

Lecture Outline

Chapter 5: Light: The Cosmic Messenger

The Essential Cosmic Perspective

Bennett Donahue Schneider Voit
Seventh Edition

© 2015 Pearson Education, Inc.

5.1 Basic Properties of Light and Matter

Our goals for learning:

- > What is light?
- > What is matter?
- > How do light and matter interact?

© 2015 Pearson Education, Inc.

>What is light?

Light is an **electromagnetic wave**.

But it also comes in "pieces" called **photons**.

"Dual nature of light"

© 2015 Pearson Education, Inc.

The Electromagnetic Spectrum

Wavelength (meters)	Frequency (hertz)	Energy (electron-volts)	Sources on Earth	Cosmic Sources
10^{-11} to 10^{-8}	10^{16} to 10^{22}	10^5 to 10^{11}	radioactive elements	gamma ray burst
10^{-8} to 10^{-6}	10^{14} to 10^{16}	10^1 to 10^5	X-ray microscope	black hole accretion disk
10^{-6} to 10^{-4}	10^{12} to 10^{14}	10^{-1} to 10^1	light bulb	Earth's chromosphere
10^{-4} to 10^{-1}	10^8 to 10^{12}	10^{-5} to 10^{-1}	people	Sun
10^{-1} to 10^1	10^4 to 10^8	10^{-8} to 10^{-2}	radar	planets, star-forming clouds
10^1 to 10^3	10^2 to 10^4	10^{-11} to 10^{-5}	microwave oven	cosmic microwave background
10^3 to 10^6	10^1 to 10^3	10^{-14} to 10^{-8}	radio transmitter	radio galaxy

© 2015 Pearson Education, Inc.

Electromagnetic Spectrum

Frequency: 3.00×10^{15} Hz

Wavelength: 1.00×10^{-7} m

Speed: 3×10^8 m/s

PLAY Electromagnetic Spectrum

© 2015 Pearson Education, Inc.

Wave Properties of Light

The length of a wave is measured from peak to peak.

Frequency tells us how many times any point on the rope (or up and down) each second.

a Shaking one end of a rope up and down generates waves moving along it.

b If you could line up electrons, they would wiggle up and down as light passes by, demonstrating that light is a wave.

Wavelength is the distance between adjacent peaks of the electric (and magnetic) field ...

... while frequency is the number of times each second that the electric (and magnetic) field vibrates up and down (or side to side) at any point.

All light travels with speed $c = 300,000$ km/s

c Light can affect both electrically charged particles and magnets, so we say that light is an electromagnetic wave.

© 2015 Pearson Education, Inc.

Wavelength and Frequency

1 cm wavelength = 1 cm, frequency = 30 GHz

0.5 cm wavelength = $\frac{1}{2}$ cm, frequency = 2×30 GHz = 60 GHz

0.25 cm wavelength = $\frac{1}{4}$ cm, frequency = 4×30 GHz = 120 GHz

wavelength x frequency = speed of light = constant

© 2015 Pearson Education, Inc.

Anatomy of a Wave

Wavelength: the distance between adjacent crests (or troughs)

Amplitude: half the difference in height between a crest and a trough

Frequency: the number of crests that pass through a point (such as the boat) each second. It is measured in units of hertz (Hz), which are cycles per second

Blink rate = Frequency

Speed: how fast the pattern of crests and troughs moves forward

PLAY Anatomy of a Wave

© 2015 Pearson Education, Inc.

Particle Property of Light

- ☐ Particles of light are called **photons**.
- ☐ Each photon has a wavelength and a frequency.
- ☐ The energy of a photon depends on its frequency.

© 2015 Pearson Education, Inc.

Wavelength, Frequency, and Energy

$$\lambda \times f = c$$

λ = wavelength, f = frequency
 $c = 3.00 \times 10^8$ m/s = speed of light

$$E = h \times f = \text{photon energy}$$

$h = 6.626 \times 10^{-34}$ joule \times s

The higher the photon energy the shorter its wavelength

© 2015 Pearson Education, Inc.

What is matter?

- ☐ Proton
 - +1 charge
- ☐ Electron
 - -1 charge
- ☐ Neutron
 - No charge

Ten million atoms could fit end to end across this dot.

The nucleus is nearly 100,000 times smaller than the atom but contains nearly all of its mass.

Atom: Electrons are "smeared out" in a cloud around the nucleus.

Nucleus: Contains positively charged protons (red) and neutral neutrons (gray).

10⁻¹⁰ meter

A single drop of water contains 10²² atoms

© 2015 Pearson Education, Inc.

Atomic Terminology

- ☐ Atomic Number = # of protons in nucleus
- ☐ Atomic Mass Number = # of protons + # of neutrons

atomic number = number of protons
 atomic mass number = number of protons + neutrons
 (A neutral atom has the same number of electrons as protons.)

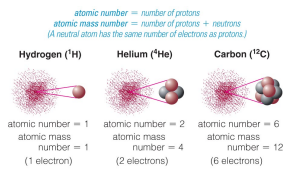
Hydrogen (¹ H)	Helium (⁴ He)	Carbon (¹² C)
atomic number = 1	atomic number = 2	atomic number = 6
atomic mass number = 1	atomic mass number = 4	atomic mass number = 12
(1 electron)	(2 electrons)	(6 electrons)

© 2015 Pearson Education, Inc.

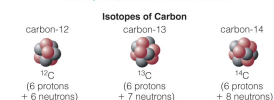
Atomic Terminology

- **Isotope:** same # of protons but different # of neutrons (^4He , ^3He)

- **Molecules:** consist of two or more atoms (H_2O , CO_2)



Different isotopes of a given element contain the same number of protons, but different numbers of neutrons.



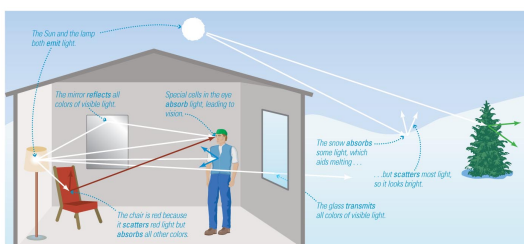
© 2015 Pearson Education, Inc.

How do light and matter interact?

- **Emission**
 - Light bulb
- **Absorption**
 - Red chair
- **Transmission**
 - Glass
- **Reflection or scattering**
 - Mirror or snow

© 2015 Pearson Education, Inc.

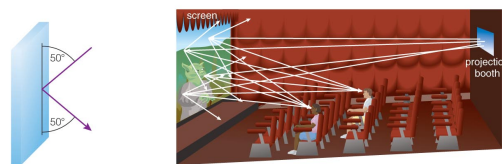
Interactions of Light with Matter



Interactions between light and matter determine the appearance of everything around us.

© 2015 Pearson Education, Inc.

Reflection and Scattering



Mirror reflects light in a particular direction.

Movie screen scatters light in all directions.

© 2015 Pearson Education, Inc.

Recap

- **What is light?**
 - Light is a form of energy.
 - Light comes in many colors that combine to form white light.
 - Light is an electromagnetic wave that also comes in individual "pieces" called photons. Each photon has a precise wavelength, frequency, and energy.
 - Forms of light are radio waves, microwaves, infrared, visible light, ultraviolet, X rays, and gamma rays.
- **What is matter?**
 - Ordinary matter is made of atoms, which are made of protons, neutrons, and electrons.

© 2015 Pearson Education, Inc.

5.2 Learning from Light

Our goals for learning:

- What are the three basic types of spectra?
- How does light tell us what things are made of?
- How does light tell us the temperatures of planets and stars?
- How does light tell us the speed of a distant object?

© 2015 Pearson Education, Inc.

➤ What are the three basic types of spectra?

Spectra of astrophysical objects are usually combinations of these three basic types.

© 2015 Pearson Education, Inc.

Introduction to Spectroscopy

- The Sun
- Toaster oven filament
- Neon lamp
- Spica (blue, O star)
- Reflected sunlight from a green leaf

Visual spectrum

Plot of Intensity vs. wavelength

PLAY Introduction to Spectroscopy

© 2015 Pearson Education, Inc.

Three Types of Spectra

The Details of Spectra - Illustrating Kirchhoff's Laws

Show	Continuous Spectrum	The spectrum shows a smooth, continuous rainbow of light. A graph of the spectrum is also continuous, noting that intensity varies slightly at different wavelengths.
Show	Emission Line Spectrum	We see bright emission lines at specific wavelengths (colors), but no other light. The graph shows an upward spike at the wavelength of each emission line.
Show	Absorption Line Spectrum	We see dark absorption lines where the cloud has absorbed light of specific wavelengths (colors). The graph shows a dip in intensity at the wavelength of each absorption line.

PLAY Illustrating Kirchhoff's Laws

© 2015 Pearson Education, Inc.

Continuous Spectrum

The light bulb produces light of all visible wavelengths (colors).

The spectrum shows a smooth, continuous rainbow of light.

A graph of the spectrum is also continuous, noting that intensity varies slightly at different wavelengths.

Hot light source

prism

Intensity

wavelength

Continuous Spectrum

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

© 2015 Pearson Education, Inc.

Emission Line Spectrum

The atoms in a warm gas cloud emit light only at specific wavelengths (colors) determined by the cloud's composition and temperature.

We see bright emission lines at specific wavelengths (colors), but no other light.

The graph shows an upward spike at the wavelength of each emission line.

cloud of gas

prism

Intensity

wavelength

Emission Line Spectrum

☐ 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.

© 2015 Pearson Education, Inc.

Absorption Line Spectrum

If light from a hot source passes through a cooler gas cloud, atoms in the cloud absorb light at wavelengths determined by the cloud's composition and temperature.

We see dark absorption lines where the cloud has absorbed light of specific wavelengths (colors).

The graph shows a dip in intensity at the wavelength of each absorption line.

hot light source

cloud of gas

prism

Intensity

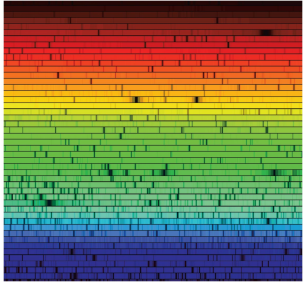
wavelength

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.

© 2015 Pearson Education, Inc.

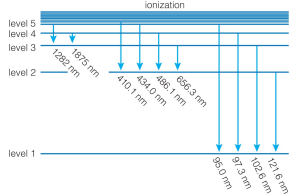
➤ How does light tell us what things are made of?



Spectrum of the Sun

© 2015 Pearson Education, Inc.

Energy Levels in Atoms



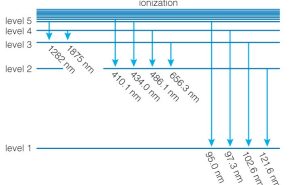
- Each type of atom has a unique set of energy levels.
- Each transition corresponds to a unique photon energy, frequency, and wavelength.

a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

Energy levels of hydrogen


© 2015 Pearson Education, Inc.

Emission and Absorption Lines



- Downward transitions produce a unique pattern of emission lines.

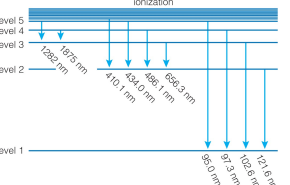
a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.



b This spectrum shows emission lines produced by downward transitions between higher levels and level 2 in hydrogen.


© 2015 Pearson Education, Inc.

Chemical Fingerprints



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

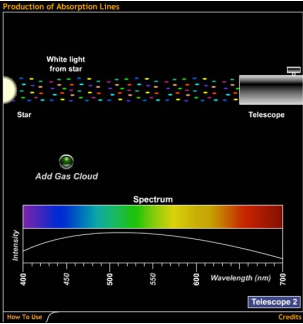
a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.



c This spectrum shows absorption lines produced by upward transitions between level 2 and higher levels in hydrogen.

© 2015 Pearson Education, Inc.

Production of Absorption Lines



White light from star

Star

Telescope

Add Gas Cloud

Spectrum

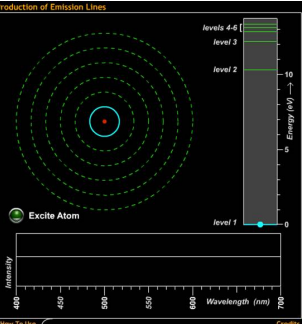
Intensity

Wavelength (nm)

Telescope 2

© 2015 Pearson Education, Inc.

Production of Emission Lines



Production of Emission Lines

Excite Atom

Intensity

Wavelength (nm)

Energy (eV)

© 2015 Pearson Education, Inc.

Chemical Fingerprints

helium

sodium

neon

Each type of atom has a unique spectral fingerprint.

© 2015 Pearson Education, Inc.

Composition of a Mystery Gas

Sample 1

- H - Hydrogen
- He - Helium
- Li - Lithium
- C - Carbon
- Na - Sodium
- Ne - Neon

PLAY Composition of a Mystery Gas

© 2015 Pearson Education, Inc.

Chemical Fingerprints

He He He O⁺ He Ne⁺⁺

hydrogen lines

Observing the fingerprints in a spectrum tells us which kinds of atoms are present.

© 2015 Pearson Education, Inc.

Example: Solar Spectrum

© 2015 Pearson Education, Inc.

Thought Question

Which letter(s) label(s) absorption lines?

A B C D E

© 2015 Pearson Education, Inc.

Thought Question

Which letter(s) label(s) absorption lines?

A B C D E

© 2015 Pearson Education, Inc.

Thought Question

Which letter(s) label(s) the peak (greatest intensity) of infrared light?

© 2015 Pearson Education, Inc.

Thought Question

Which letter(s) label(s) the peak (greatest intensity) of infrared light?

© 2015 Pearson Education, Inc.

Thought Question

Which letter(s) label(s) emission lines?

© 2015 Pearson Education, Inc.

Thought Question

Which letter(s) label(s) emission lines?

© 2015 Pearson Education, Inc.

How does light tell us the temperatures of planets and stars?

At relatively low temperatures, the poker emits only infrared light that we cannot see.

As it gets hotter, it begins to glow.

It gets brighter as it heats up (demonstrating Law 1) . . .

. . . and changes from red to white in color (demonstrating Law 2).

© 2015 Pearson Education, Inc.

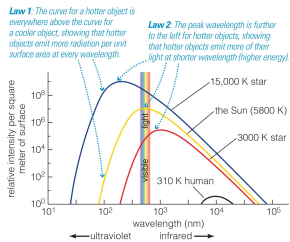
Thermal Radiation

- 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**.

© 2015 Pearson Education, Inc.

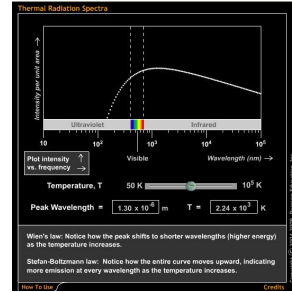
Properties of Thermal Radiation

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



© 2015 Pearson Education, Inc.

Wien's Law



PLAY Wien's Law

© 2015 Pearson Education, Inc.

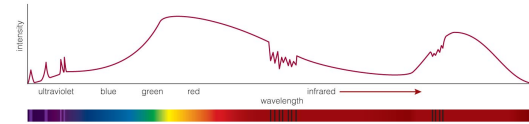
Thought Question

Which is hottest?

- A blue star
- A red star
- A planet that emits only infrared light

© 2015 Pearson Education, Inc.

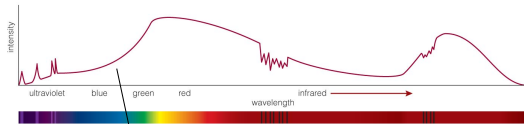
Interpreting an Actual Spectrum



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

© 2015 Pearson Education, Inc.

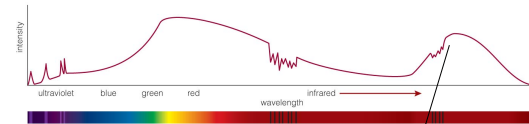
What is this object?



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.

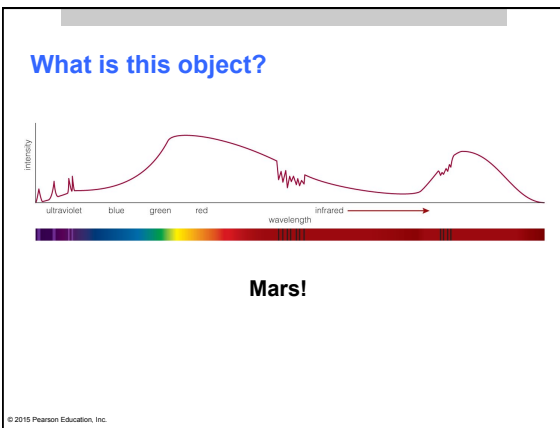
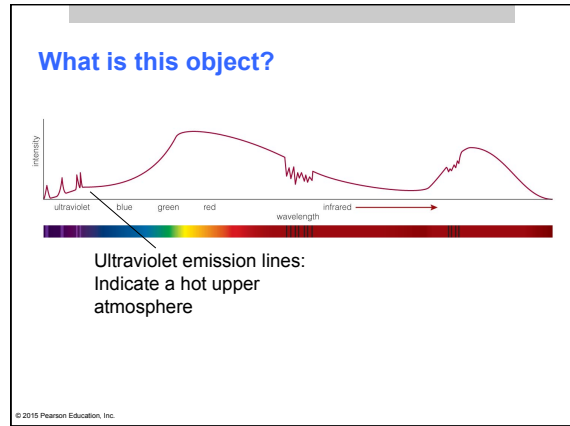
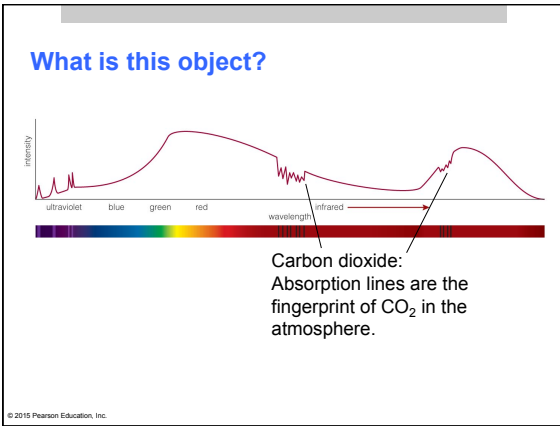
© 2015 Pearson Education, Inc.

What is this object?



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

© 2015 Pearson Education, Inc.



How does light tell us the speed of a distant object?

train stationary

The pitch this person hears... is the same as the pitch this person hears.

a. The whistle sounds the same no matter where you stand near a stationary train.

train moving to right

Behind the train, sound waves stretch to longer wavelength (lower frequency and pitch). In front of the train, sound waves bunch up to shorter wavelength (higher frequency and pitch).

b. For a moving train, the sound you hear depends on whether the train is moving toward you or away from you.

light source moving to right

The light source is moving away from this person so the light appears redder (longer wavelengths). The light source is moving toward this person so the light appears bluer (shorter wavelengths).

c. We get the same basic effect from a moving light source (although the shifts are usually too small to notice with our eyes).

The Doppler Effect

© 2015 Pearson Education, Inc.

The Doppler Effect

PLAY **Hearing the Doppler Effect as a Car Passes**

© 2015 Pearson Education, Inc.

Explaining the Doppler Effect

PLAY **Understanding the Cause of the Doppler Effect**

© 2015 Pearson Education, Inc.

Same for light

PLAY The Doppler Effect for Visible Light

© 2015 Pearson Education, Inc.

Measuring the Shift

Laboratory spectrum
Lines at rest wavelengths. Stationary

Object 1 Lines redshifted:
Object moving away from us. Moving Away

Object 2 Greater redshift:
Object moving away faster than object 1. Away Faster

Object 3 Lines blueshifted:
Object moving toward us. Moving Toward

Object 4 Greater blueshift:
Object moving toward us faster than object 3. Toward Faster

Blueshift object is moving towards us.

Redshift object is moving away from us.

© 2015 Pearson Education, Inc.

The amount of blue or red shift tells us an object's speed toward or away from us.

PLAY The Doppler Shift of an Emission-Line Spectrum

© 2015 Pearson Education, Inc.

Doppler shift tells us ONLY about the part of an object's motion toward or away from us.

Star 1 is moving directly away from us, so the Doppler shift tells us its full speed.

Star 2 is moving across our line of sight, but not toward or away from us. The Doppler shift measures no speed at all.

Star 3 is moving diagonally away from us. The Doppler shift tells us the part of the star's speed away from us... but not the part of the speed across our line of sight.

MA INTERACTIVE FIGURE

© 2015 Pearson Education, Inc.

Measuring Redshift

PLAY The Doppler Shift of an Emission-Line Spectrum

© 2015 Pearson Education, Inc.

Measuring Redshift

PLAY Doppler Shift of Absorption Lines

© 2015 Pearson Education, Inc.

Measuring Velocity

PLAY Determining the Velocity of a Gas Cloud

© 2015 Pearson Education, Inc.

Measuring Velocity

PLAY Determining the Velocity of a Cold Cloud of Hydrogen Gas

© 2015 Pearson Education, Inc.

Recap

- What are the three basic types of spectra?
 - Continuous spectrum, emission line spectrum, absorption line spectrum
- How does light tell us what things are made of?
 - Each atom has a unique fingerprint.
 - We can determine which atoms something is made of by looking for their fingerprints in the spectrum.

© 2015 Pearson Education, Inc.

- How does light tell us the temperatures of planets and stars?
 - Nearly all large or dense objects emit a continuous spectrum that depends on temperature.
 - The spectrum of that thermal radiation tells us the object's temperature.

© 2015 Pearson Education, Inc.

- How does light tell us the speed of a distant object?
 - The Doppler effect tells us how fast an object is moving toward or away from us.
 - Blueshift: objects moving toward us
 - Redshift: objects moving away from us

© 2015 Pearson Education, Inc.

5.3 Collecting Light with Telescopes

Our goals for learning:

- How do telescopes help us learn about the universe?
- Why do we put telescopes into space?

© 2015 Pearson Education, Inc.

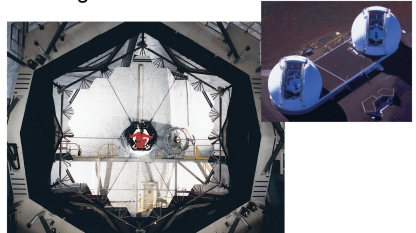
➤ How do telescopes help us learn about the universe?

- ❑ Telescopes collect more light than our eyes ⇒ **light-collecting area**
- ❑ Telescopes can see more detail than our eyes ⇒ **angular resolution**
- ❑ Telescopes/instruments can detect light that is invisible to our eyes (e.g., infrared, ultraviolet)

© 2015 Pearson Education, Inc.

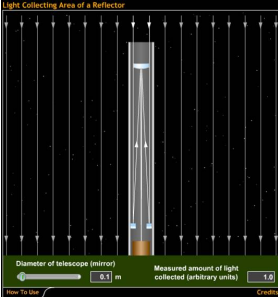
Bigger is better

1. Larger light-collecting area
2. Better angular resolution



© 2015 Pearson Education, Inc.

Bigger is better




PLAY Light Collecting Area of a Reflector

© 2015 Pearson Education, Inc.

Angular Resolution

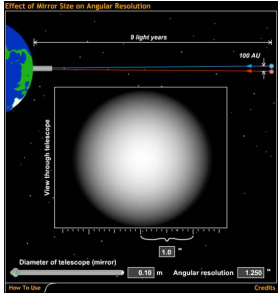
- ❑ The *minimum* angular separation that the telescope can distinguish



PLAY Angular Resolution Explained Using Approaching Car Lights

© 2015 Pearson Education, Inc.

Angular Resolution: Smaller Is Better

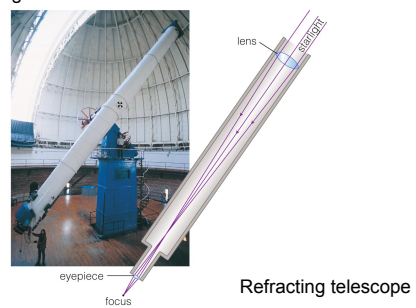


PLAY Effect of Mirror Size on Angular Resolution

© 2015 Pearson Education, Inc.

Basic Telescope Design

- ❑ Refracting: lenses



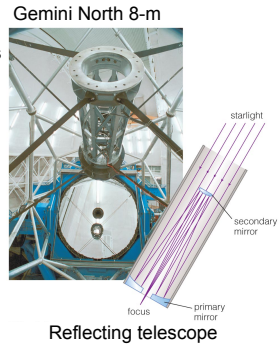
Yerkes 1-m refractor

Refracting telescope

© 2015 Pearson Education, Inc.

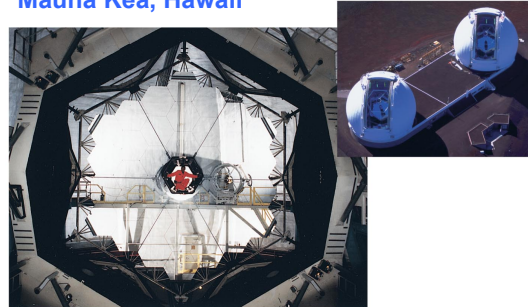
Basic Telescope Design

- Reflecting: mirrors
- Most research telescopes today are reflecting

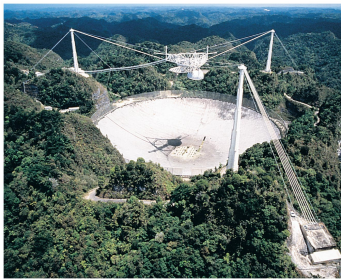


© 2015 Pearson Education, Inc.

Keck I and Keck II Mauna Kea, Hawaii



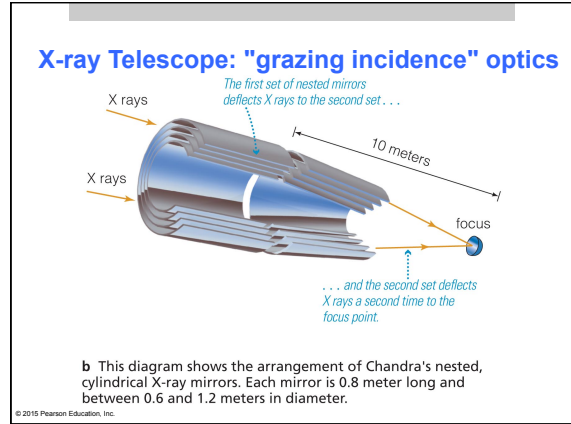
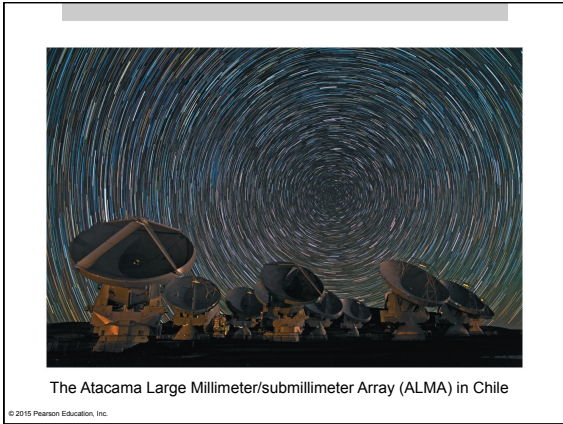
Different designs for different wavelengths of light



Interferometry

- This technique allows two or more small telescopes to work together to obtain the *angular resolution* of a larger telescope.





Why do we put telescopes into space?

It is NOT because they are closer to the stars!

Recall our 1-to-10 billion scale:

- Sun size of grapefruit
- Earth size of a tip of a ballpoint pen, 15 m from Sun
- Nearest stars 4000 km away
- Hubble orbit microscopically above tip of a ballpoint pen-size Earth

© 2015 Pearson Education, Inc.

Observing problems due to Earth's atmosphere

1. Light pollution

© 2015 Pearson Education, Inc.

2. Turbulence causes *twinkling* ⇒ blurs images

Star viewed with ground-based telescope

View from Hubble Space Telescope

© 2015 Pearson Education, Inc.

3. Atmosphere absorbs most of EM spectrum, including all UV and X ray and most infrared.

major space observatories

Fermi Swift Chandra Hubble Spitzer Planck

gamma ray X ray ultraviolet visible infrared radio

100 km

10 km

sea level

© 2015 Pearson Education, Inc.

Telescopes in space solve all three problems.

- Location/technology can help overcome light pollution and turbulence.
- Nothing short of going to space can solve the problem of atmospheric absorption of light.

But extremely expensive!



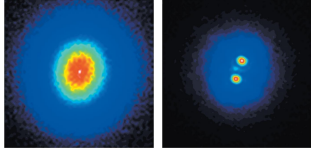
a Artist's illustration of the Chandra X-Ray Observatory, which orbits Earth.

© 2015 Pearson Education, Inc.

Improvements for ground-based telescopes

Adaptive optics

- Rapid changes in mirror shape compensate for atmospheric turbulence.



a Atmospheric distortion makes this ground-based image of a double star look like a single star.

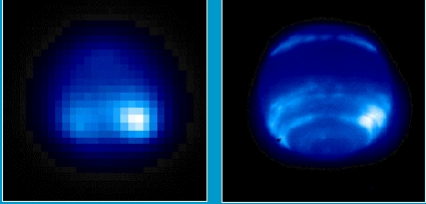
b When the same telescope is used with adaptive optics, the two stars are clearly distinguished. The angular separation between the two stars is 0.28 arcsecond.

Without adaptive optics With adaptive optics

© 2015 Pearson Education, Inc.

Adaptive optics: Neptune

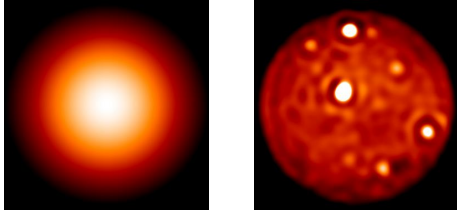
without *with*



© 2015 Pearson Education, Inc.


Adaptive Optics

- Jupiter's moon Io observed with the Keck telescope



without adaptive optics with adaptive optics

© 2015 Pearson Education, Inc.



The Moon would be a great spot for an observatory (but at what price?).

© 2015 Pearson Education, Inc.

Recap

- How do telescopes help us learn about the universe?
 - We can see fainter objects and more detail than we can see by eye. Specialized telescopes allow us to learn more than we could from visible light alone.
- Why do we put telescopes into space?
 - They are above Earth's atmosphere and therefore not subject to light pollution, atmospheric distortion, or atmospheric absorption of light.

© 2015 Pearson Education, Inc.