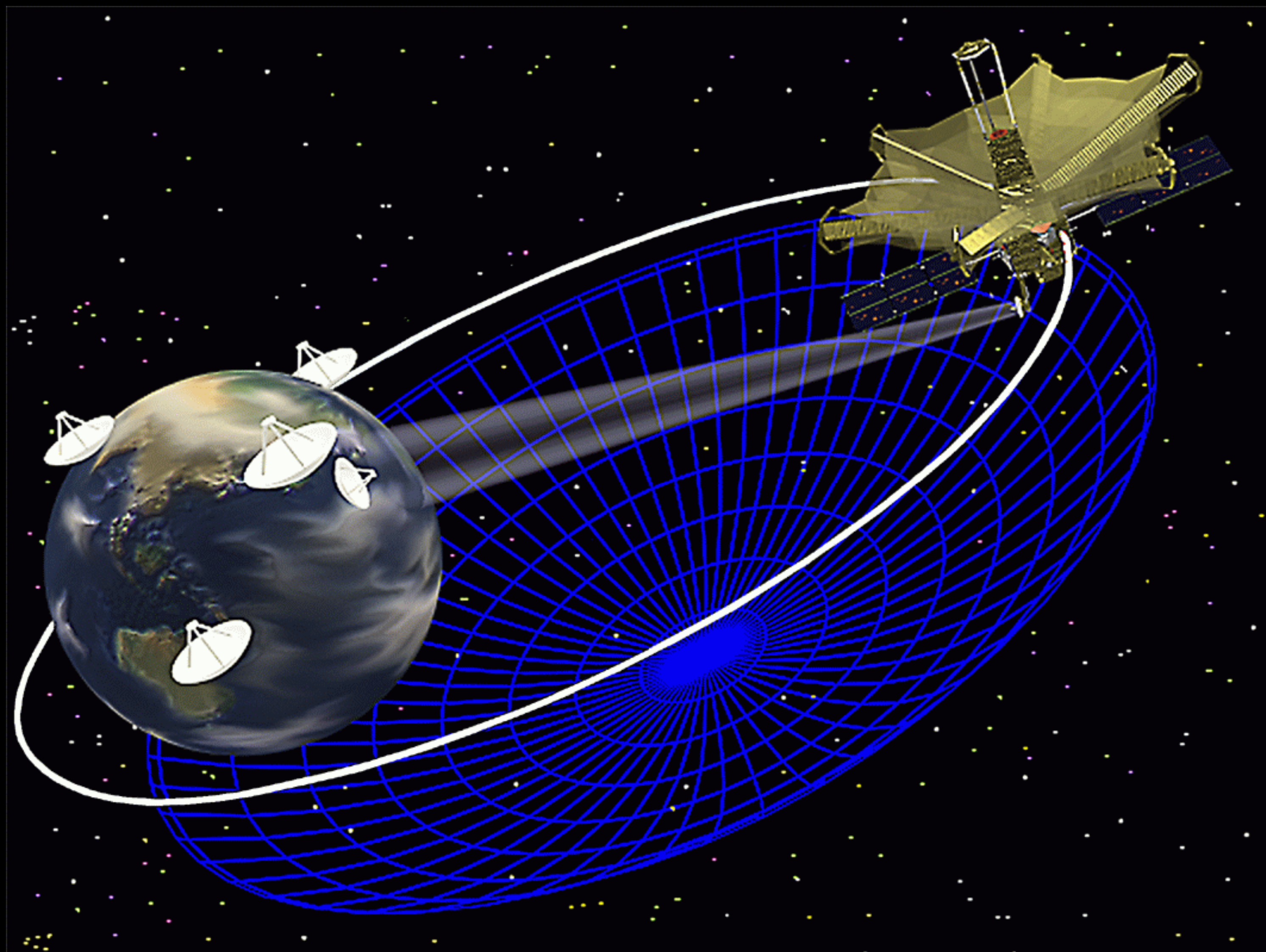
A radio telescope uses a large concave dish to reflect radio waves to a focus



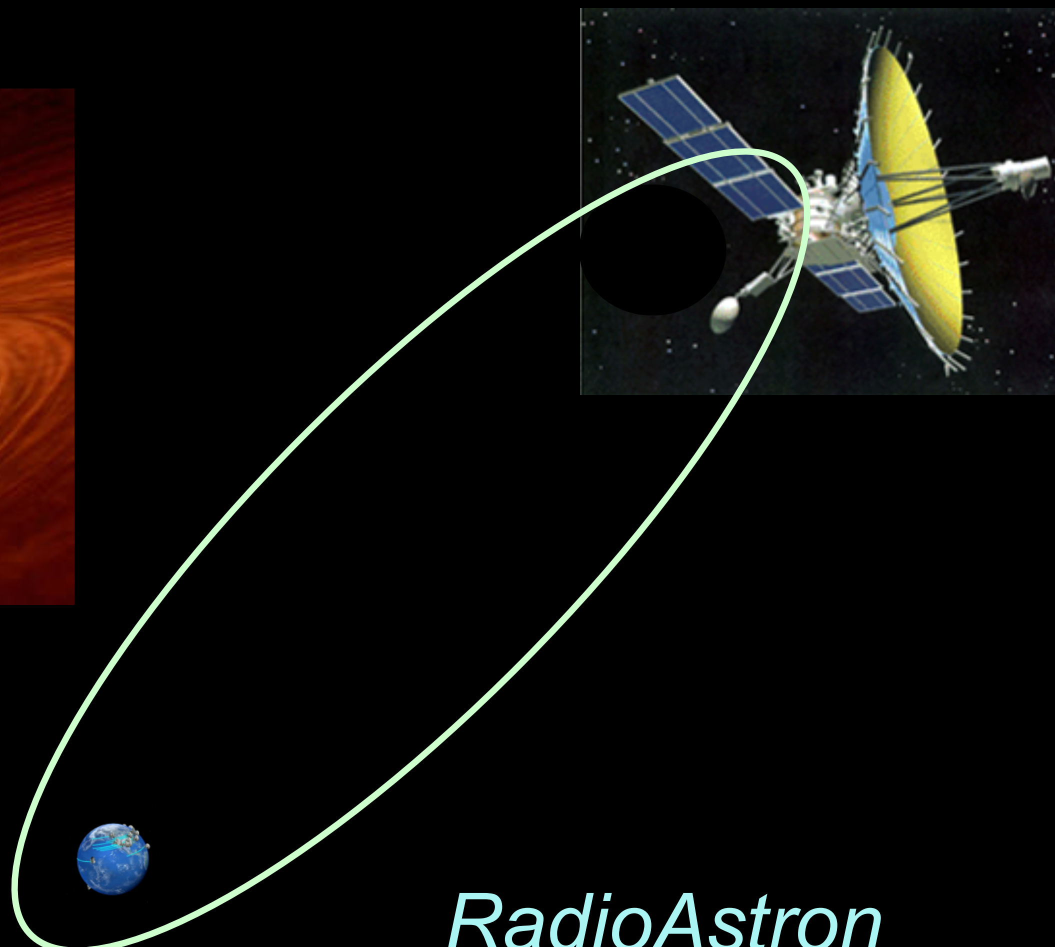
- Radio telescopes use large reflecting antennas or dishes to focus radio waves
- Very large dishes provide reasonably sharp radio images

Higher resolution is achieved with interferometry techniques that link smaller dishes together

Space very-long-baseline interferometry



Black holes

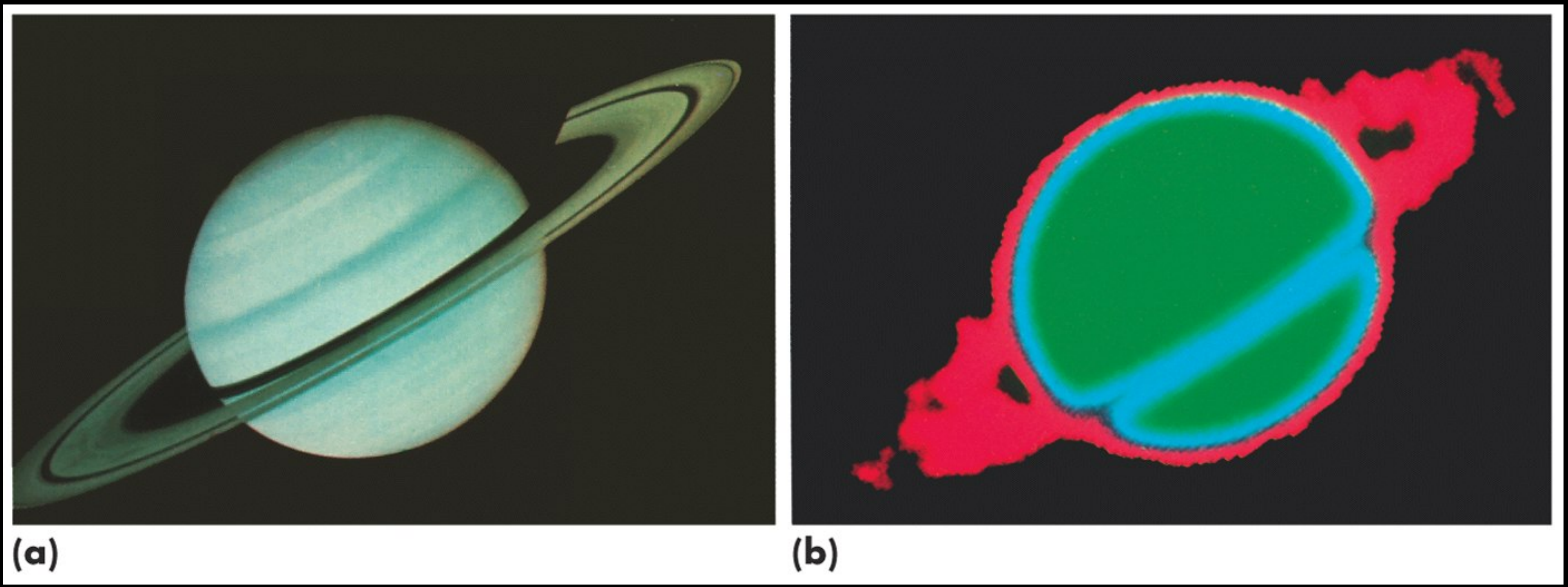


RadioAstron

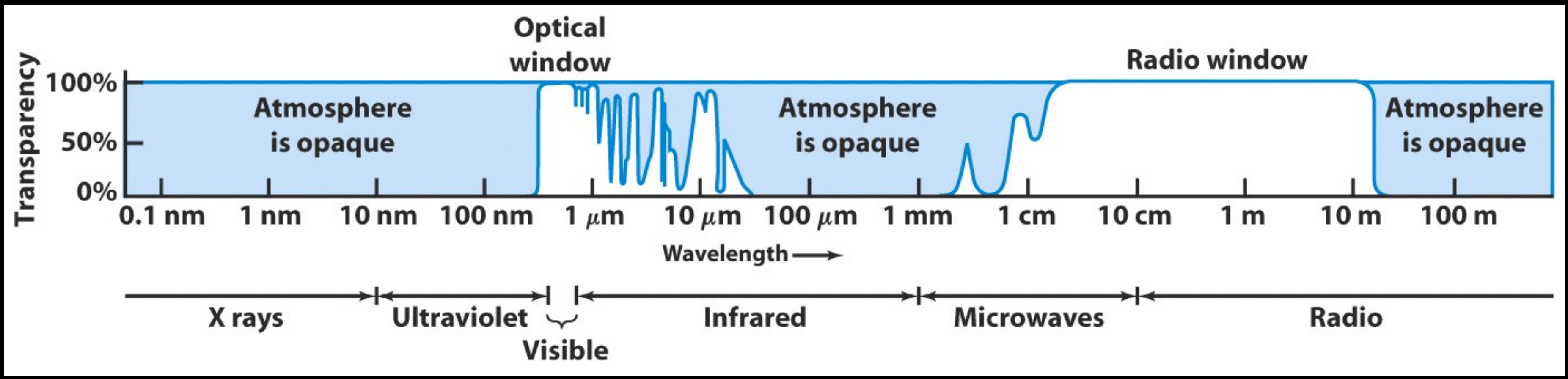
Ground-space VLBI mission

Resolving power: θ =10 microarcseconds

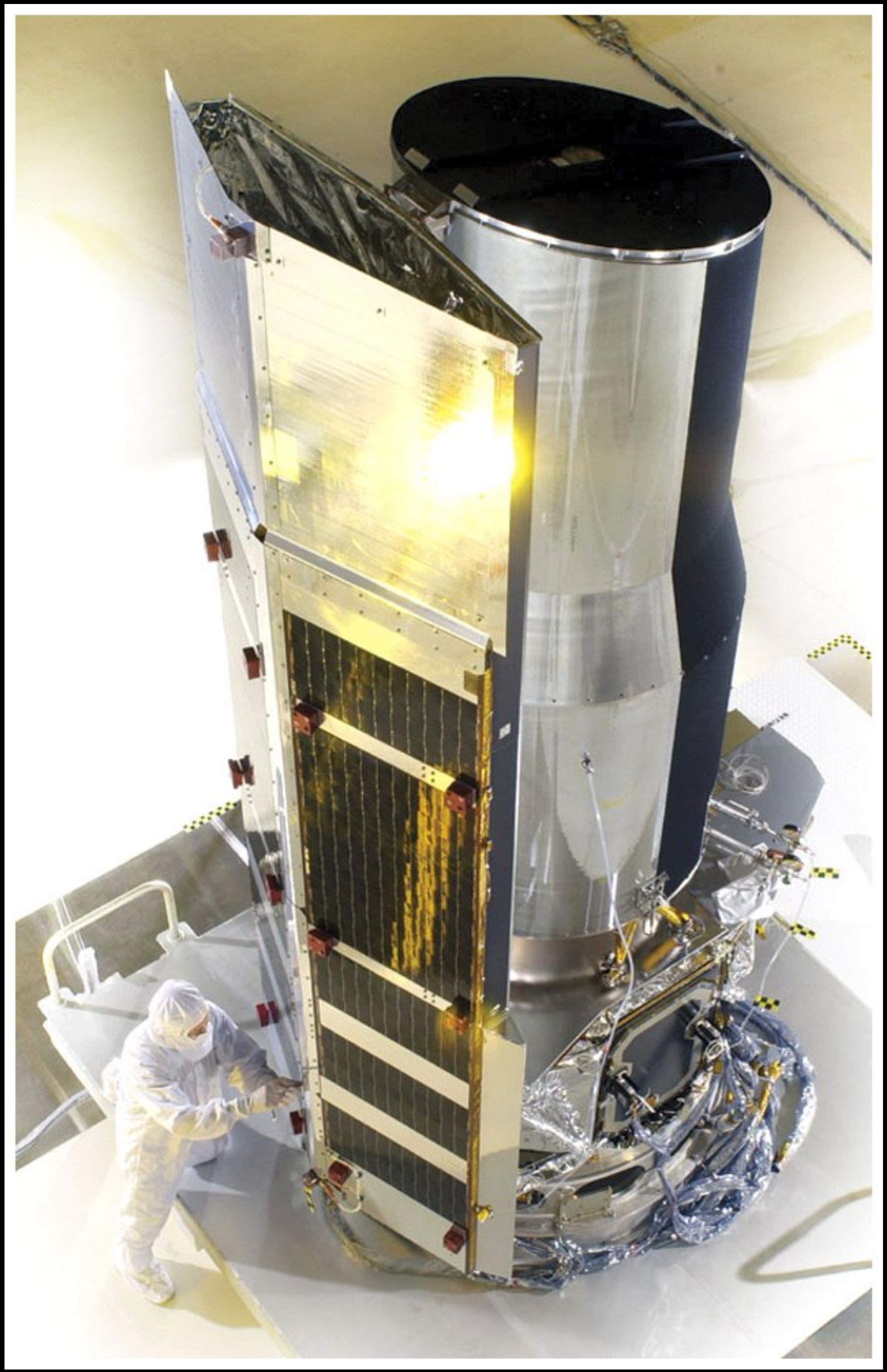
Optical and Radio Views of Saturn



Telescopes in orbit around the Earth detect radiation that does not penetrate the atmosphere

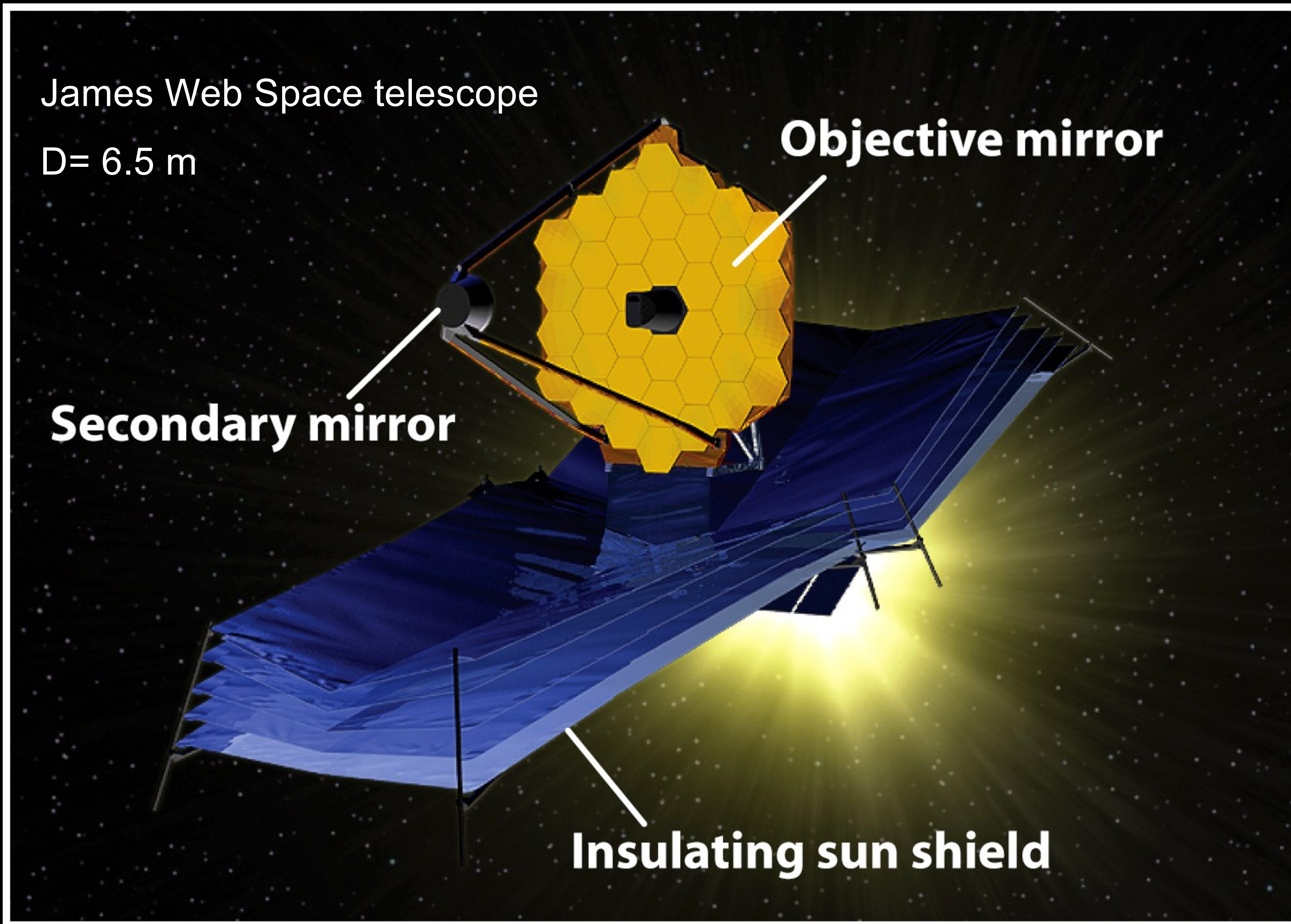


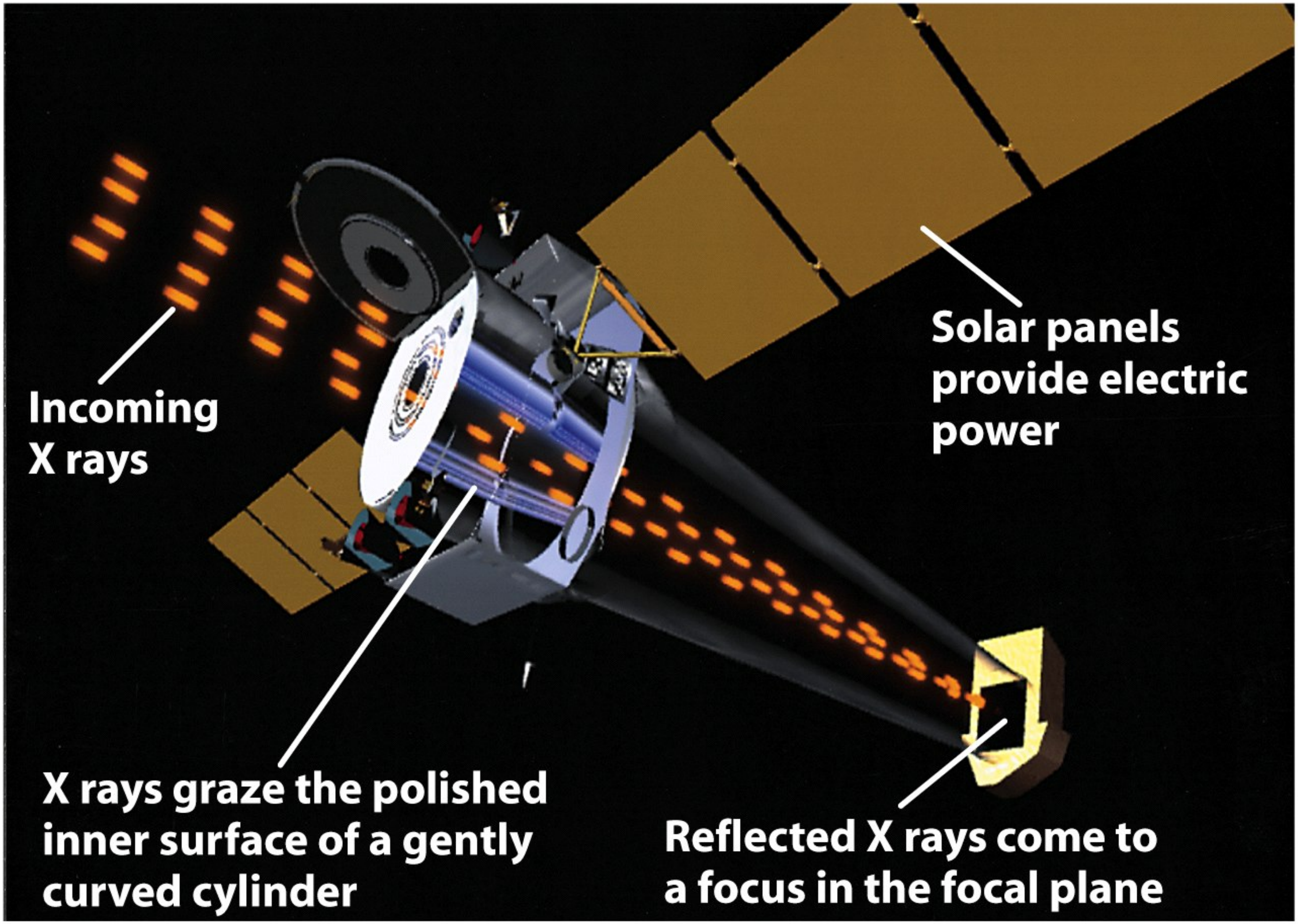
- The Earth's atmosphere absorbs much of the radiation that arrives from space
- The atmosphere is transparent chiefly in two wavelength ranges known as the optical window and the radio window
- A few wavelengths in the near-infrared also reach the ground



- For observations at wavelengths to which the Earth’s atmosphere is opaque, astronomers depend on telescopes carried above the atmosphere by rockets or spacecraft

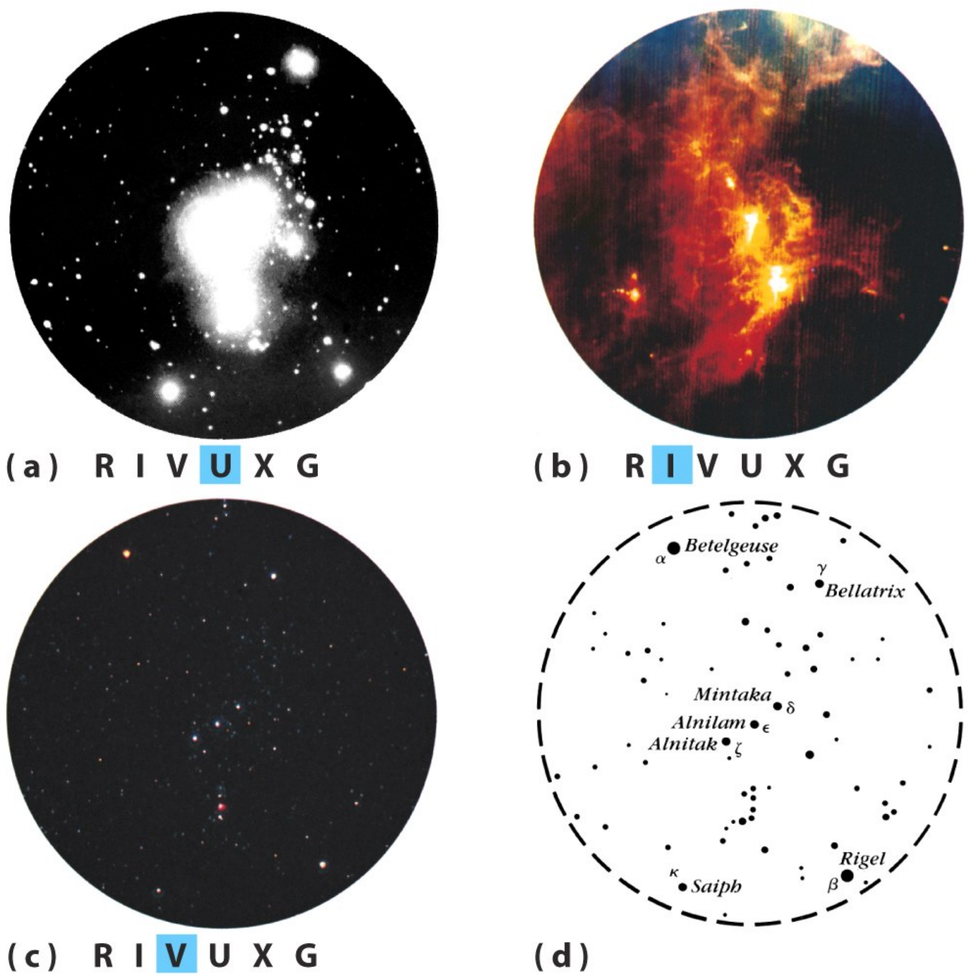
The Hubble Space Telescope

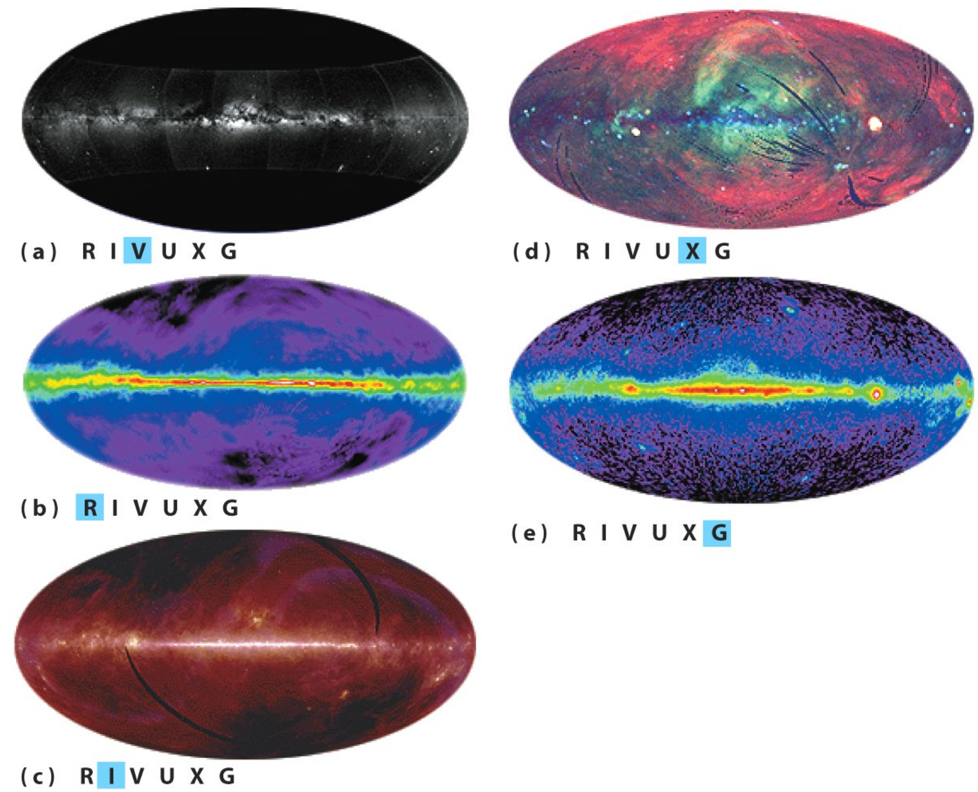

James Web Space telescope
D= 6.5 m
Objective mirror
Secondary mirror
Insulating sun shield

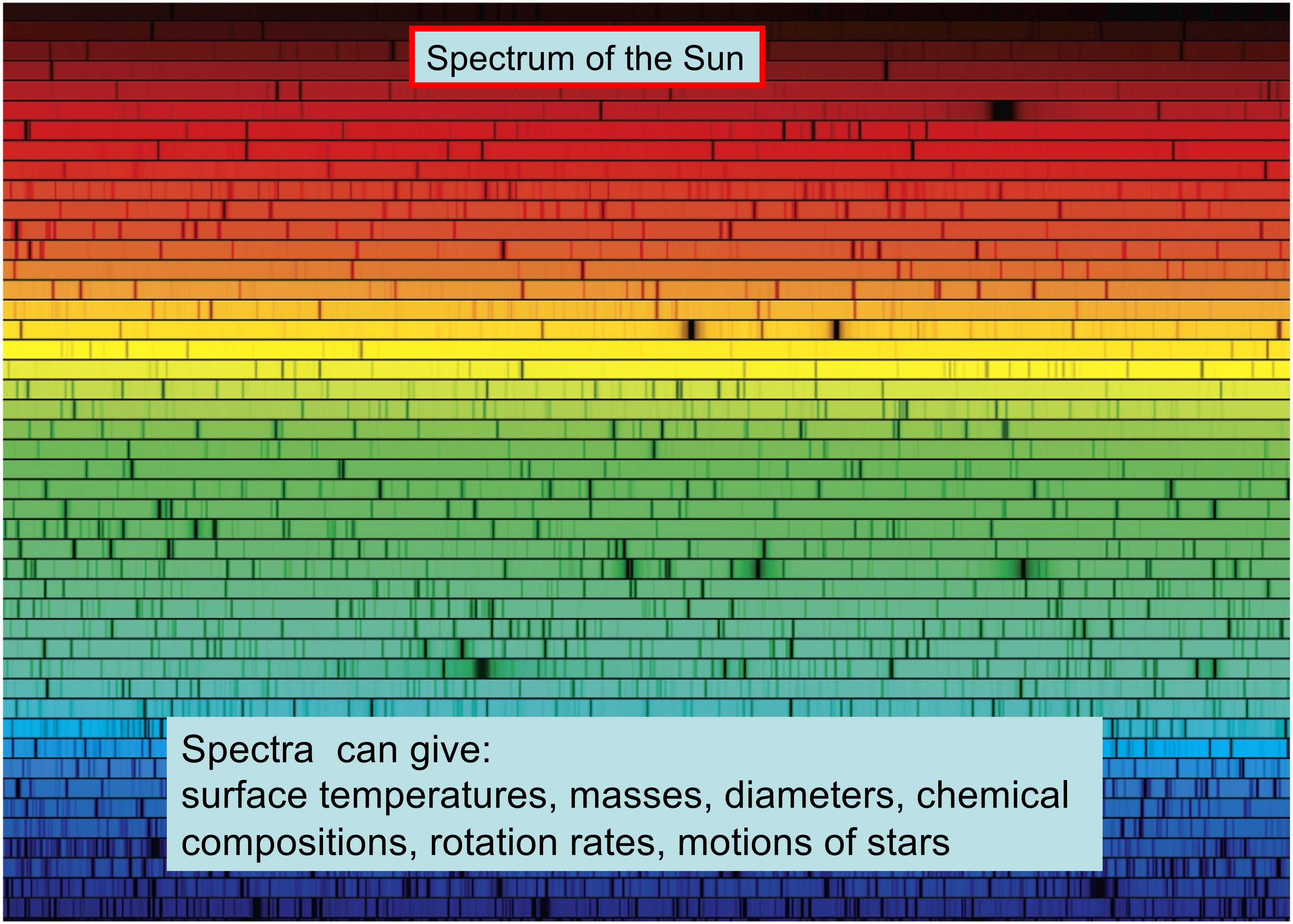


(a) Chandra X-ray Observatory

Satellite-based observatories provide new information about the universe and permit coordinated observation of the sky at all wavelengths







Spectra can give:
surface temperatures, masses, diameters, chemical compositions, rotation rates, motions of stars

Chapter 4 Opener
Discovering the Universe, Eighth Edition

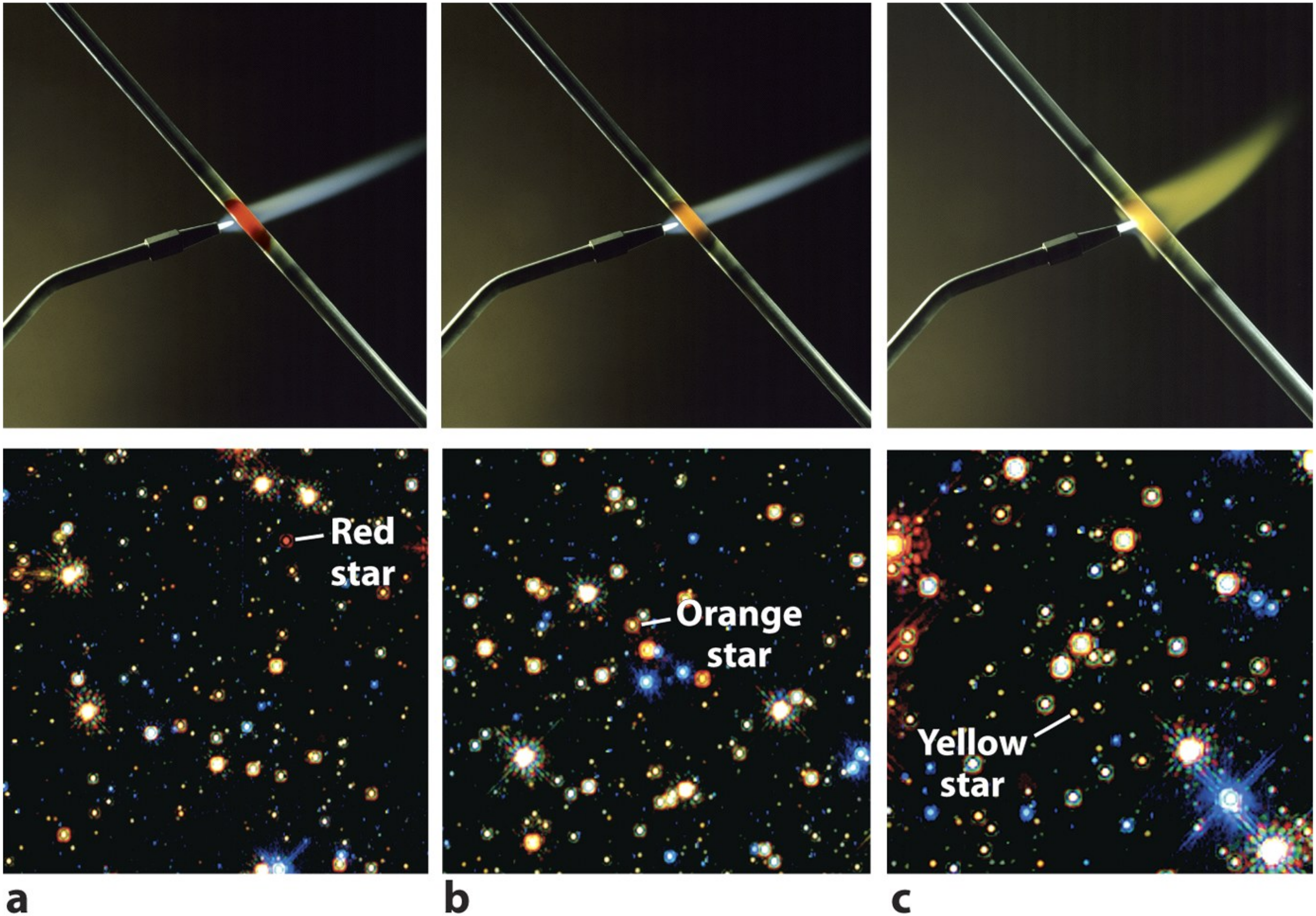
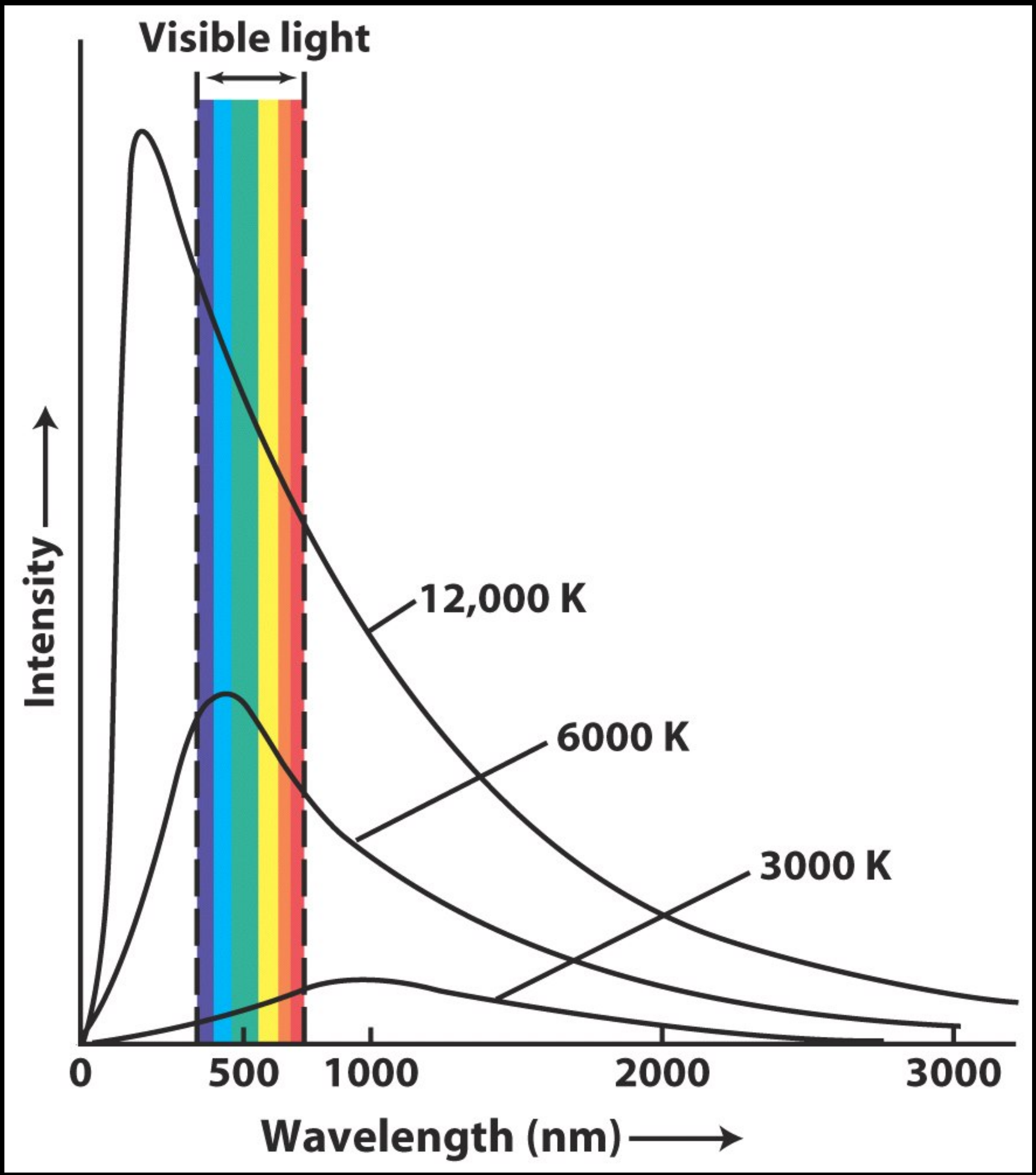


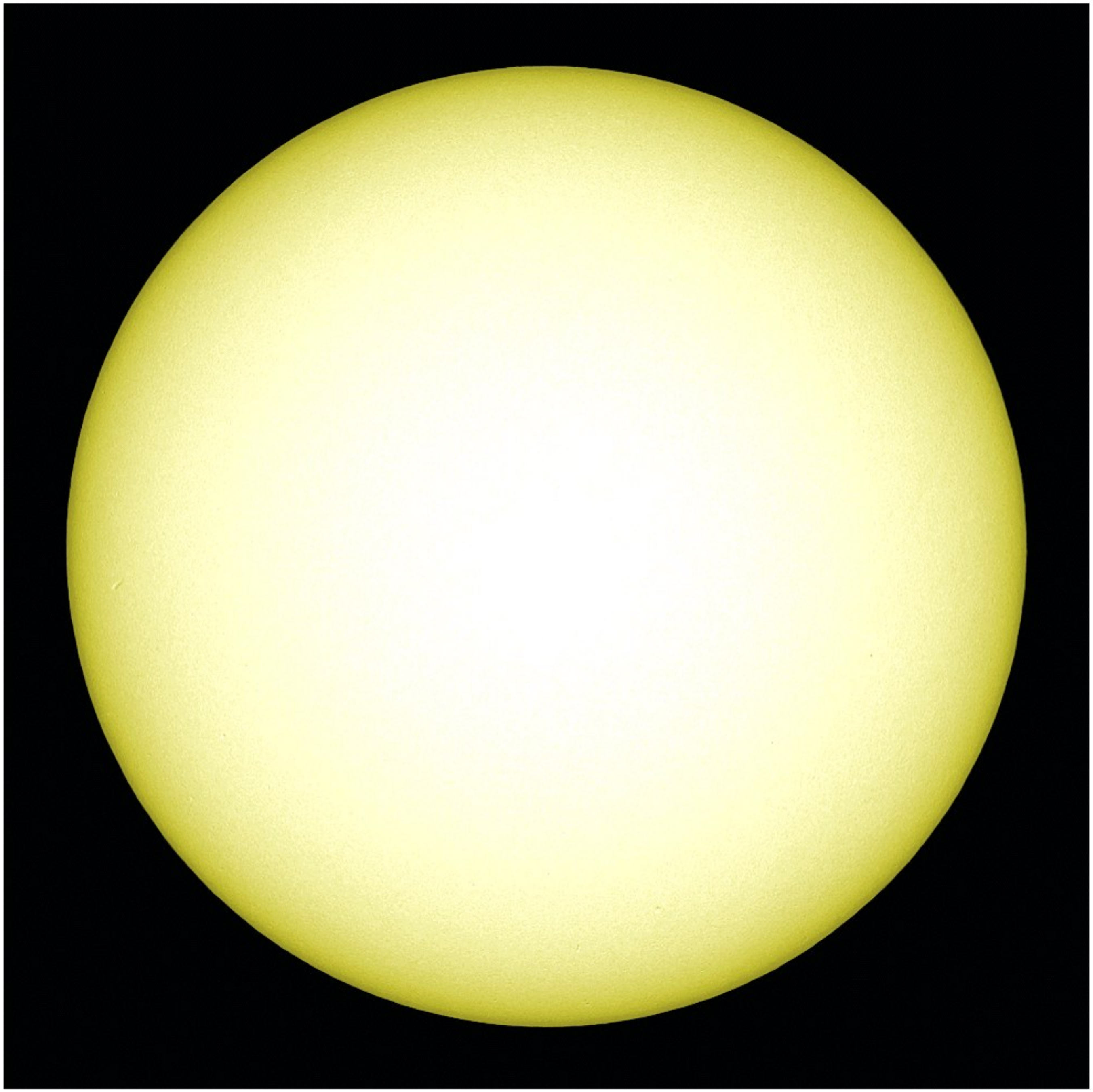
Figure 4-1
Discovering the Universe, Eighth Edition

Wien's law and the Stefan-Boltzmann law are useful tools for analyzing glowing objects like stars



- A blackbody is a hypothetical object that is a perfect absorber of electromagnetic radiation at all wavelengths
- Stars closely approximate the behavior of blackbodies, as do other hot, dense objects
- The intensities of radiation emitted at various wavelengths by a blackbody at a given temperature are shown by a blackbody curve


Betelgeuse
Bellatrix
Mintaka
"Great
Nebula"
Rigel

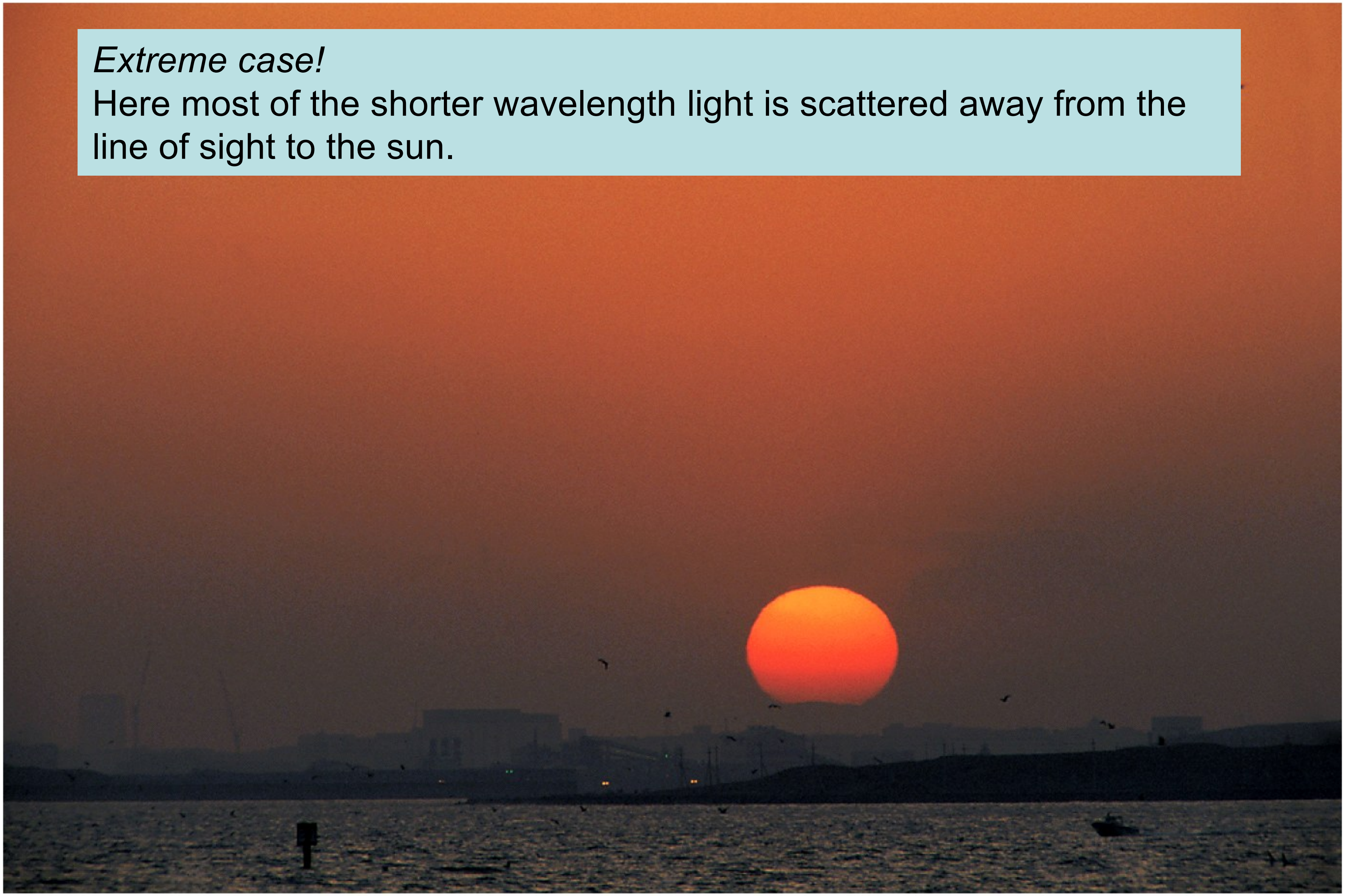


Unnumbered 4 p108a

Discovering the Universe, Eighth Edition

Note:
Atmosphere scatters light

Shorter wavelength light is scattered more than longer wavelength light



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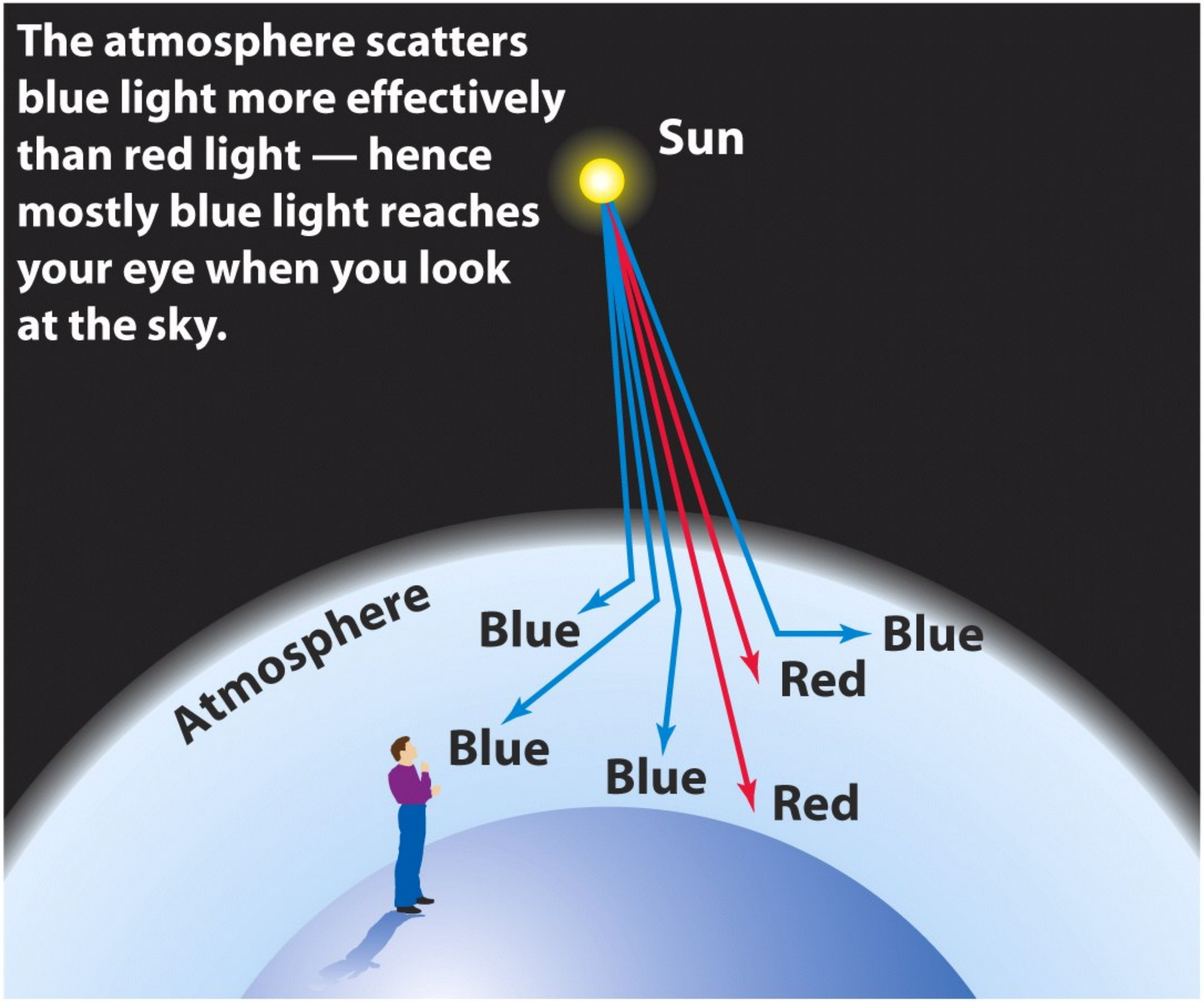
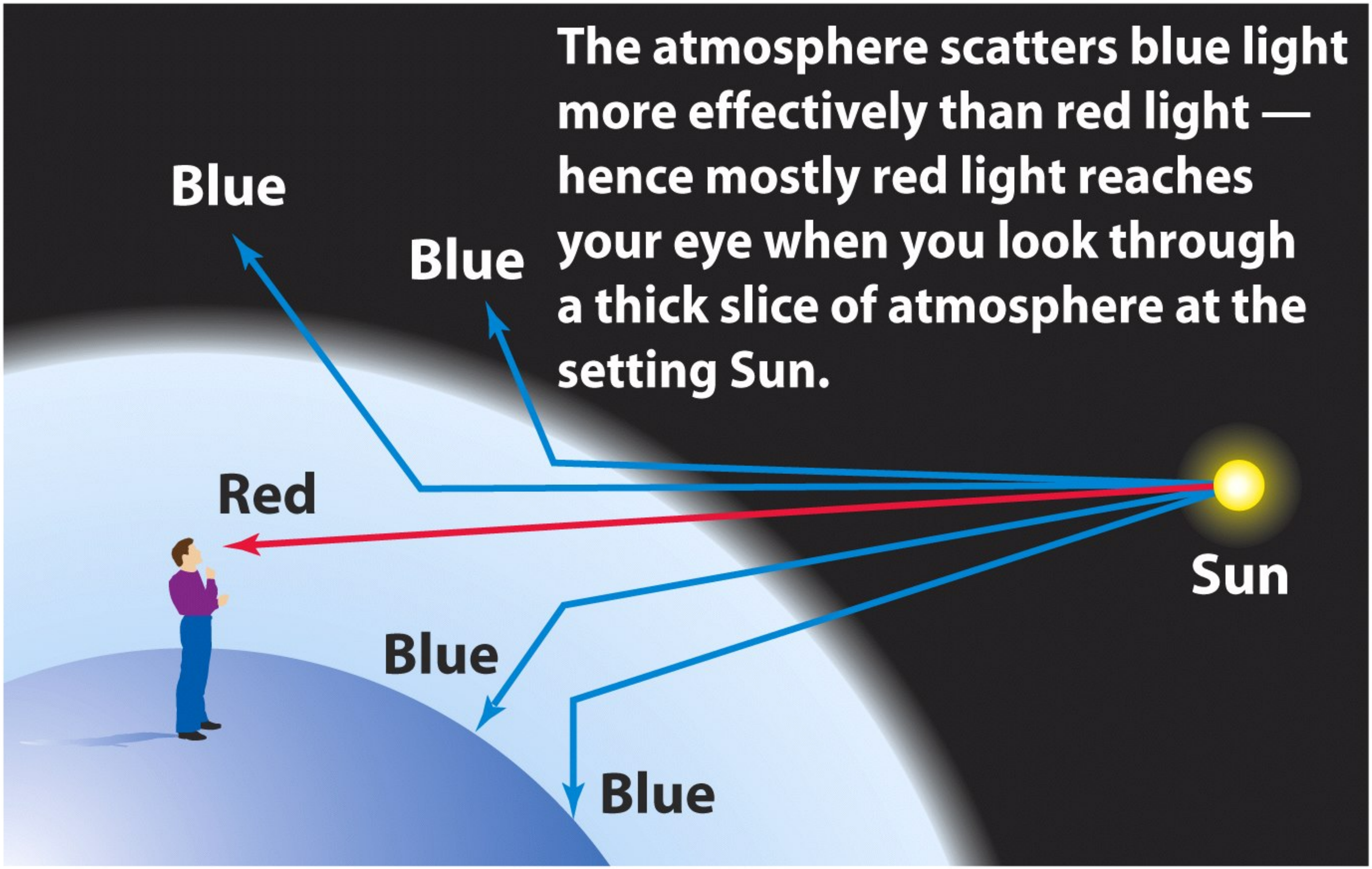
Discovering the Universe, Eighth Edition



(a) Why the sky looks blue



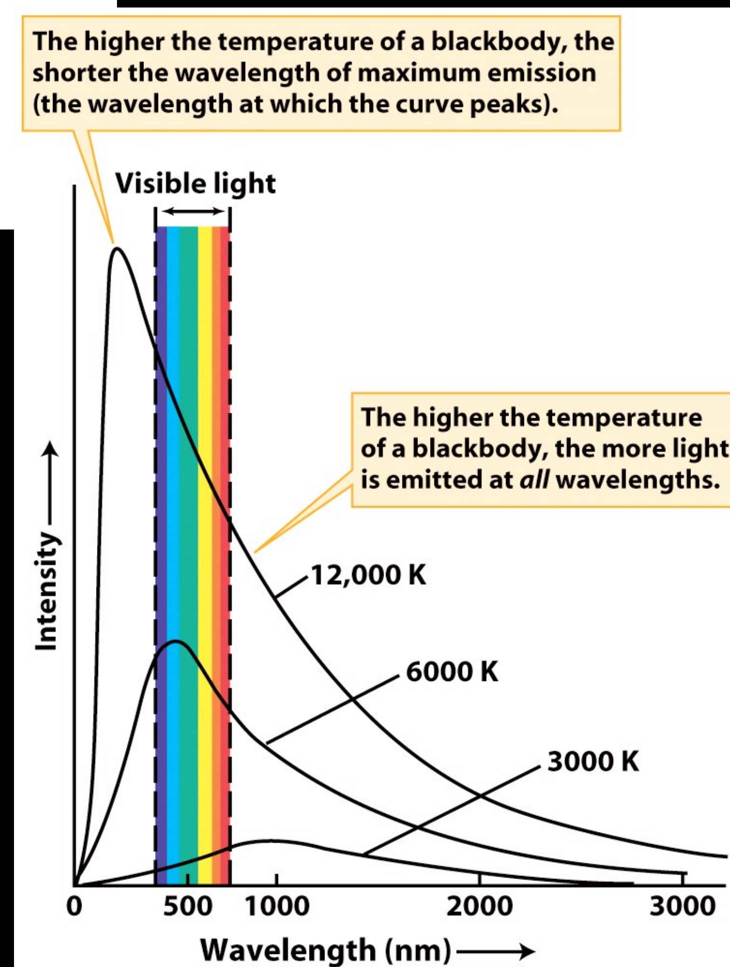
(b) Why the setting Sun looks red

Wien’s Law for a Blackbody

$$\lambda_{max} = \frac{0.0029 \text{ K m}}{T}$$

λ_{max} = wavelength of maximum emission of the object (in meters)

T = temperature of the object (in kelvins)



- Example:
- λ_{max}= 500 nm, then
- T = 0.0029 K m / 500 nm
- = 0.0029 / 5.0 10^{-7} K
- = 5800 K

Stefan-Boltzmann Law

The Stefan-Boltzmann law states that a blackbody radiates electromagnetic waves with a total energy flux F (watts per square metre) directly proportional to the fourth power of the Kelvin temperature T of the object:

$$F = \sigma T^4$$

F=energy flux in Joules per second per square meter of surface of object

$\sigma = 5.670 \cdot 10^{-8}\ W\ m^{-2}\ K^{-4}$

T=object's surface temperature in K

Luminosity, an intrinsic quantity

Luminosity L (watts) is the total energy emitted by a star every second.

If we know how much energy is emitted every second from a 1m² patch on the star (from the Stefan-Boltzmann Law), then we can easily calculate the total energy emitted every second from the entire star's surface.

Multiplying the flux from the 1m² patch by the star's whole surface area:

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

where R = radius of the star in *m*

Example: What is the luminosity of the Sun?

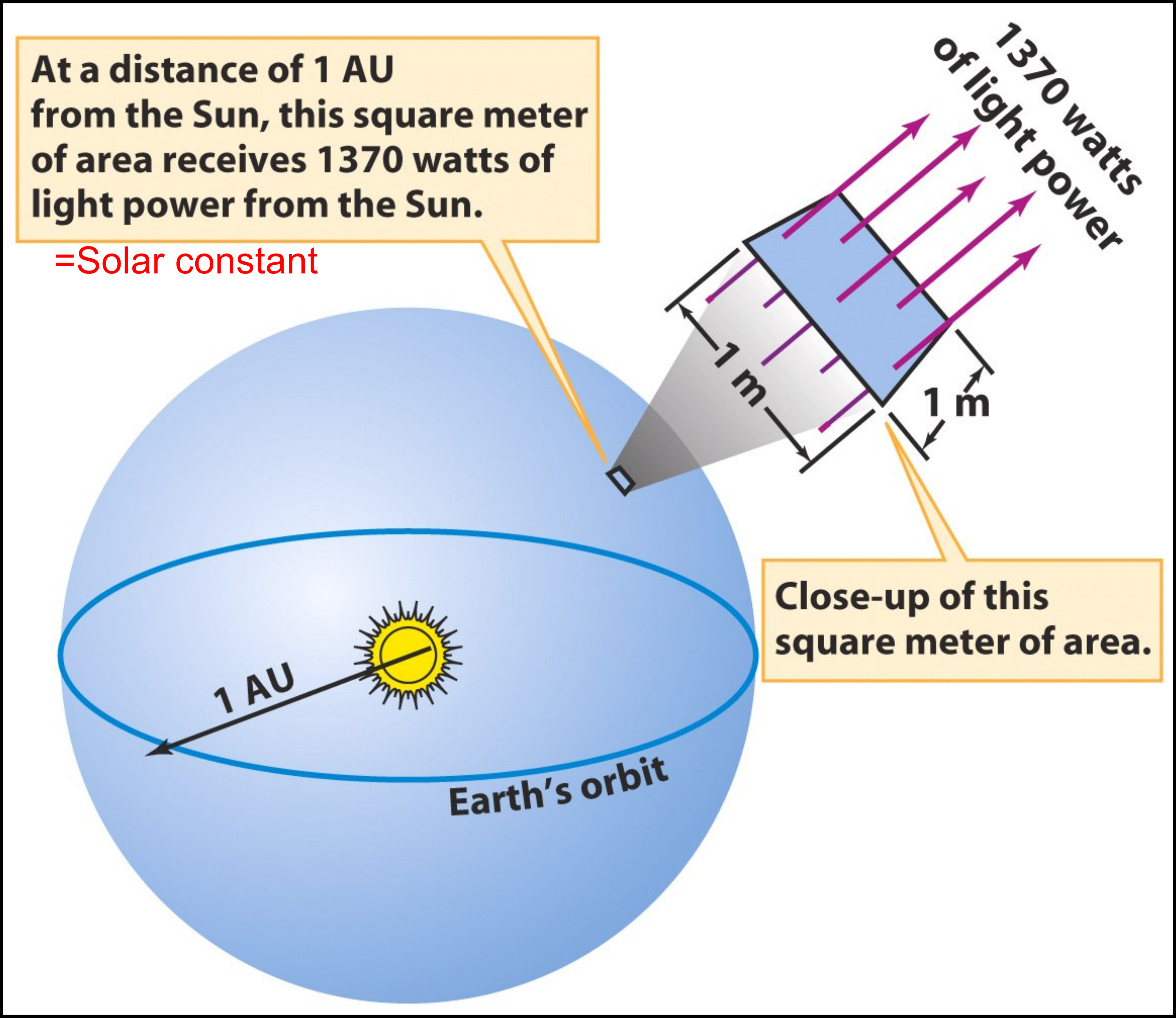
$T = 5780$ K (Surface temperature of the Sun)

$R_{sun} = 696{,}000$ km (Radius of Sun)

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

$= 4\pi \times (6.96 \times 10^8)^2 \times 5.670 \cdot 10^{-8} \times 5780^4$

$L = 3.85 \times 10^{26}$ W (Luminosity of Sun)



At a distance of 1 AU from the Sun, this square meter of area receives 1370 watts of light power from the Sun.
=Solar constant
1370 watts of light power
1 m
1 m
Close-up of this square meter of area.
1 AU
Earth's orbit

Example: What is the power per square meter received from the Sun at Earth's distance?

$T = 5780$ K

$R_{sun} = 696{,}000$ km

$L = 4\pi R^2 \times \sigma T^4$ (Luminosity)

$= 4\pi \times (6.96 \times 10^8)^2 \times 5.670 \cdot 10^{-8} \times 5780^4$

$= 3.85 \times 10^{26}$ W

$F_d = L / (4\pi\ d^2)$ (Flux at distance d from celestial object)

$= 3.85 \times 10^{26} / (4\pi \times (1.5 \times 10^{11})^2)$

$= 1360\ W/m^2$

Light has property of wave and particle

Energy of a photon:

$E = hc/\lambda$

$= h\nu$

$h = 6.67 \bullet 10^{-34}$ Js

(Planck's constant)

- Example:
- Green light: λ = 500 nm
-
-
- $E = 6.67 \cdot 10^{-34} \cdot 3 \cdot 10^{8} / (5 \cdot 10^{-7})$
- $= 4.00 \cdot 10^{-19}$ J

TABLE 4–1 Some Properties of Electromagnetic Radiation

	Wavelength (nm)	Photon energy (eV)*	Blackbody temperature (K)
Radio	$>10^7$	$<10^{-4}$	<0.03
Microwave**	10^7 to 4×10^5	10^{-4} to 3×10^{-3}	0.03 to 30
Infrared	4×10^5 to 7×10^2	3×10^{-3} to 2	30 to 4100
Visible	7×10^2 to 4×10^2	2 to 3	4100 to 7300
Ultraviolet	4×10^2 to 10^1	3 to 10^3	7300 to 3×10^6
X ray	10^1 to 10^{-2}	10^3 to 10^5	3×10^6 to 3×10^8
Gamma ray	$<10^{-2}$	$>10^5$	$>3 \times 10^8$

Note: $>$ means greater than; $<$ means less than.
*1 eV = 1.6×10^{-19} J.
**Microwaves, listed here separately, are often classified as radio waves or infrared radiation.

Table 4-1
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Unnumbered 4 p110
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Gustav Kirchhoff and Robert Bunsen

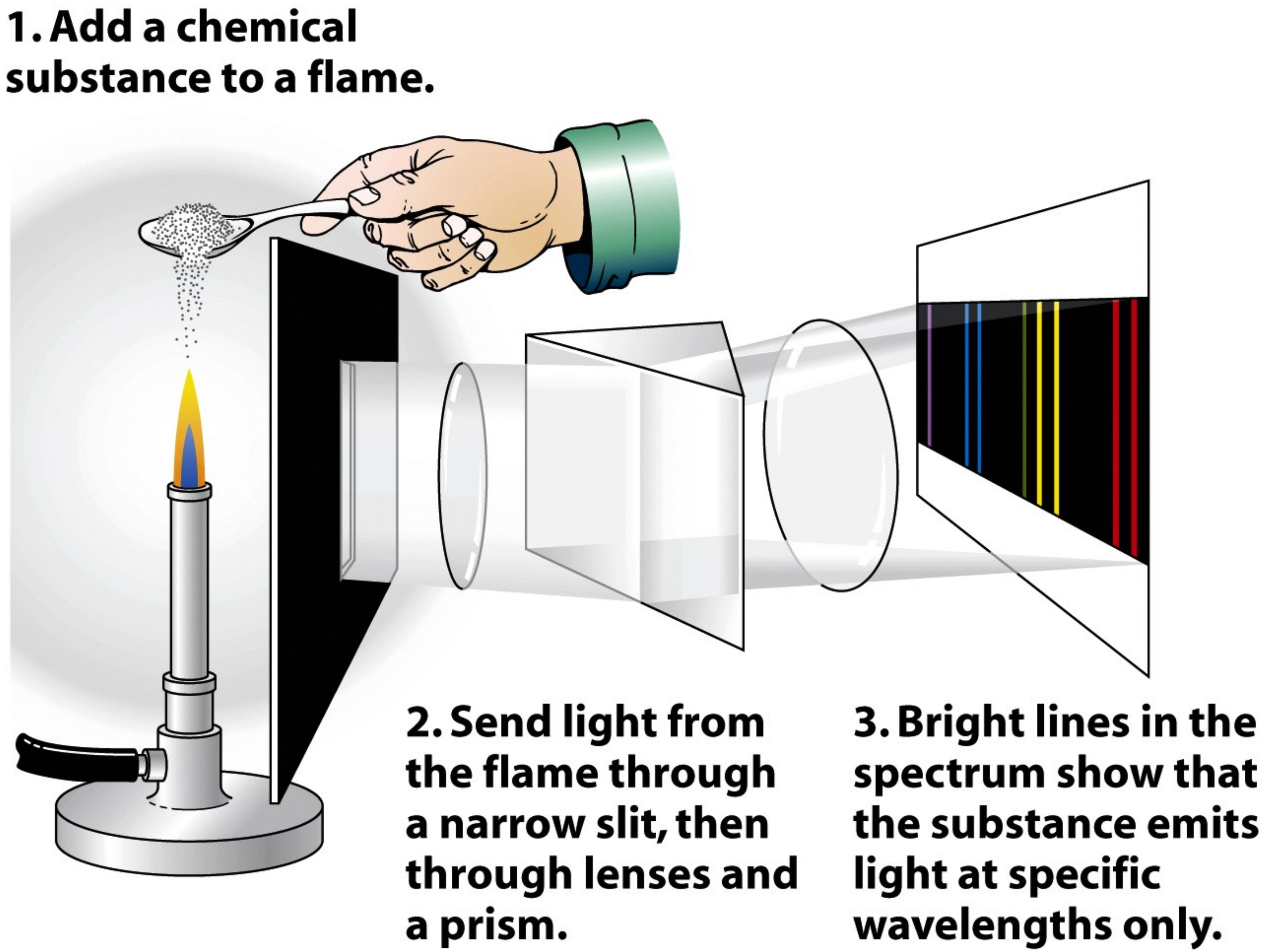

Figure 4-5
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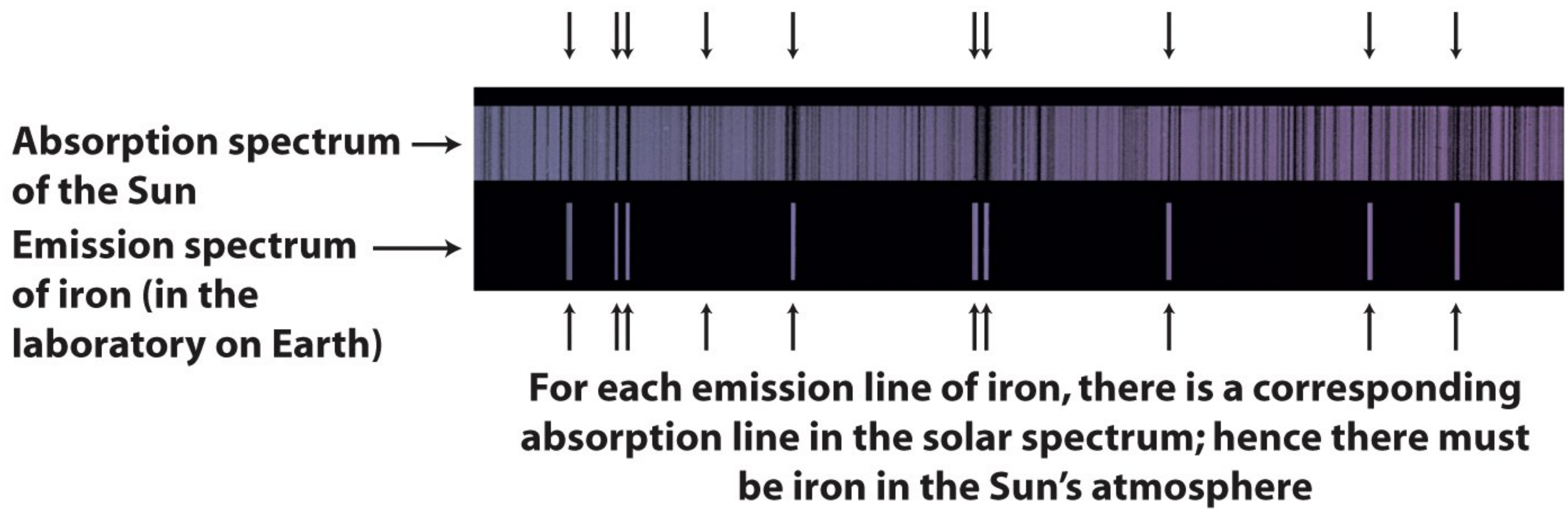

Figure 4-6
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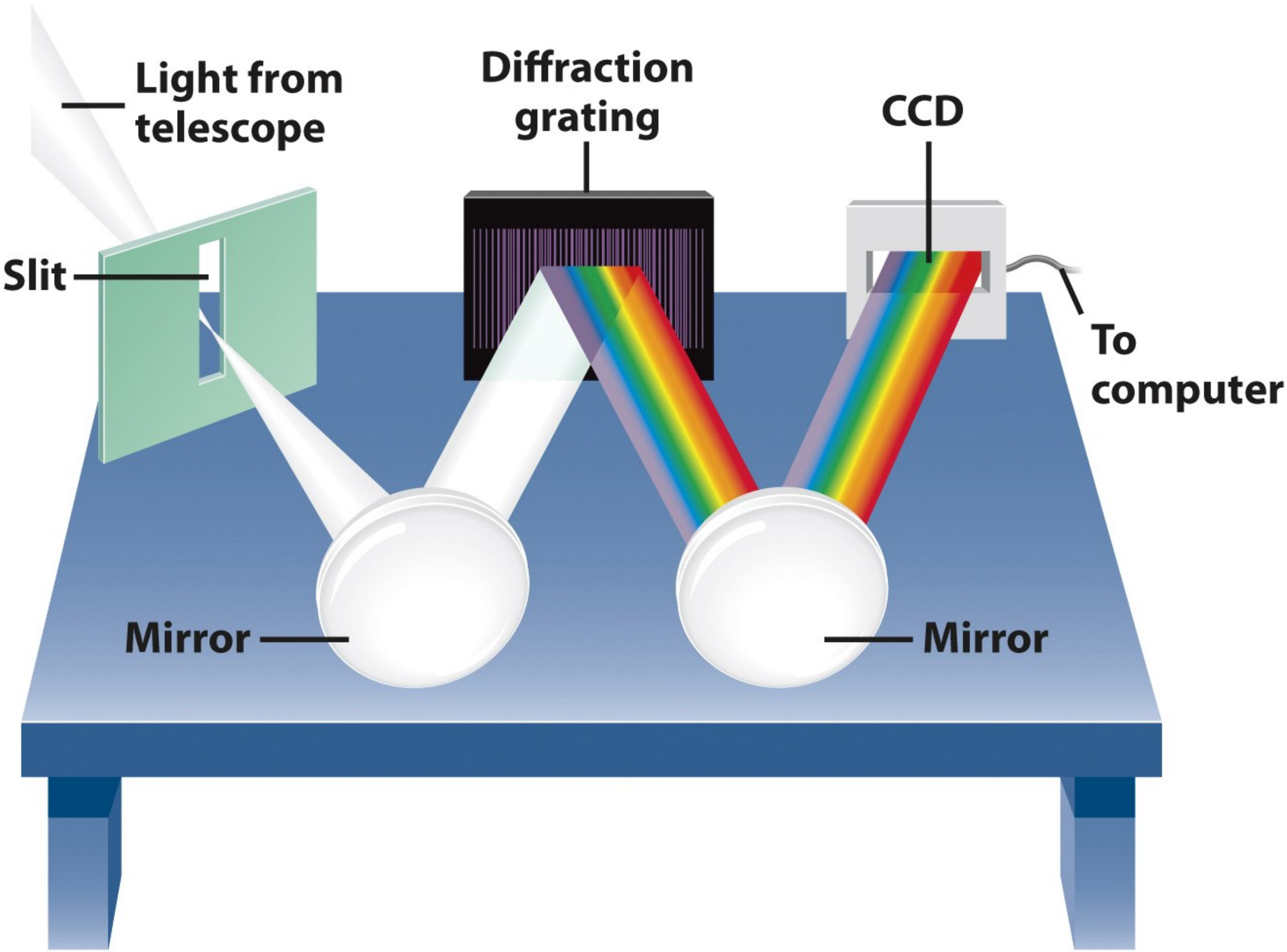

Figure 4-7a
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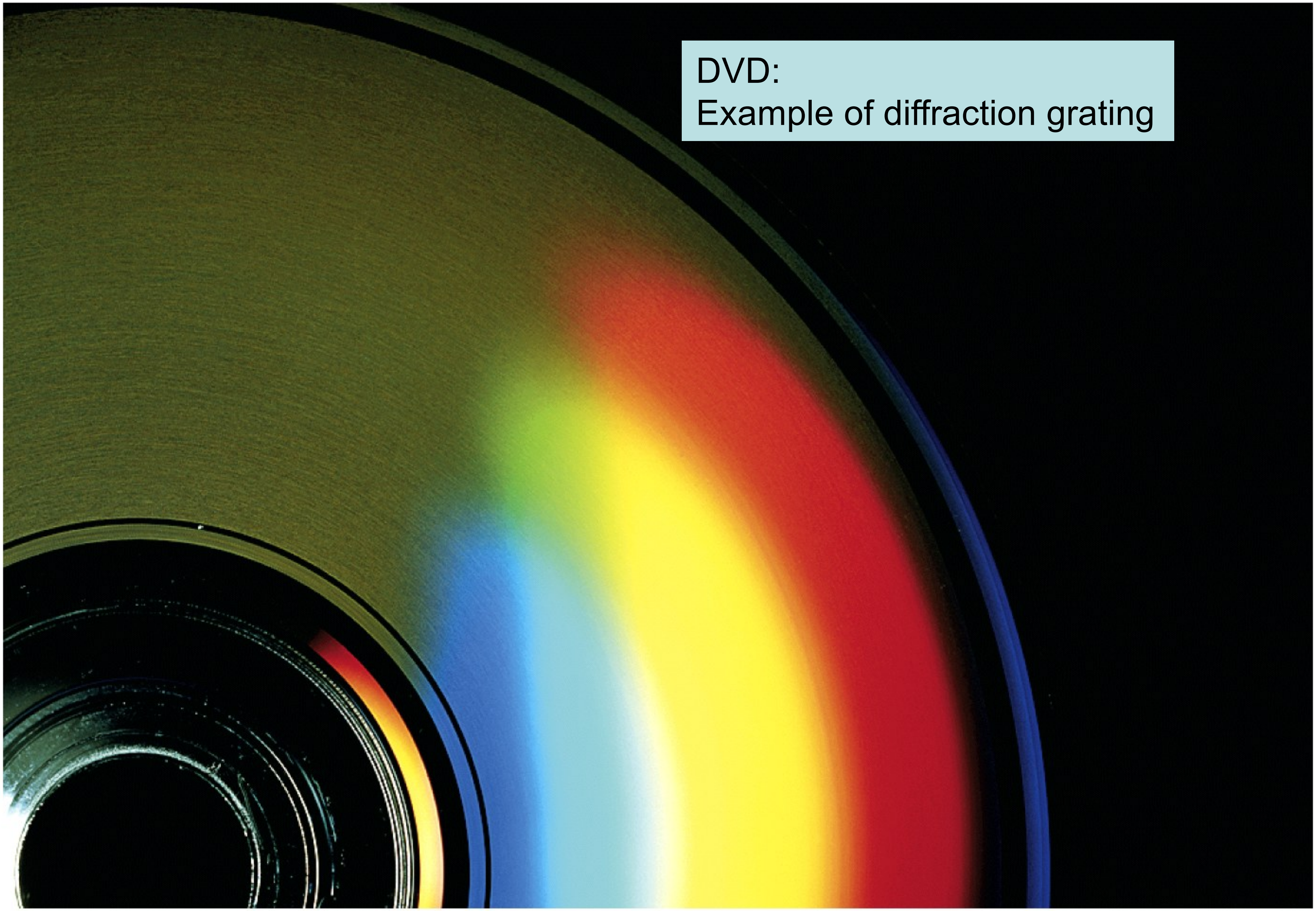

Figure 4-7c
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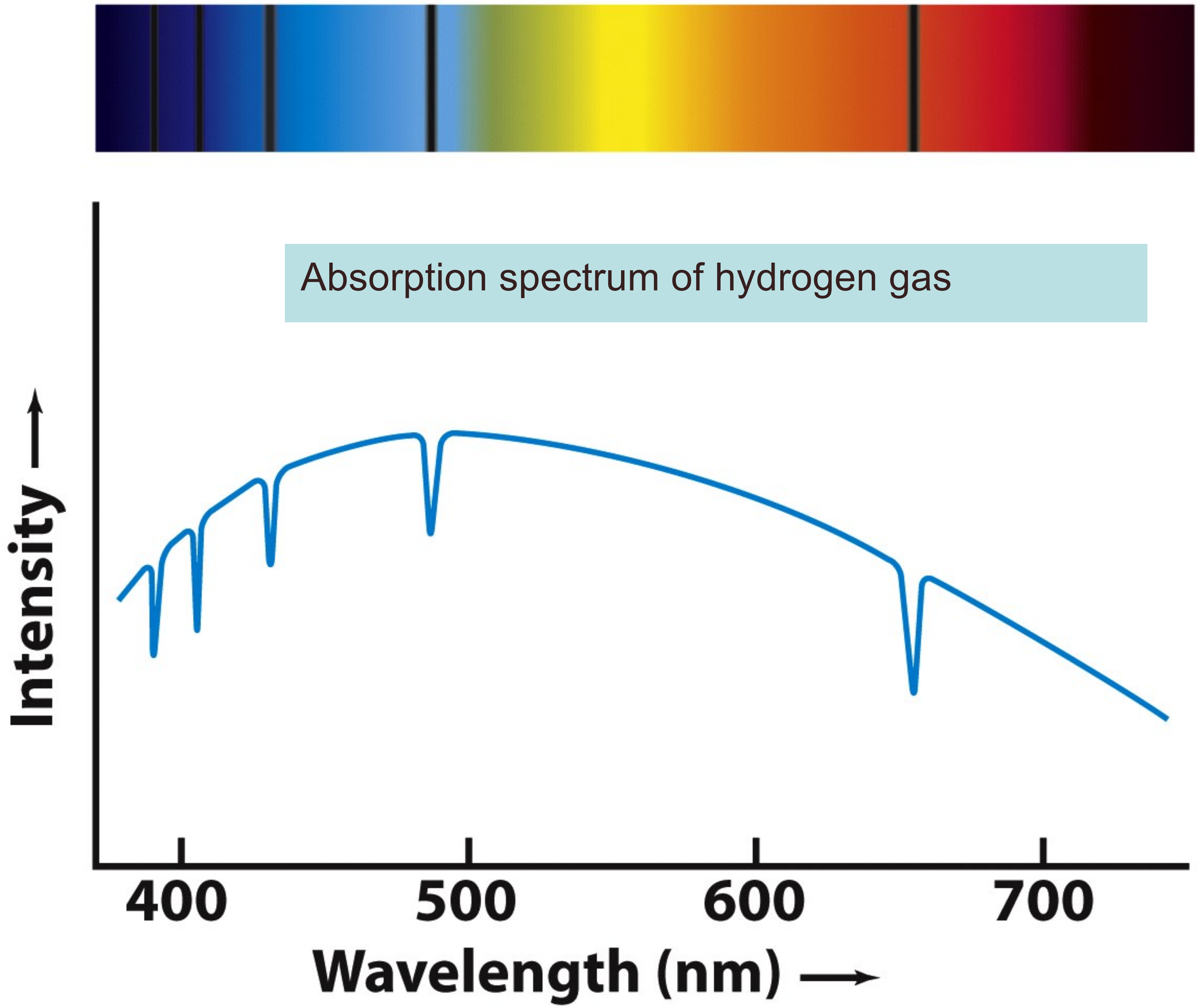

Figure 4-8ab
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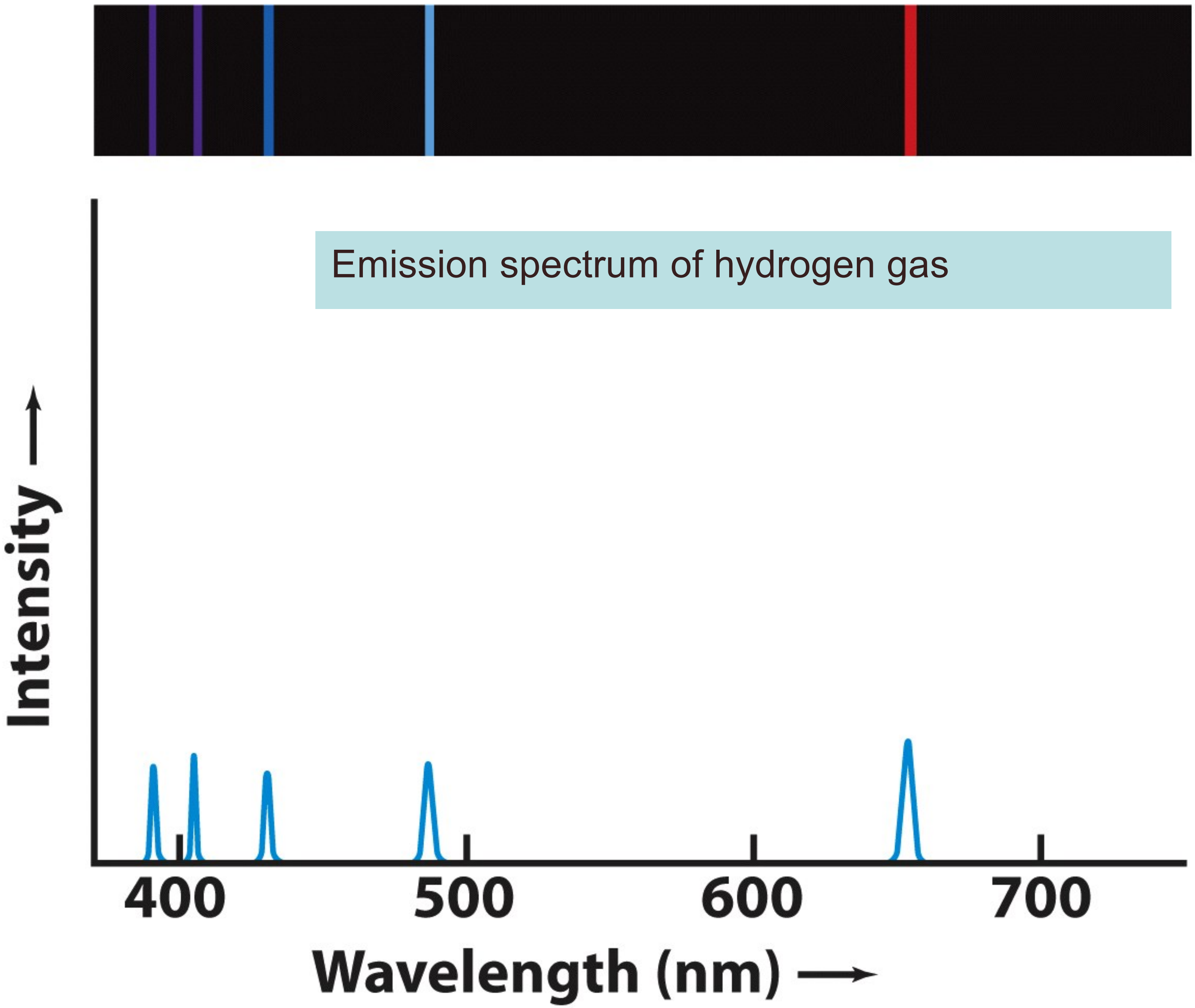

Figure 4-8cd
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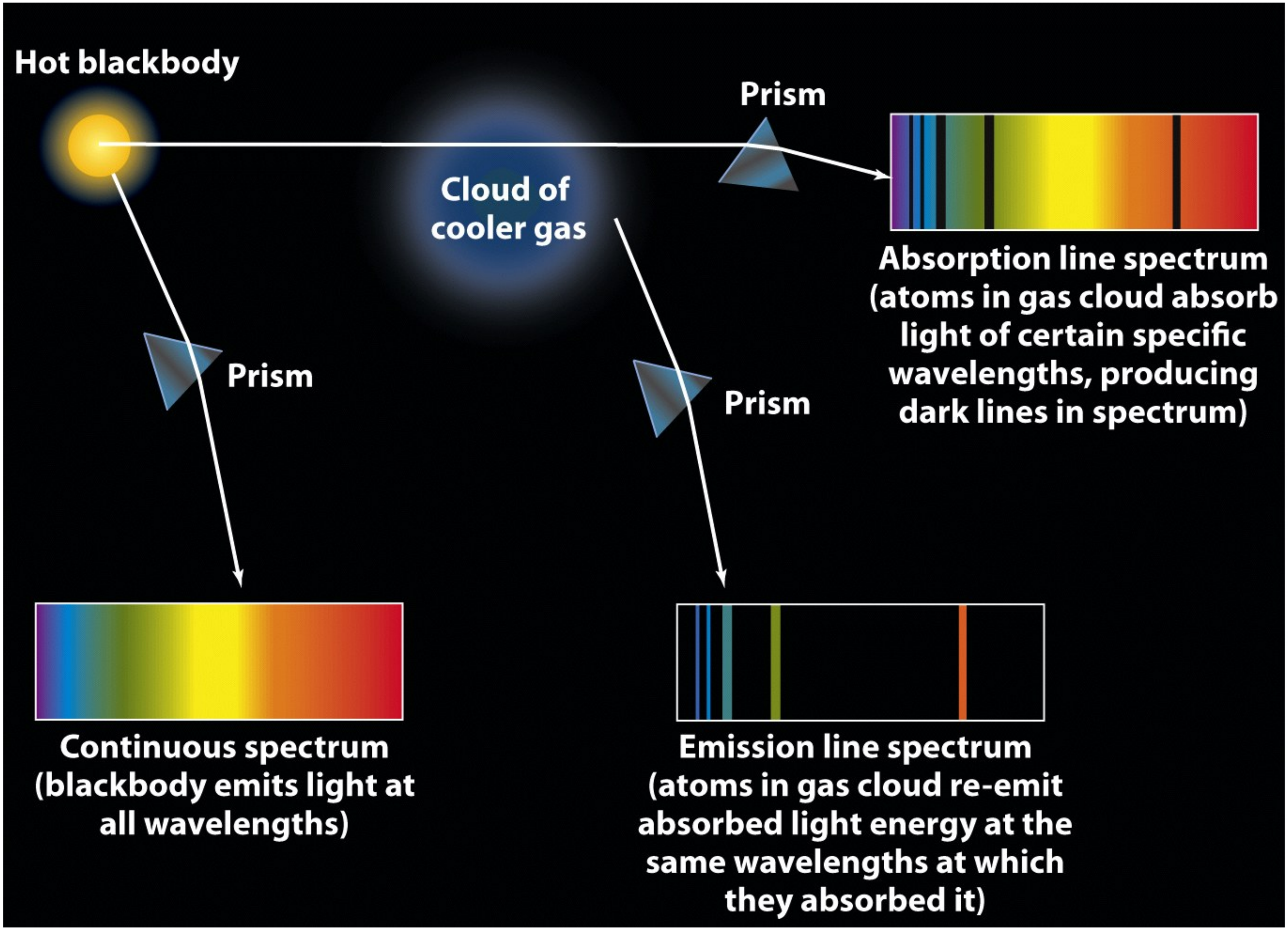

Figure 4-9
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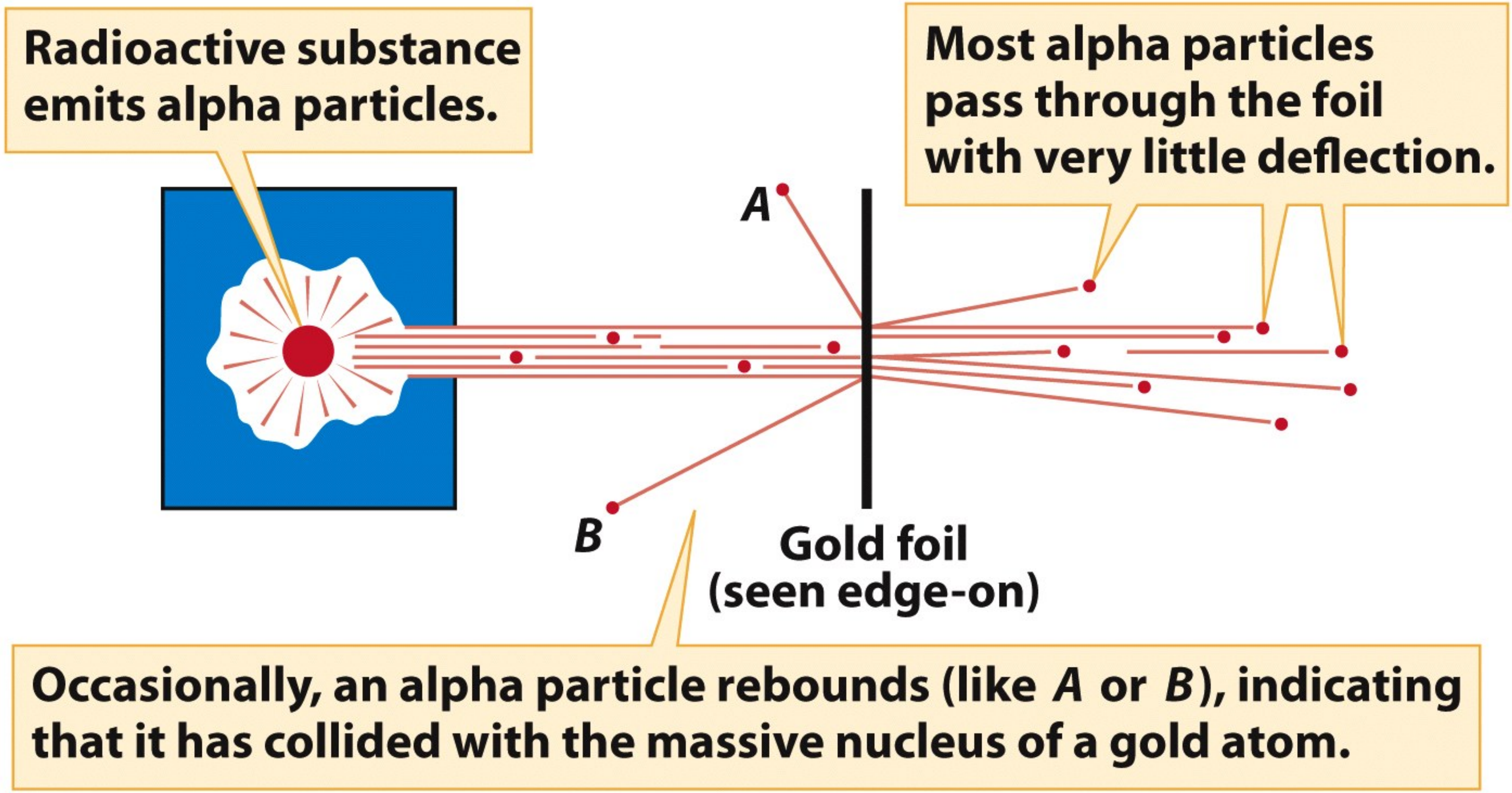

Figure 4-10
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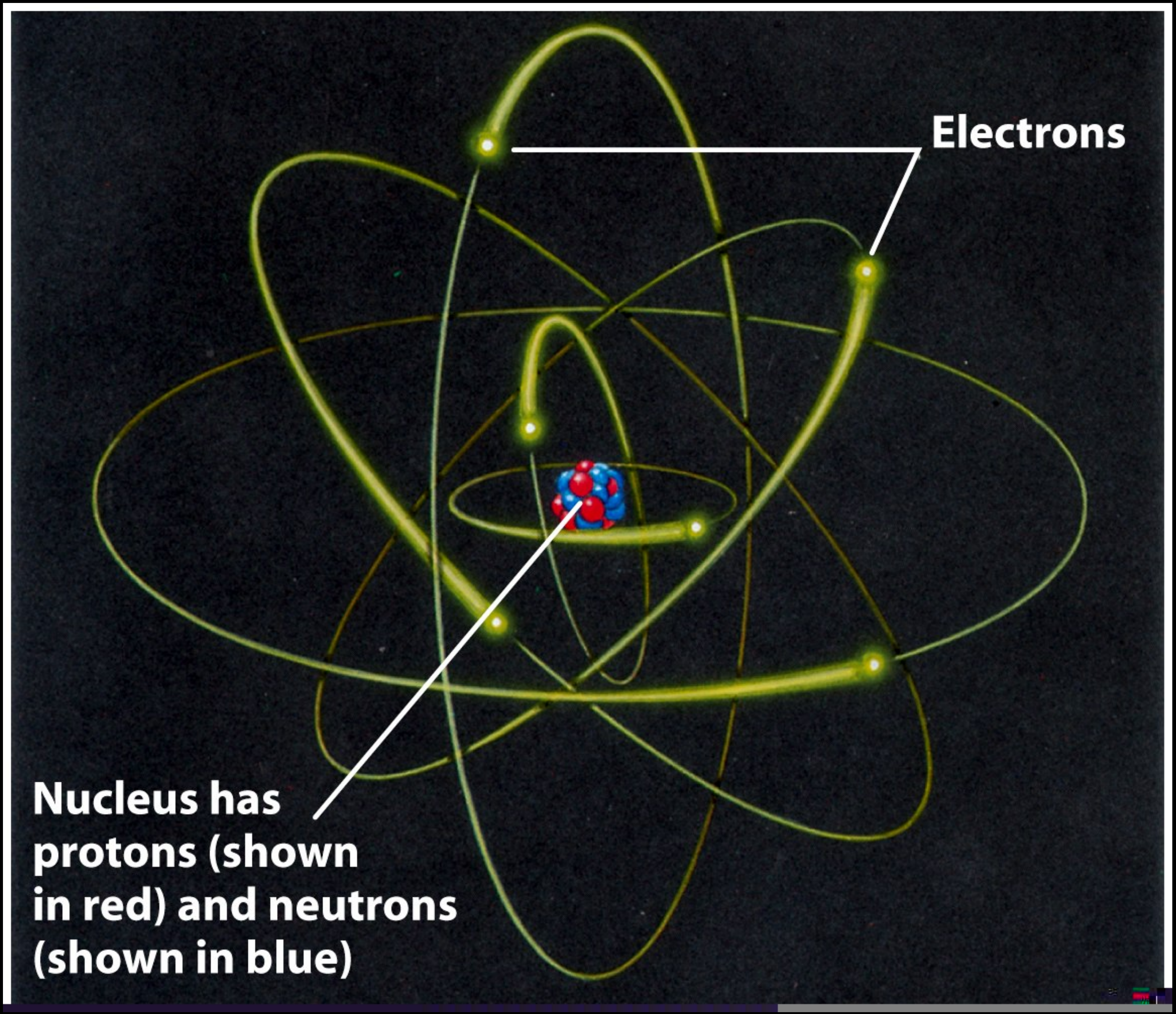
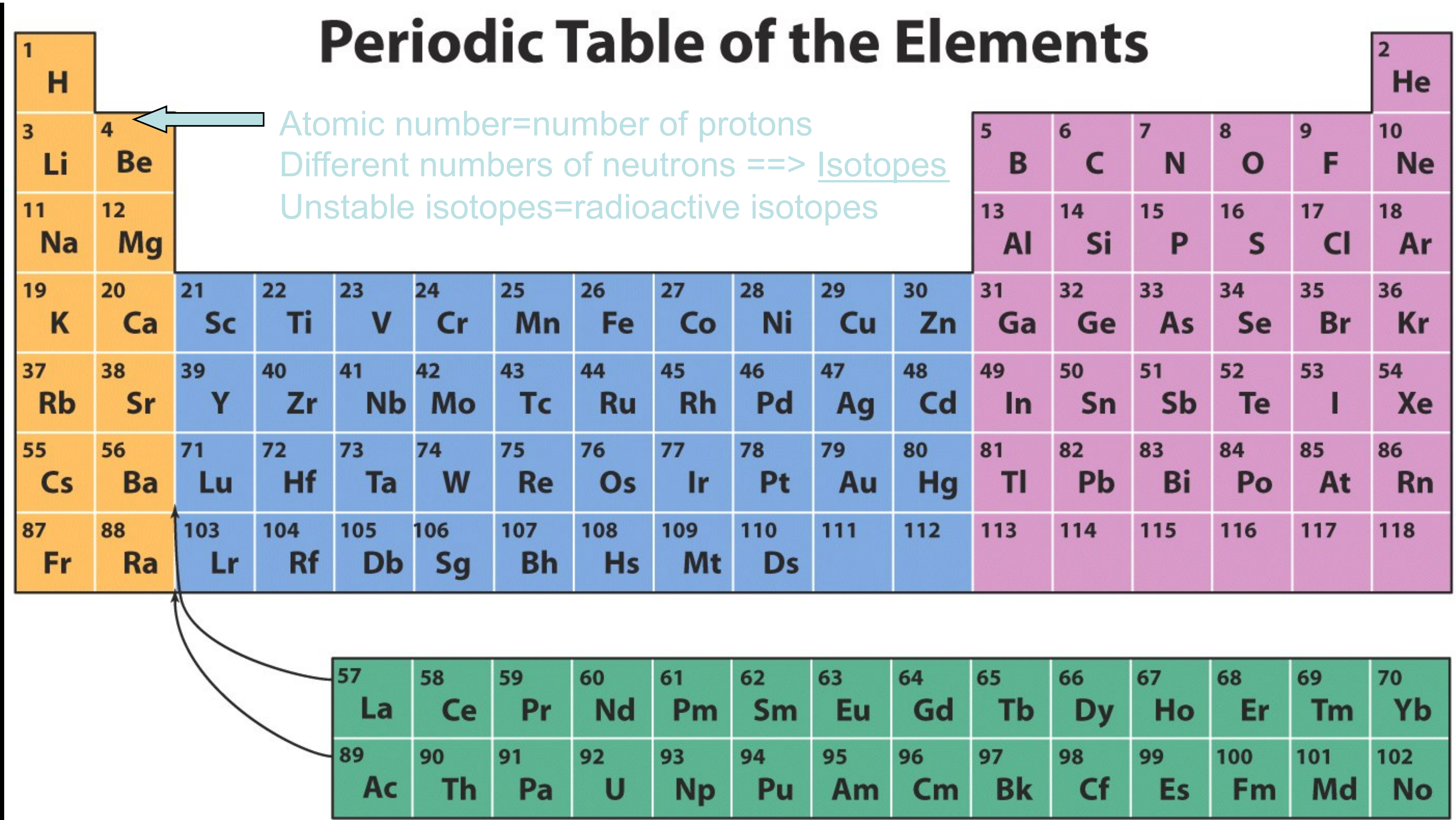

Electrons
Nucleus has protons (shown in red) and neutrons (shown in blue)



- The number of protons in an atom's nucleus is the **atomic number** for that particular element. It determines the element.
- The same element may have different numbers of neutrons in its nucleus.
- These slightly different kinds of elements are called **isotopes.**

TABLE 4-2 The Four Fundamental Forces of Nature

Name	Strength (compared to the strong force)	Range of effect (from each object)
Strong force	1	Inside atomic nuclei
Electromagnetic force	1/137	Throughout the universe
Weak force	10^{-5}	Inside atomic nuclei
Gravitational force	6×10^{-39}	Throughout the universe

Table 4-2
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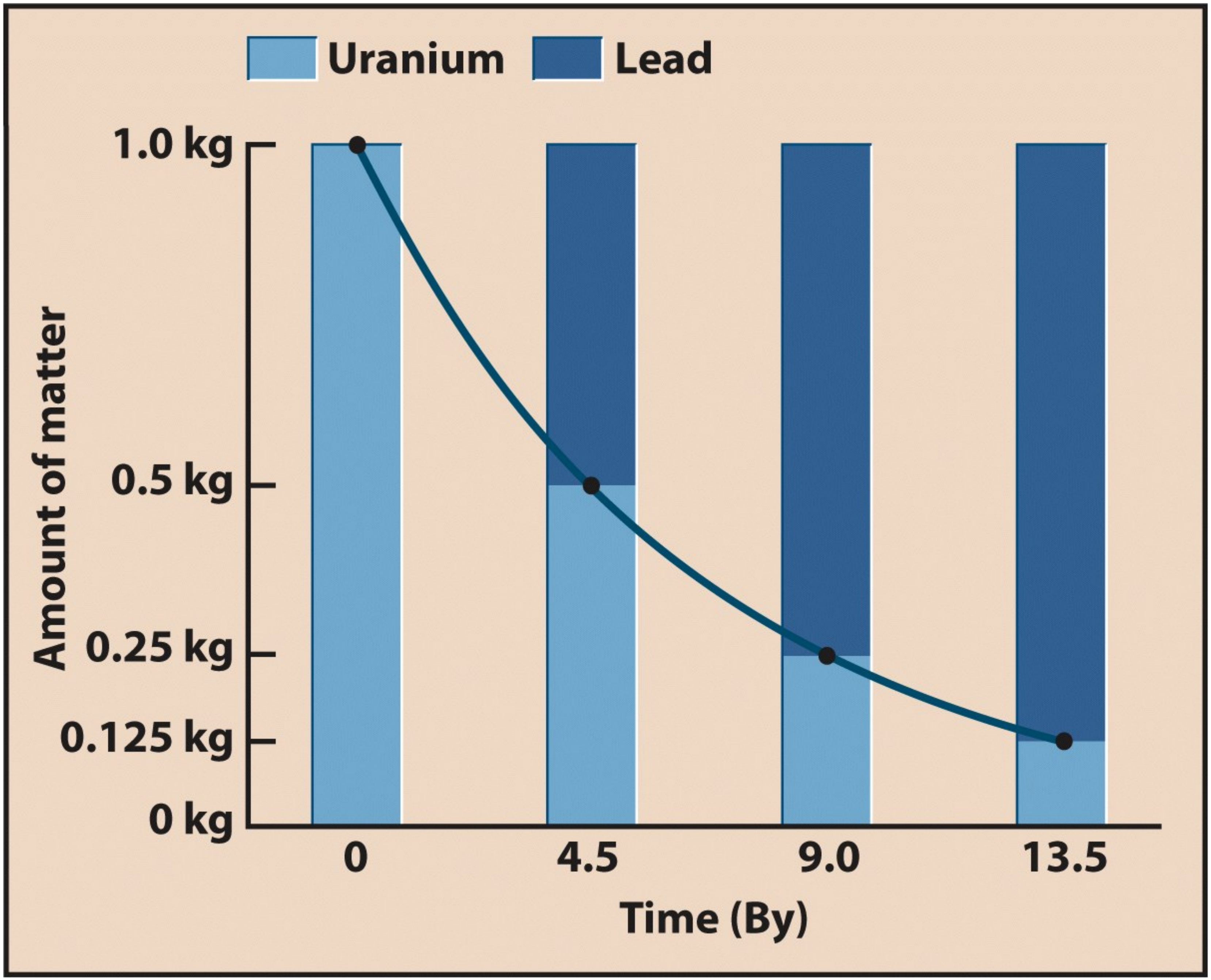

Astronomer's Toolbox 4-2
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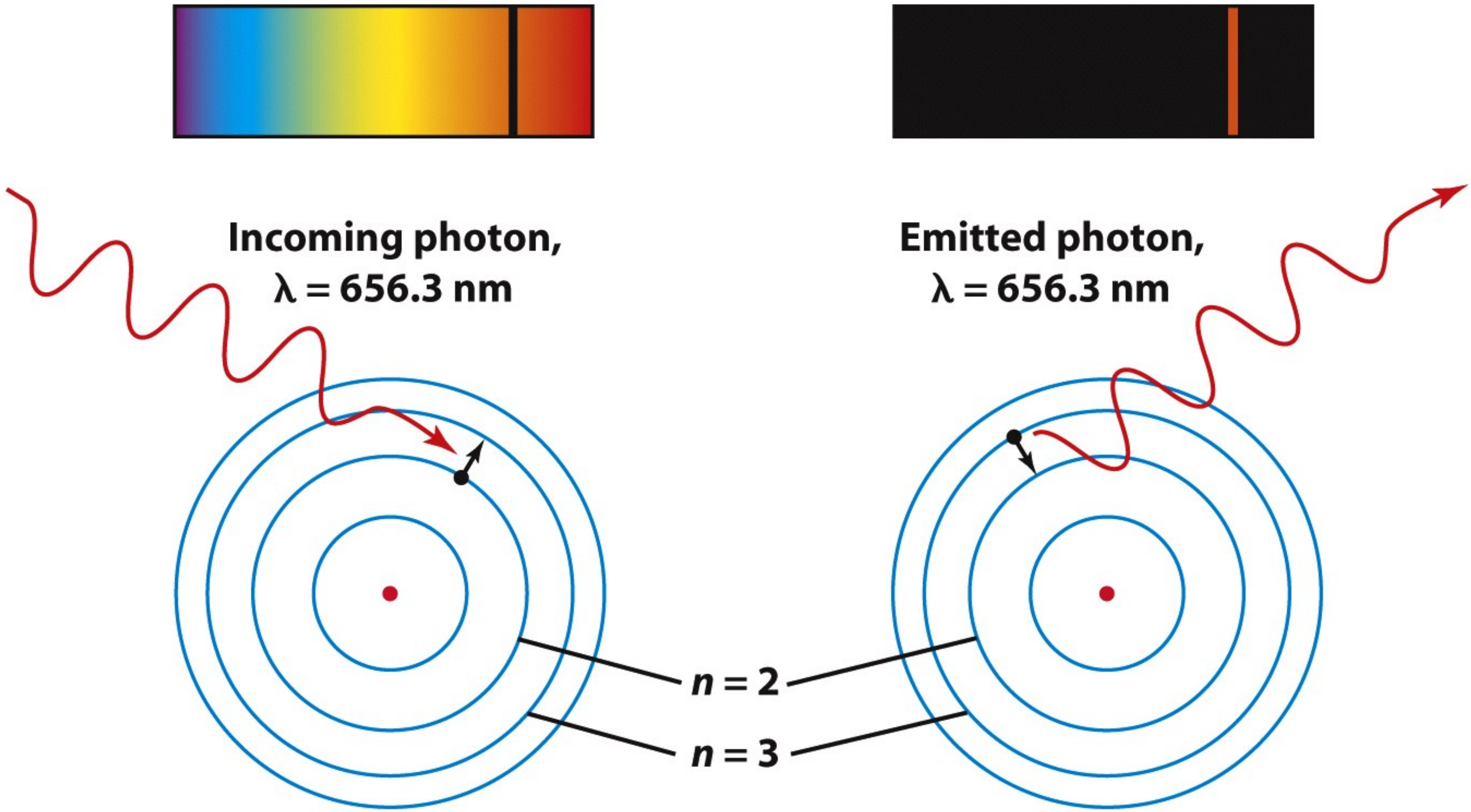

a Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up to the $n = 3$ orbit

b Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon

Figure 4-12
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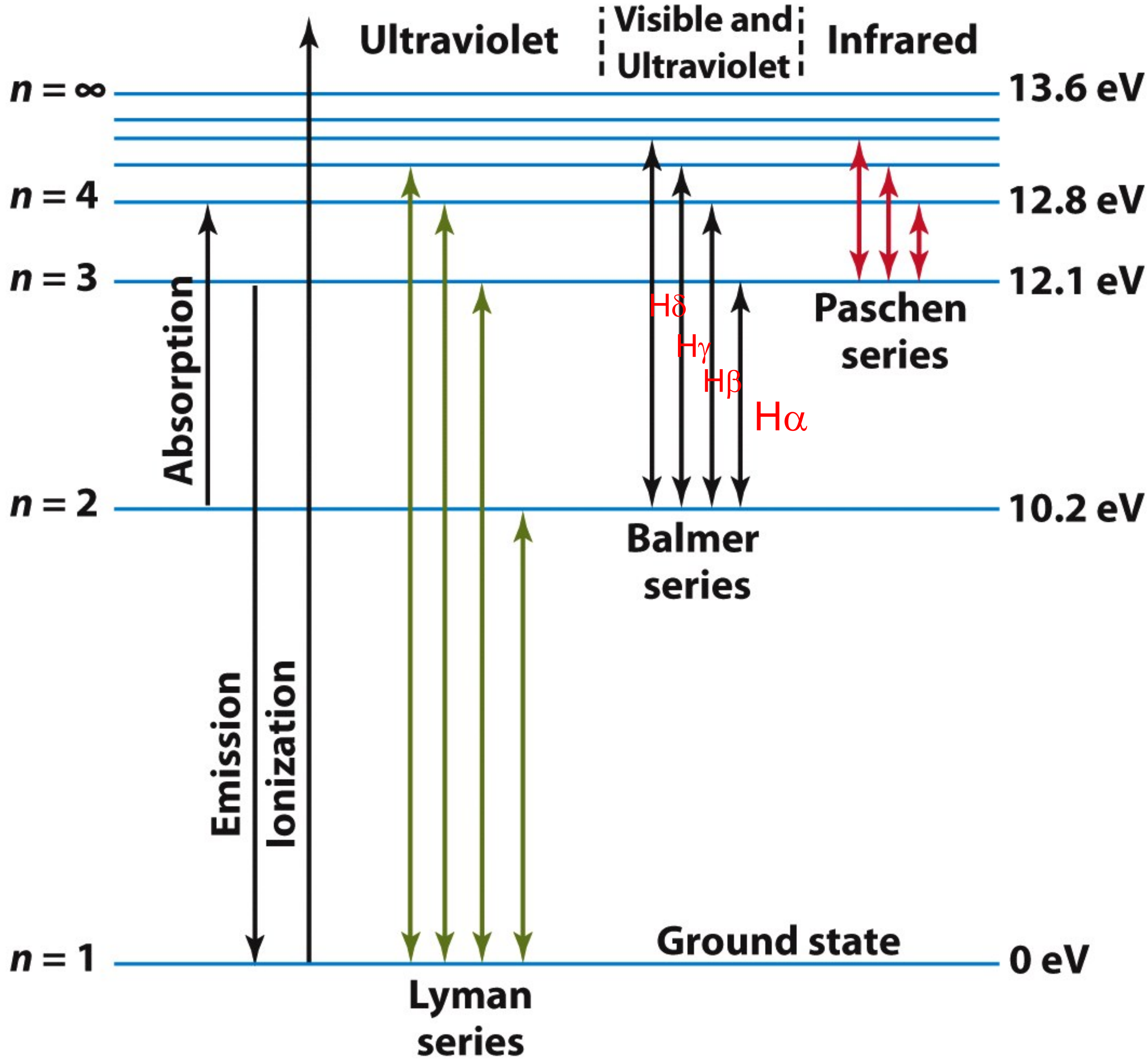

Figure 4-11
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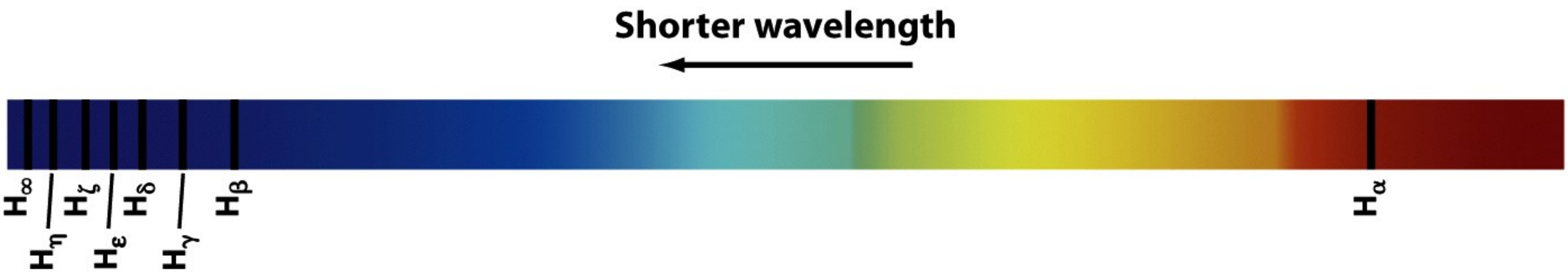

Figure 4-13
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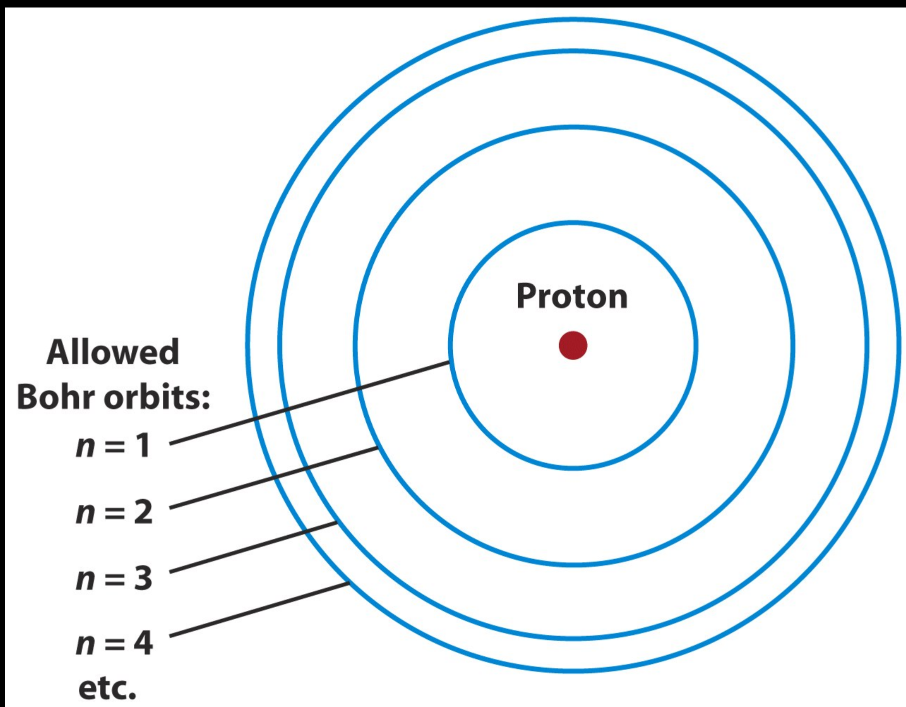
Spectral lines are produced when an electron jumps from one energy level to another within an atom

Classical Bohr model of an atom



- The nucleus of an atom is surrounded by electrons that occupy only certain orbits or energy levels
- When an electron jumps from one energy level to another, it emits or absorbs a photon of appropriate energy (and hence of a specific wavelength). $E=hc/\lambda$
- The spectral lines of a particular element correspond to the various electron transitions between energy levels in atoms of that element.

Stars in the interstellar gas cloud NGC 2363

The hydrogen gas absorbs and reemits red light (Hα)

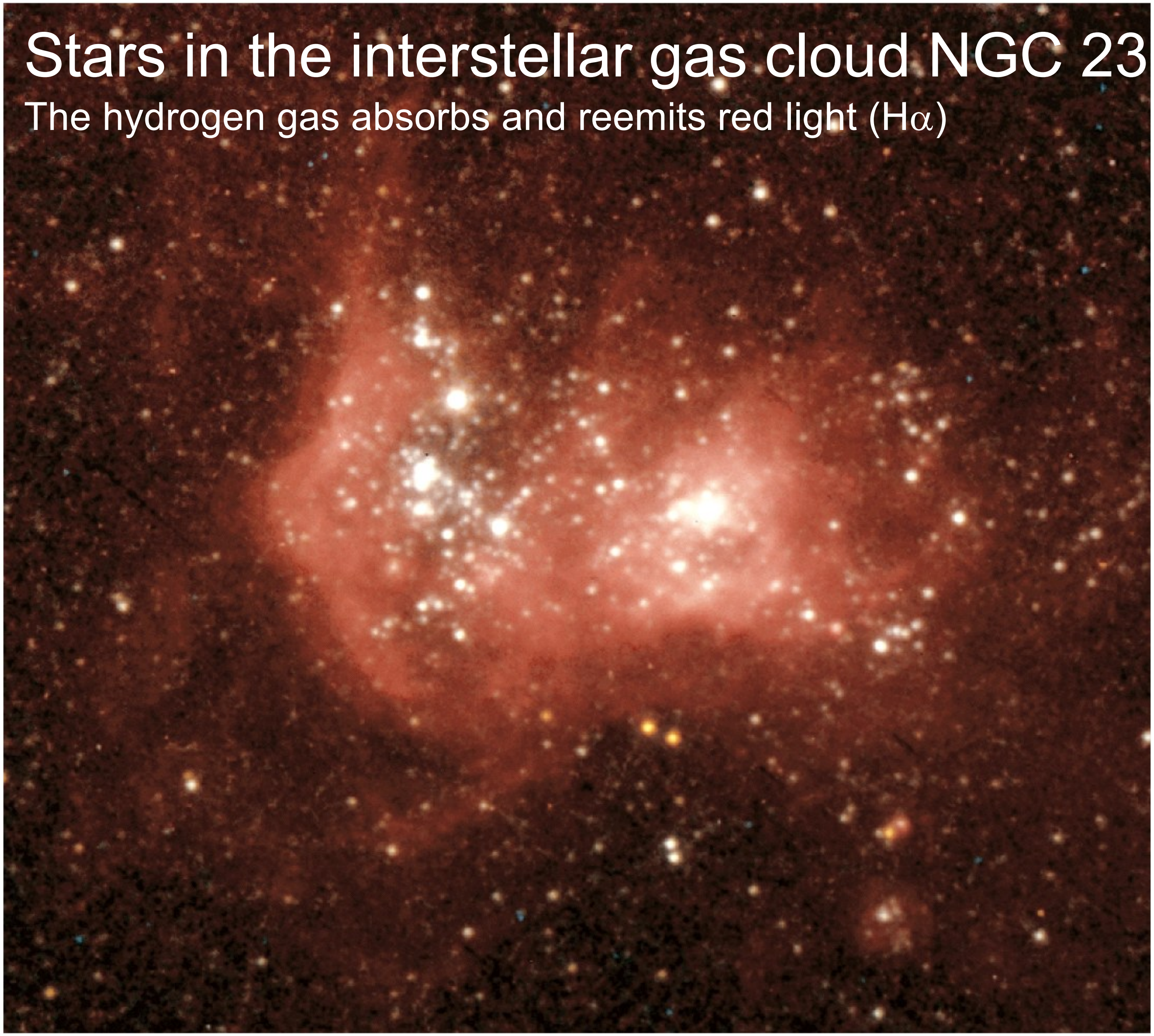


Figure 4-14a
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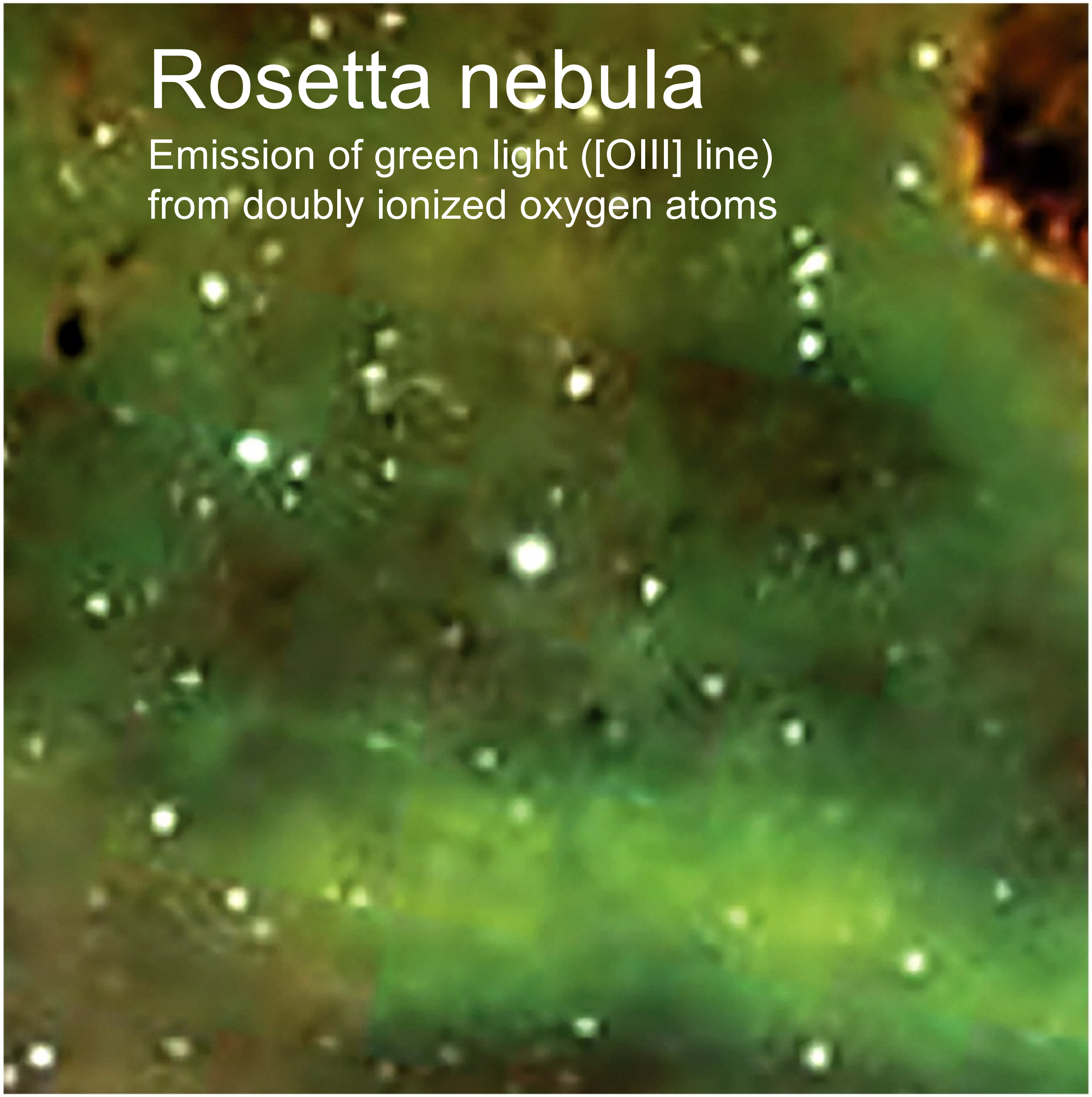

Figure 4-14b
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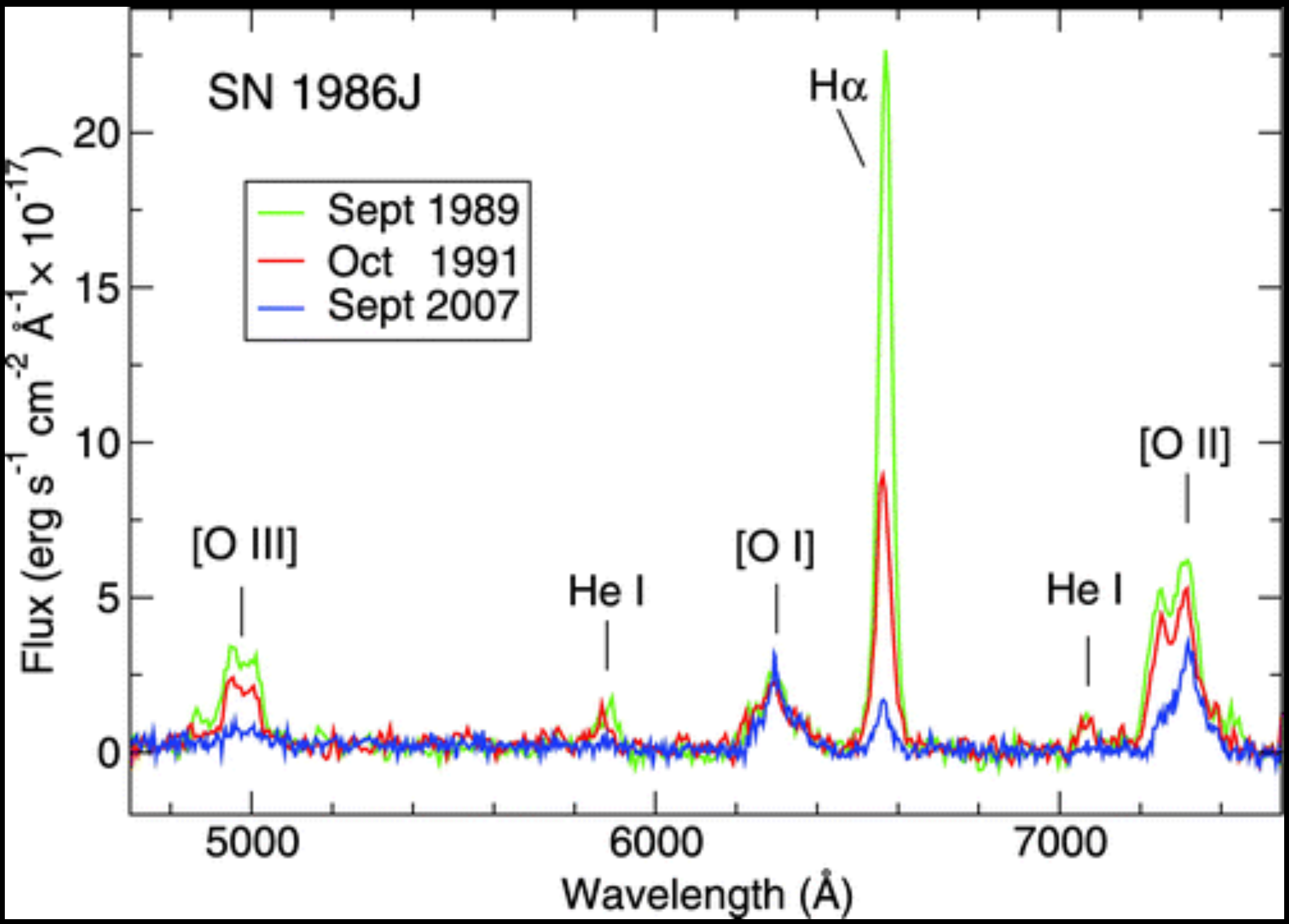
Spectrum of an exploded star, a supernova, 10 Mpc away from earth



- Christian Doppler 1803 - 1853

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

$\Delta\lambda$: wavelength shift
λ_0 : wavelength if source is at rest
v : radial velocity of source
c : speed of light

Doppler shift

Radial velocity of astronomical object can be measured

$v/c = \Delta\lambda/\lambda_0$

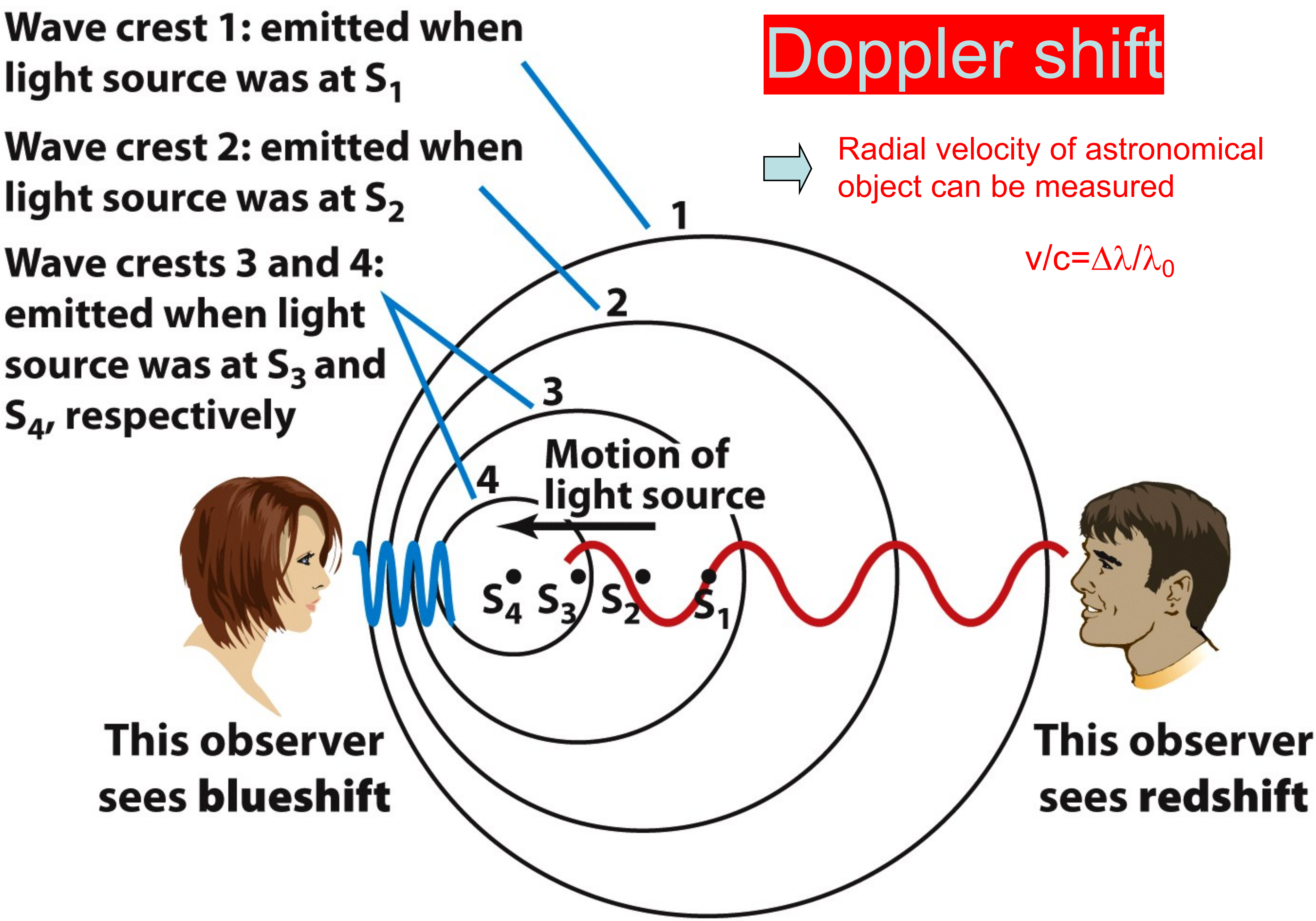


Figure 4-15
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Doppler Shifts

- **Red Shift**: The object is moving away from the observer (+ velocity). Wavelength increases.
- **Blue Shift**: The object is moving towards the observer (- velocity). Wavelength decreases.

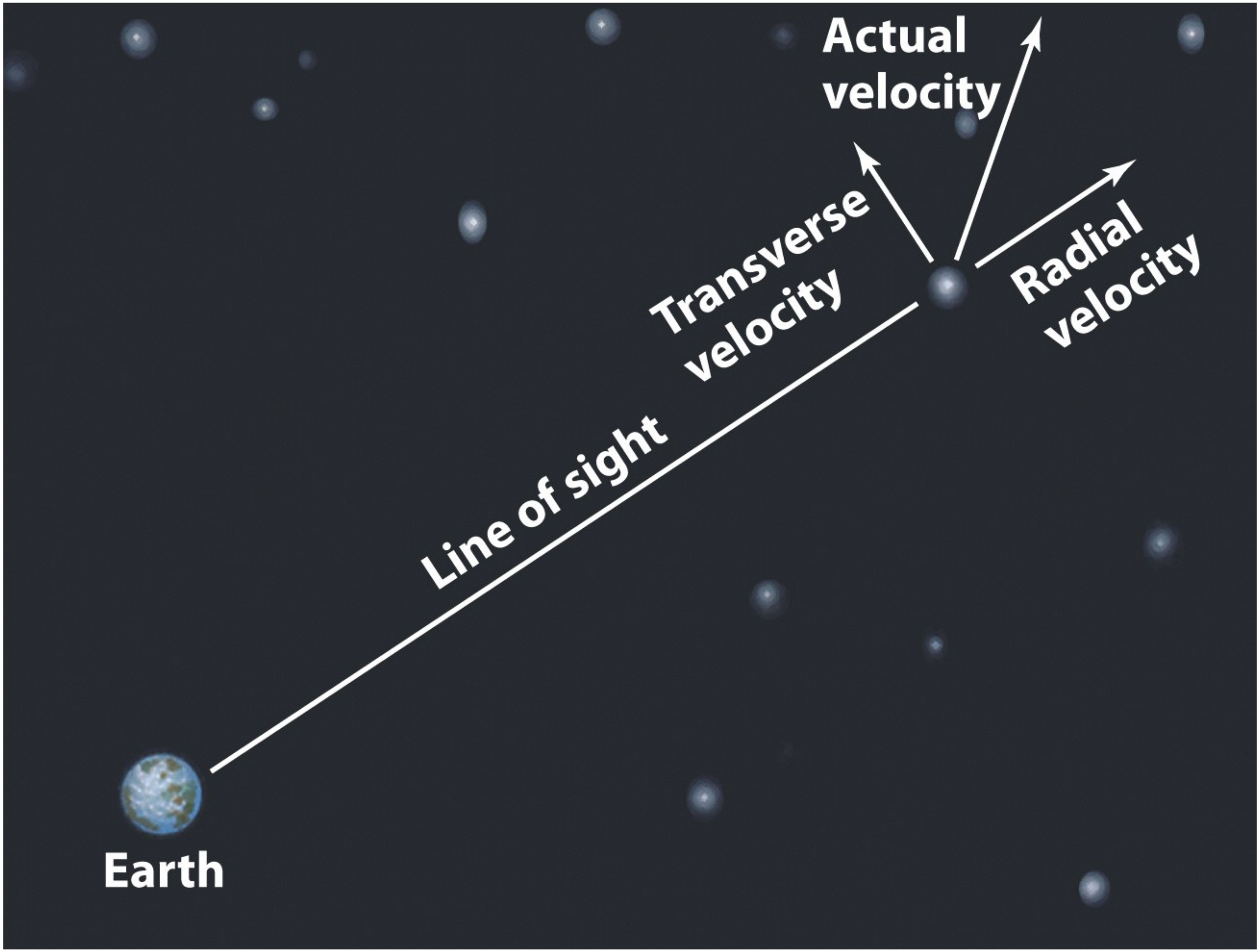

Figure 4-16
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