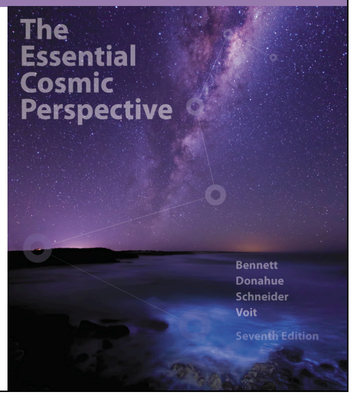
Lecture Outline

Chapter 5: Light: The Cosmic Messenger



5.1 Basic Properties of Light and Matter

Our goals for learning:

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

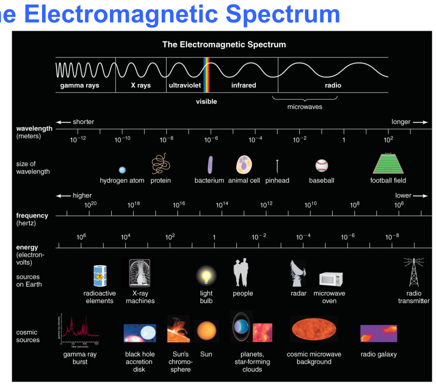
What is light?

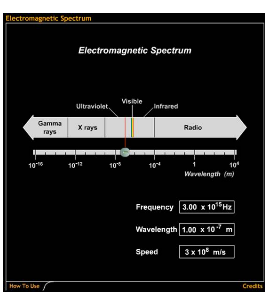
Light is an **electromagnetic wave.**

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

"Dual nature of light"

The Electromagnetic Spectrum

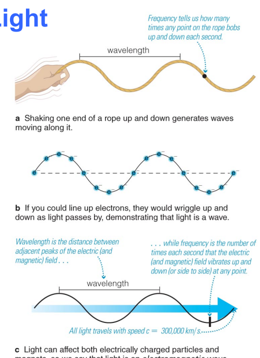




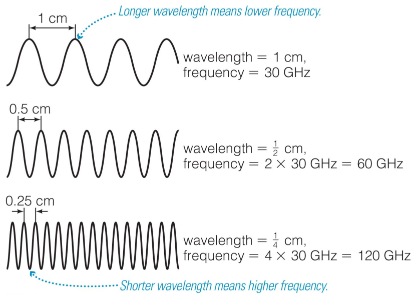
PLAY Electromagnetic Spectrum

Wave Properties of Light

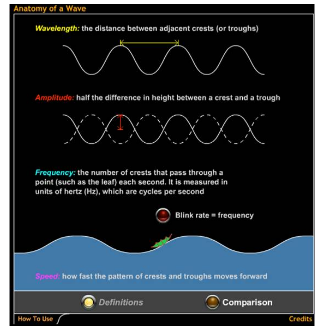
The length of a wave is measured from peak to peak.



Wavelength and Frequency



wavelength x frequency = speed of light = constant



PLAY Anatomy of a Wave

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.

Wavelength, Frequency, and Energy

$$\lambda \times f = c$$

$$\lambda = \text{wavelength}, \quad f = \text{frequency}$$

$$c = 3.00 \times 10^{8} \text{ m/s} = \text{speed of light}$$

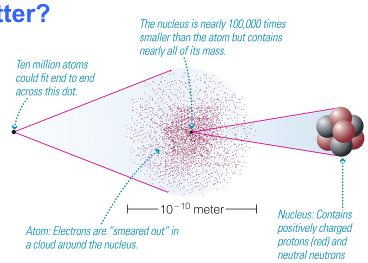
$$E = h \times f = \text{photon energy}$$

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

The higher the photon energy the shorter its wavelength

What is matter?

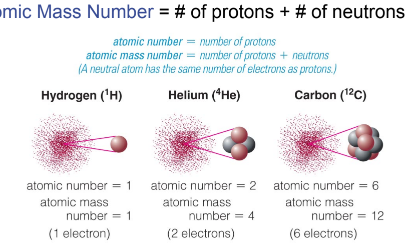
- Proton
  - +1 charge
- Electron
  - -1 charge
- Neutron
  - No charge



A single drop of water contains 10^{22} atoms

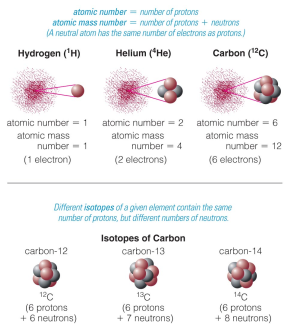
Atomic Terminology

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



Atomic Terminology

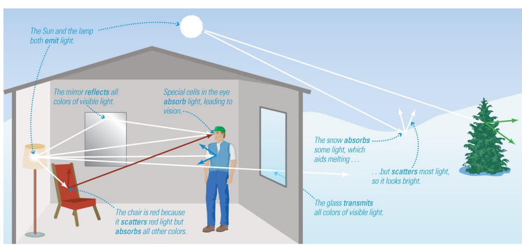
- Isotope: same # of protons but different # of neutrons (^4He, ^3He)
- Molecules: consist of two or more atoms (H_2O, CO_2)



➢How do light and matter interact?

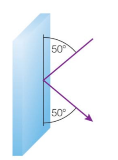
- Emission
  - Light bulb
- Absorption
  - Red chair
- Transmission
  - Glass
- Reflection or scattering
  - Mirror or snow

Interactions of Light with Matter

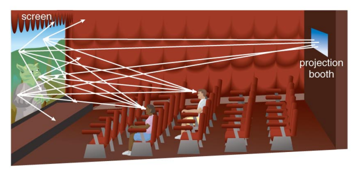


Interactions between light and matter determine the appearance of everything around us.

Reflection and Scattering



Mirror reflects light in a particular direction.



Movie screen scatters light in all directions.

Recap

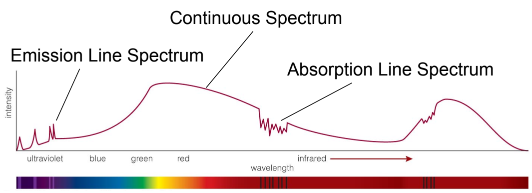
- What is light?
  - Light is a form of energy.
  - Light comes in many colors that combine to form white light.
  - Light is an electromagnetic wave that also comes in individual "pieces" called photons. Each photon has a precise wavelength, frequency, and energy.
  - Forms of light are radio waves, 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.

5.2 Learning from Light

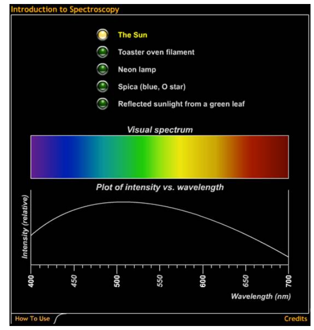
Our goals for learning:

- ➢ 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?

➢What are the three basic types of spectra?

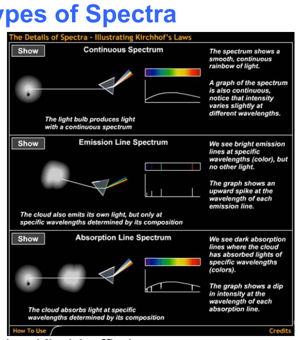


Spectra of astrophysical objects are usually combinations of these three basic types.



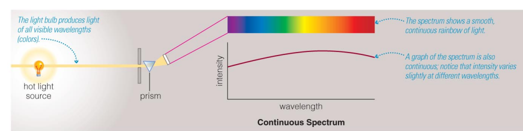
Introduction to Spectroscopy

Three Types of Spectra



PLAY Illustrating Kirchhoff's Laws

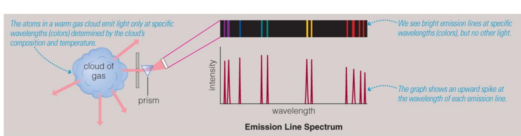
Continuous Spectrum



a

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

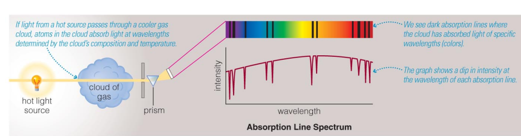
Emission Line Spectrum



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.

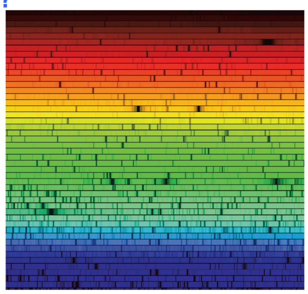
Absorption Line Spectrum



c

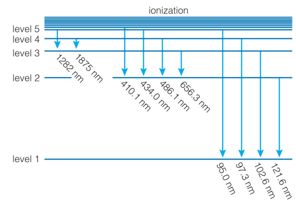
- ❑A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.

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



Spectrum of the Sun

Energy Levels in Atoms

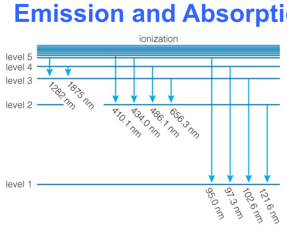


a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

Energy levels of hydrogen

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

Emission and Absorption Lines

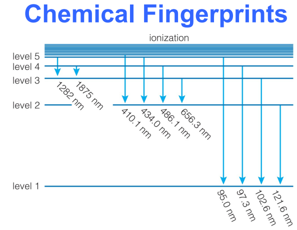


a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

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

- Downward transitions produce a unique pattern of emission lines.

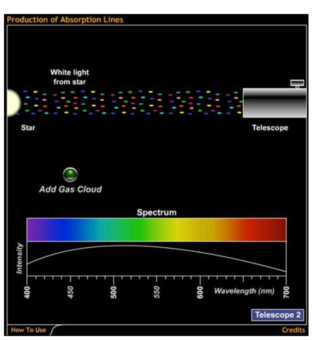
Chemical Fingerprints



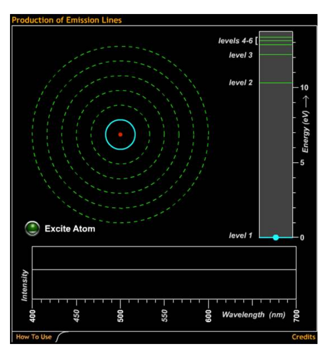
a Energy level transitions in hydrogen correspond to photons with specific wavelengths. Only a few of the many possible transitions are labeled.

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

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



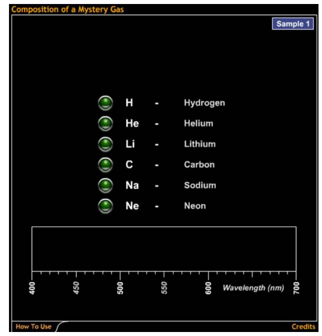
PLAY Production of Absorption Lines



PLAY Production of Emission Lines

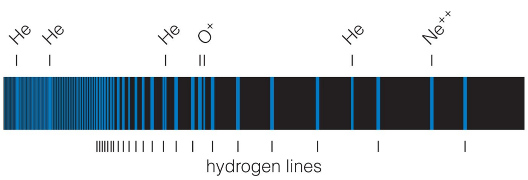
Chemical Fingerprints

- Each type of atom has a unique spectral fingerprint.



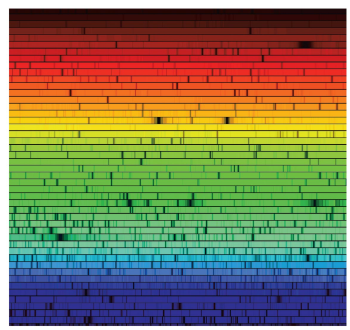
PLAY Composition of a Mystery Gas

Chemical Fingerprints



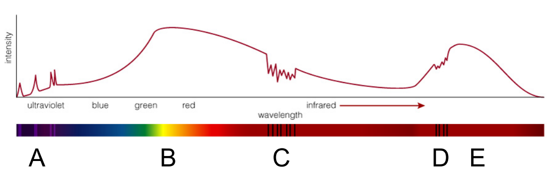
- Observing the fingerprints in a spectrum tells us which kinds of atoms are present.

Example: Solar Spectrum



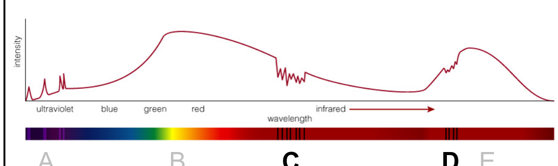
Thought Question

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



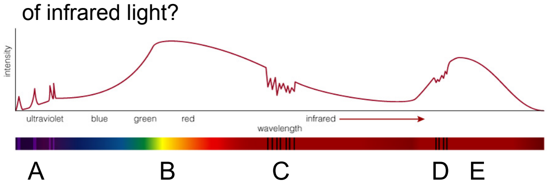
Thought Question

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



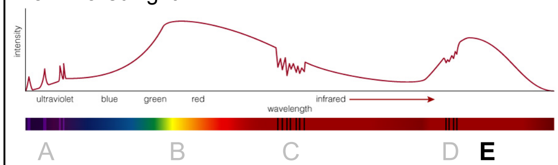
Thought Question

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



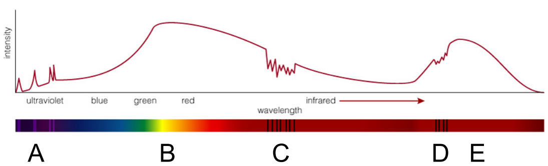
Thought Question

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



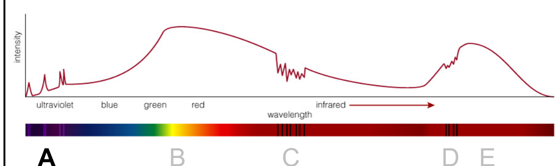
Thought Question

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

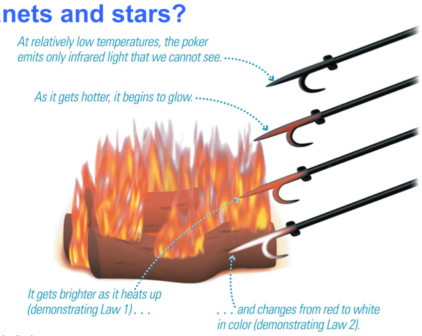


Thought Question

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



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

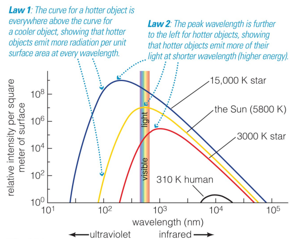


Thermal Radiation

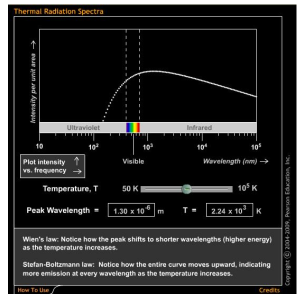
- Nearly all large or dense objects emit thermal radiation, including stars, planets, and you.
- An object's thermal radiation spectrum depends on only one property: its **temperature.**

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*)



Wien's Law



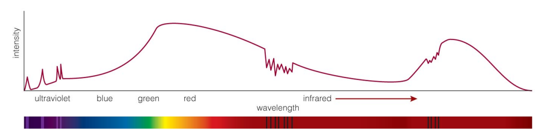
PLAY Wien's Law

Thought Question

Which is hottest?

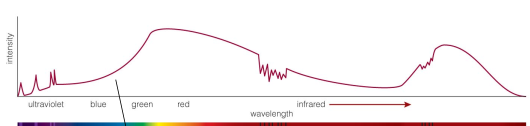
A. A blue star
B. A red star
C. A planet that emits only infrared light

Interpreting an Actual Spectrum



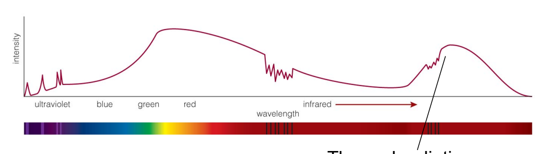
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What is this object?



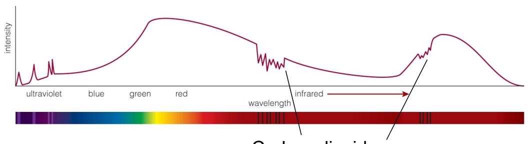
Reflected sunlight: Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed—the object must look red.

What is this object?



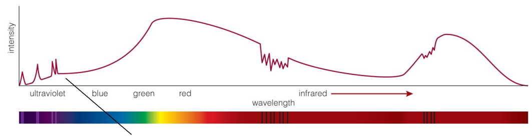
Thermal radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K.

What is this object?



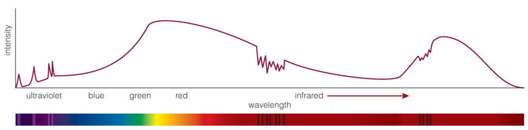
Carbon dioxide: Absorption lines are the fingerprint of CO_2 in the atmosphere.

What is this object?



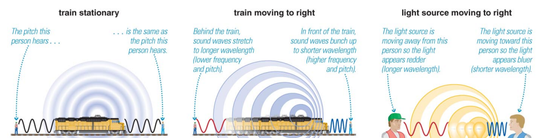
Ultraviolet emission lines: Indicate a hot upper atmosphere

What is this object?



Mars!

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



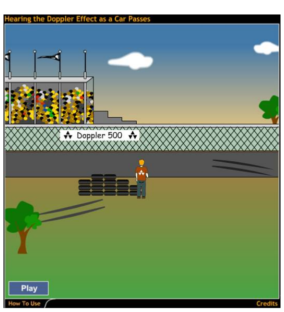
a The whistle sounds the same no matter where you stand near a stationary train.

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

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

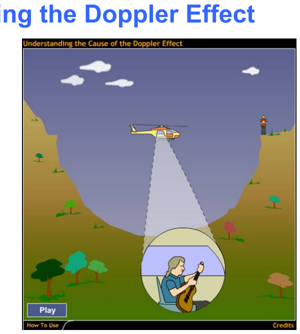
The Doppler Effect

The Doppler Effect



PLAY Hearing the Doppler Effect as a Car Passes

Explaining the Doppler Effect

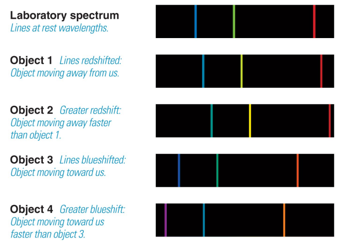


PLAY Understanding the Cause of the Doppler Effect

Same for light

PLAY The Doppler Effect for Visible Light

Measuring the Shift



Stationary

Moving Away

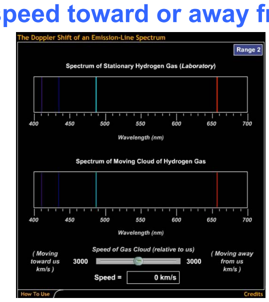
Away Faster

Moving Toward

Toward Faster

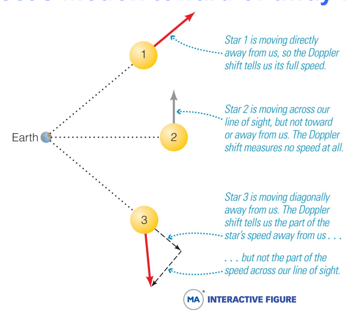
- Blueshift object is moving towards us.
- Redshift object is moving away from us.

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

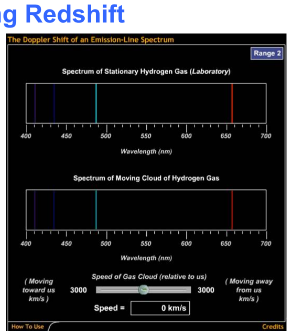


PLAY The Doppler Shift of an Emission Line Spectrum

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

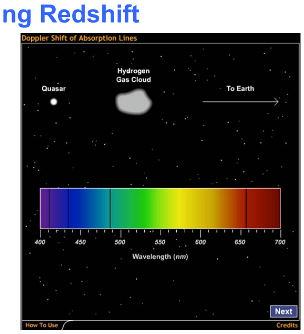


Measuring Redshift



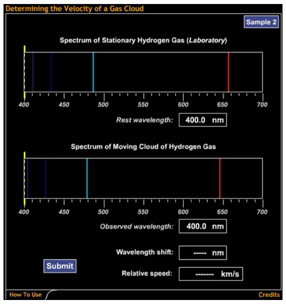
PLAY The Doppler Shift of an Emission Line Spectrum

Measuring Redshift



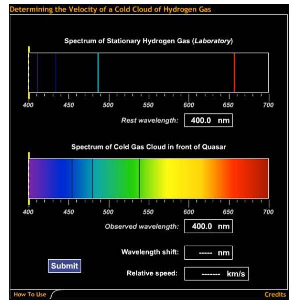
PLAY Doppler Shift of Absorption Lines

Measuring Velocity



PLAY Determining the Velocity of a Gas Cloud

Measuring Velocity



PLAY Determining the Velocity of a Cold Cloud of Hydrogen Gas

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.

- 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.

- 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

5.3 Collecting Light with Telescopes

Our goals for learning:

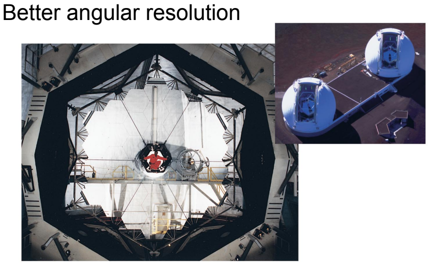
- How do telescopes help us learn about the universe?
- Why do we put telescopes into space?

➢How do telescopes help us learn about the universe?

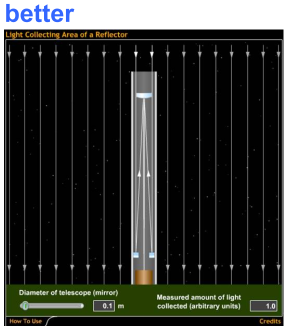
- ❑Telescopes collect more light than our eyes ⇒ **light-collecting area**
- ❑Telescopes can see more detail than our eyes ⇒ **angular resolution**
- ❑Telescopes/instruments can detect light that is invisible to our eyes (e.g., infrared, ultraviolet)

Bigger is better

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



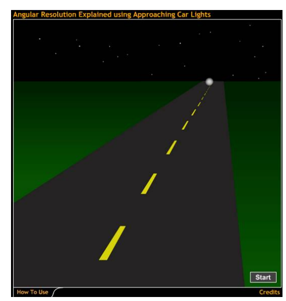
Bigger is better



PLAY Light Collecting Area of a Reflector

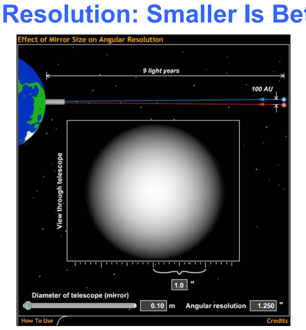
Angular Resolution

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



PLAY Angular Resolution Explained Using Approaching Car Lights

Angular Resolution: Smaller Is Better

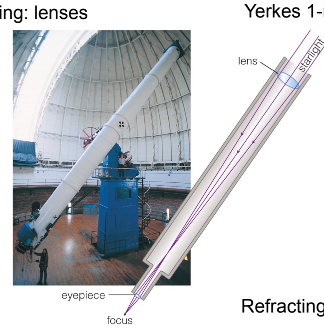


PLAY Effect of Mirror Size on Angular Resolution

Basic Telescope Design

- ❑ Refracting: lenses

Yerkes 1-m refractor

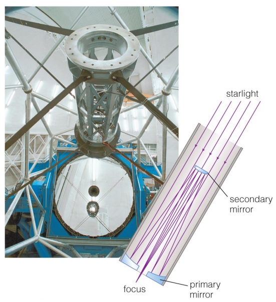


Refracting telescope

Basic Telescope Design

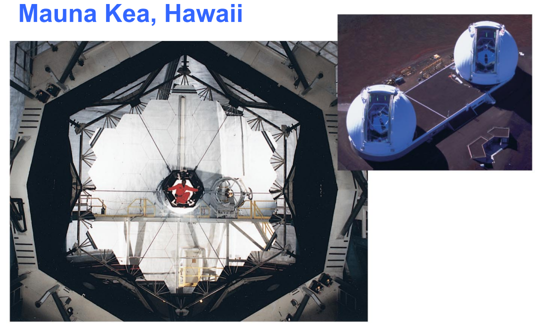
- Reflecting: mirrors
- Most research telescopes today are reflecting

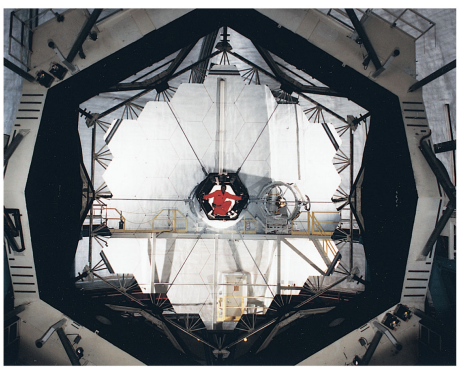
Gemini North 8-m



Reflecting telescope

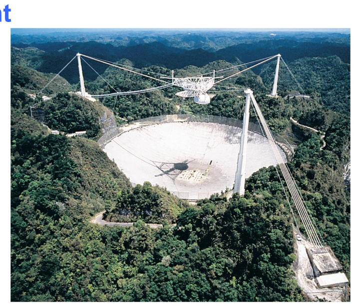
Keck I and Keck II Mauna Kea, Hawaii





Mauna Kea, Hawaii

Different designs for different wavelengths of light



Radio telescope (Arecibo, Puerto Rico)

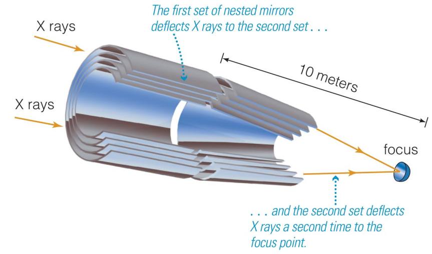
Interferometry

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

Karl G. Jansky Very Large Array (JVLA), New Mexico

The Atacama Large Millimeter/submillimeter Array (ALMA) in Chile

X-ray Telescope: "grazing incidence" optics



b This diagram shows the arrangement of Chandra's nested, cylindrical X-ray mirrors. Each mirror is 0.8 meter long and between 0.6 and 1.2 meters in diameter.

➢Why do we put telescopes into space?

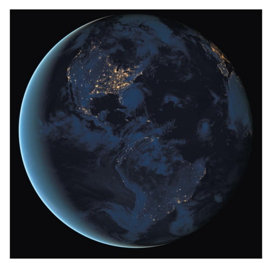
It is NOT because they are closer to the stars!

Recall our 1-to-10 billion scale:

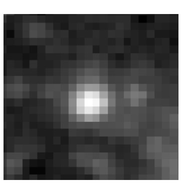
- Sun size of grapefruit
- Earth size of a tip of a ballpoint pen, 15 m from Sun
- Nearest stars 4000 km away
- Hubble orbit microscopically above tip of a ballpoint pen-size Earth

Observing problems due to Earth's atmosphere

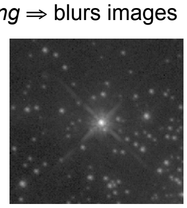
1. Light pollution



2. Turbulence causes *twinkling* ⇒ blurs images

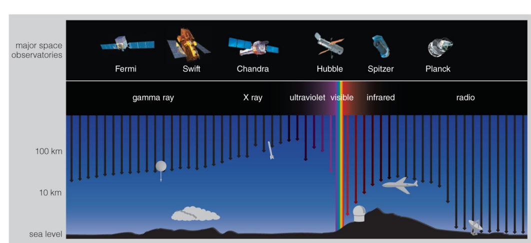


Star viewed with ground-based telescope



View from Hubble Space Telescope

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



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.

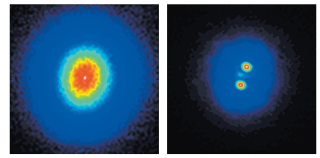
But extremely expensive!

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

Improvements for ground-based telescopes

Adaptive optics

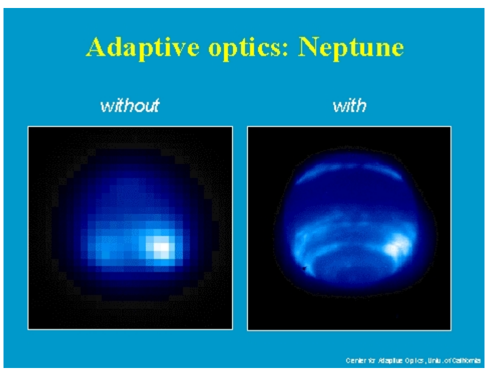
- Rapid changes in mirror shape compensate for atmospheric turbulence.



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

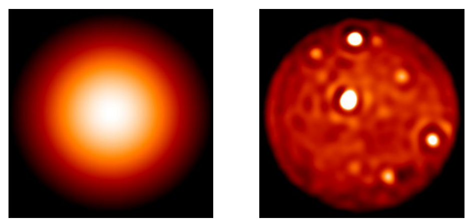
b When the same telescope is used with adaptive optics, the two stars are clearly distinguished. The angular separation between the two stars is 0.28 arcsecond.

Without adaptive optics — With adaptive optics

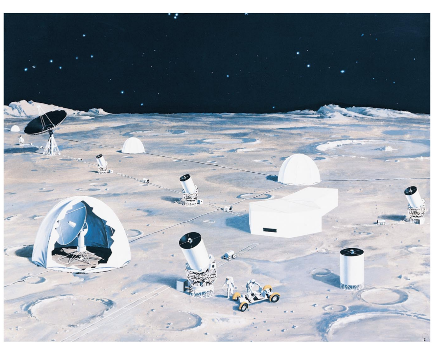


Adaptive Optics

- Jupiter's moon Io observed with the Keck telescope



without adaptive optics — with adaptive optics



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

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.