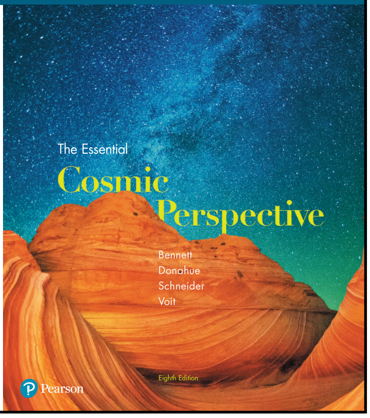
Lecture Outline

Chapter 5: Light
The Cosmic Messenger



1

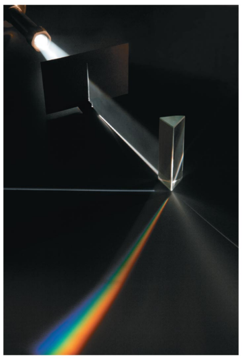
5.1 Basic Properties of Light and Matter

Our goals for learning:

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

2

What is light?



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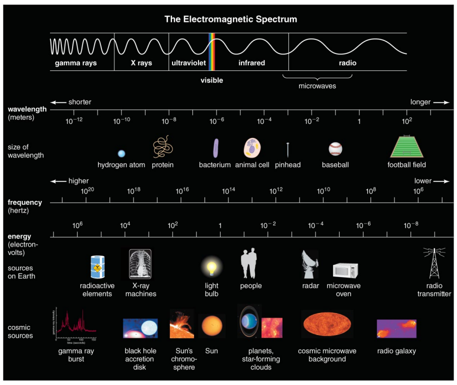
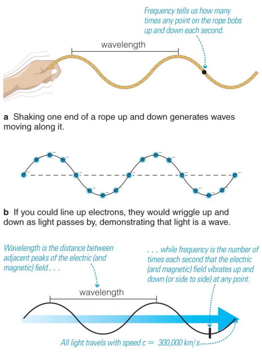


4

Light is an **electromagnetic wave.**

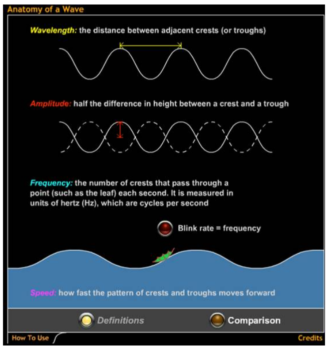


a Shaking one end of a rope up and down generates waves moving along it.

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

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

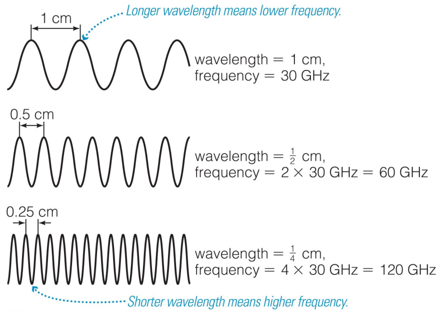
5



PLAY Anatomy of a Wave

6

Wavelength and Frequency



wavelength x frequency = speed of light = constant

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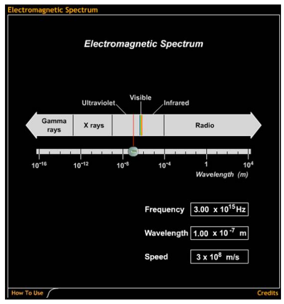
The Electromagnetic Spectrum



PLAY Electromagnetic Spectrum

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Particles 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.

9

Wavelength, Frequency, and Energy

$$\lambda \times f = c$$
$$\lambda = \text{wavelength}, \quad f = \text{frequency}$$
$$c = 3.00 \times 10^8 \text{ m/s} = \text{speed of light}$$

$$E = h \times f = \text{photon energy}$$
$$h = 6.626 \times 10^{-34} \text{ joule} \times \text{s}$$

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Thought Question

The higher the photon energy,

A. the longer its wavelength.
B. the shorter its wavelength.
C. Energy is independent of wavelength.

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Thought Question

The higher the photon energy,

A. the longer its wavelength.
B. the shorter its wavelength.
C. Energy is independent of wavelength.

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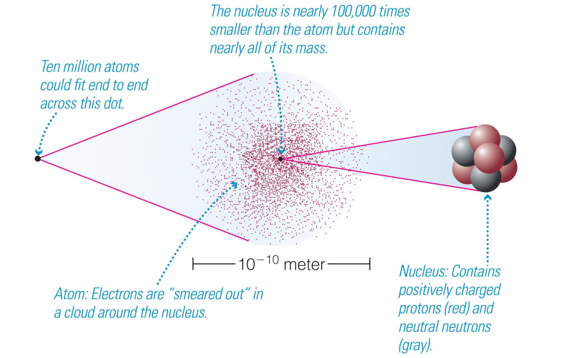
What is matter?



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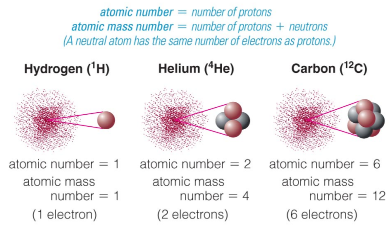
Atomic Terminology

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



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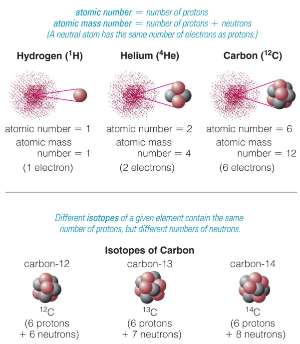
Atomic Terminology

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



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How do light and matter interact?

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

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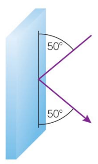
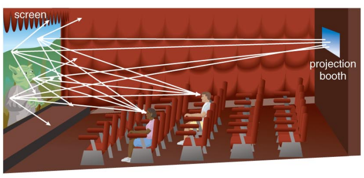
Reflection and Scattering





Mirror reflects light in a particular direction.

Movie screen scatters light in all directions.

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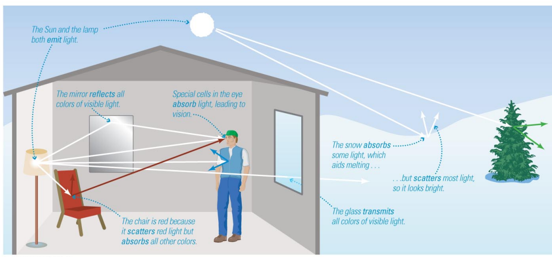
Interactions of Light with Matter



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

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Thought Question

Why is a rose red?

A. The rose absorbs red light.
B. The rose transmits red light.
C. The rose emits red light.
D. The rose reflects red light.

19

Thought Question

Why is a rose red?

A. The rose absorbs red light.
B. The rose transmits red light.
C. The rose emits red light.
D. The rose reflects red light.

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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?

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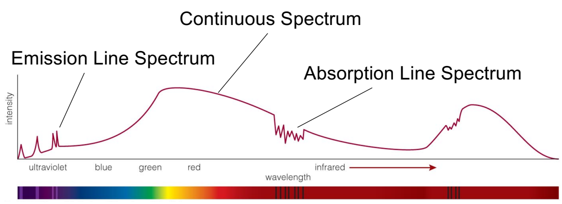
What are the three basic types of spectra?



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

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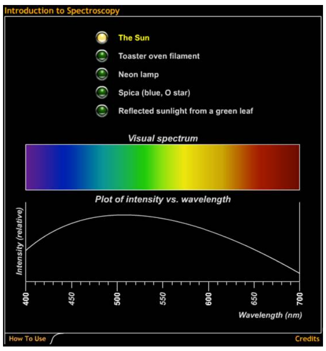

PLAY Introduction to Spectroscopy

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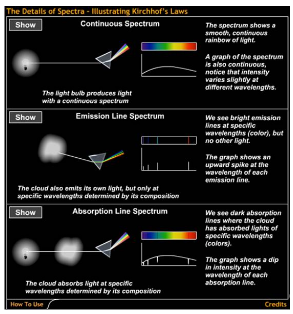
Three Types of Spectra



PLAY Illustrating Kirchhoff's Laws

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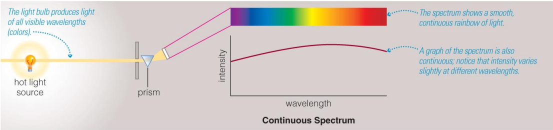
Continuous Spectrum



a

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

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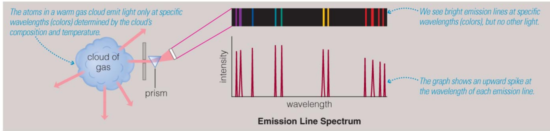
Emission Line Spectrum



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.

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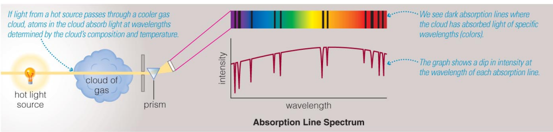
Absorption Line Spectrum



c

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

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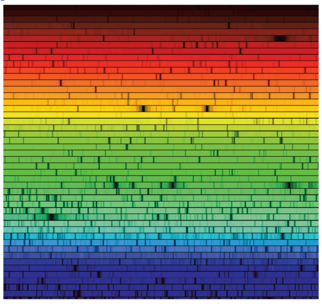
How does light tell us what things are made of?



Spectrum of the Sun

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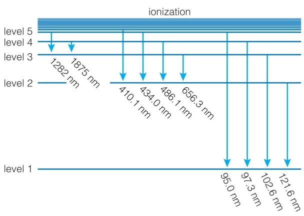
Chemical Fingerprints



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.

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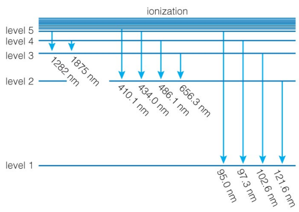
Chemical Fingerprints



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.

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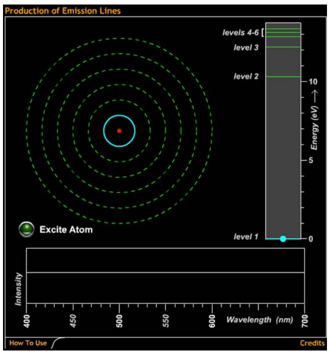

PLAY Production of Emission Lines

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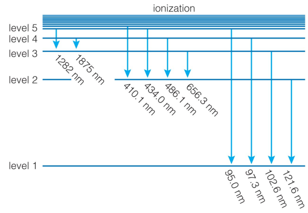
Chemical Fingerprints



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.

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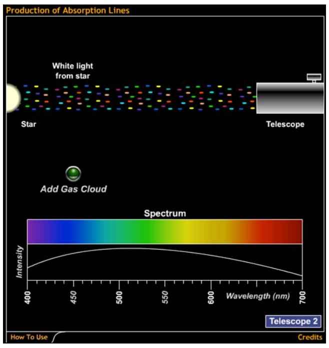

PLAY Production of Absorption Lines

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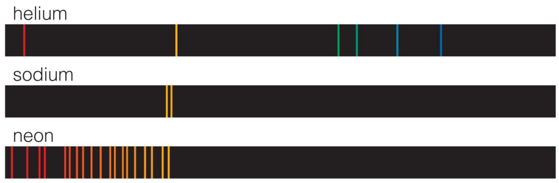
Chemical Fingerprints



- Each type of atom has a unique spectral fingerprint.

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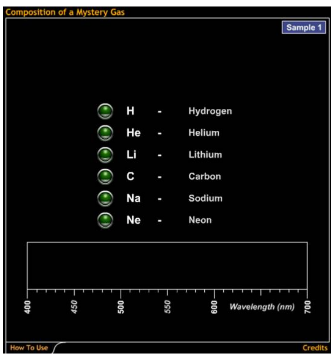

PLAY Composition of a Mystery Gas

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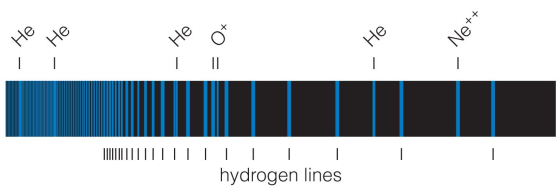
Chemical Fingerprints



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

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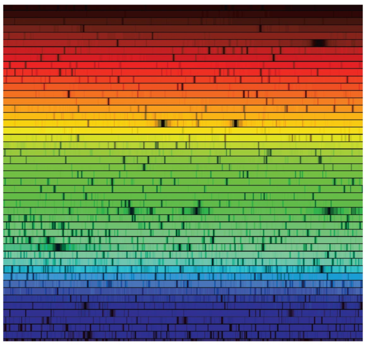
Example: Solar Spectrum



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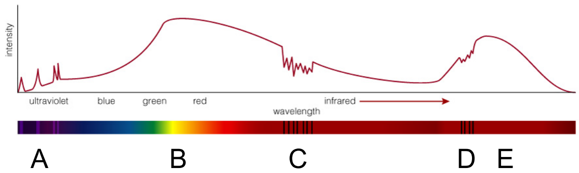
Thought Question

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



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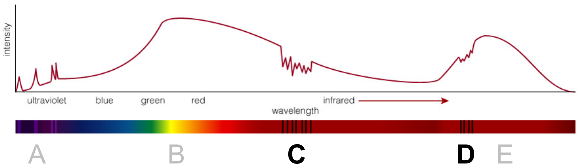

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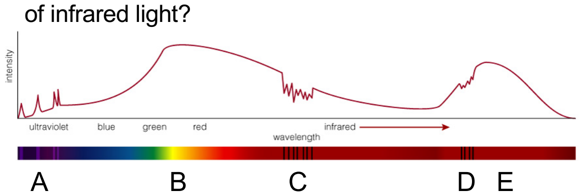
Thought Question

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



40

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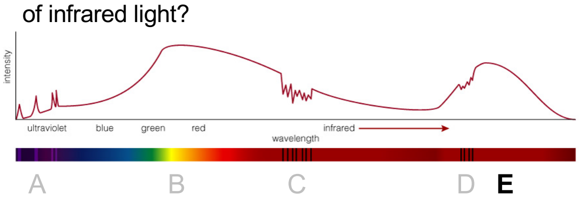

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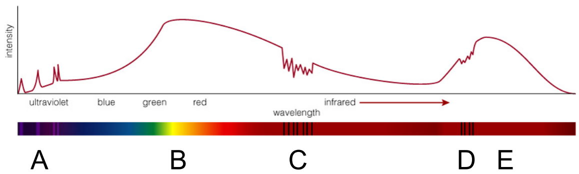
Thought Question

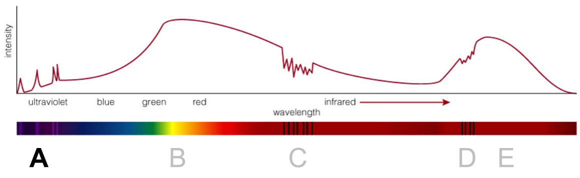
Which letter(s) label(s) emission lines?



42

Thought Question

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



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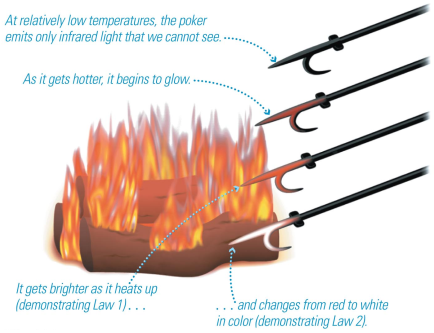
How does light tell us the temperatures of planets and stars?



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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.**

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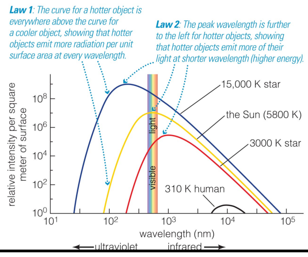
Properties of Thermal Radiation

1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.



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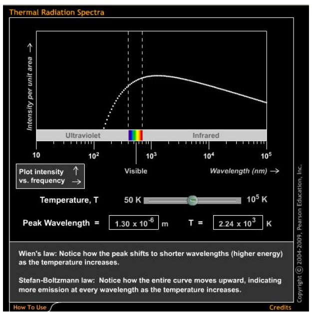
Wien's Law



PLAY Wien's Law

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Thought Question

Which is hottest?

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

48

Thought Question

Which is hottest?

A. A blue star

B. A red star

C. A planet that emits only infrared light

49

Thought Question

Why don't we glow in the dark?

A. People do not emit any kind of light.

B. People only emit light that is invisible to our eyes.

C. People are too small to emit enough light for us to see.

D. People do not contain enough radioactive material.

50

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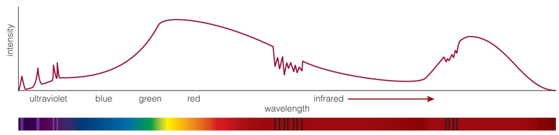
Interpreting an Actual Spectrum



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

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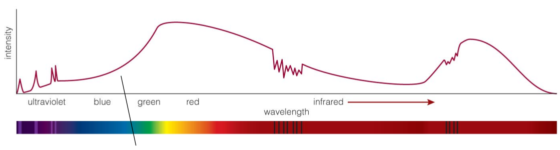
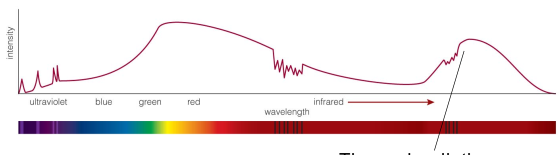
What is this object?



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.

53

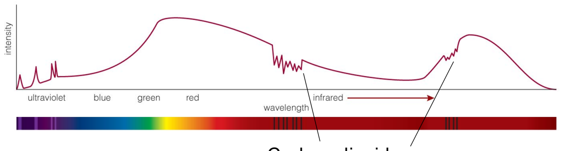
What is this object?



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

54

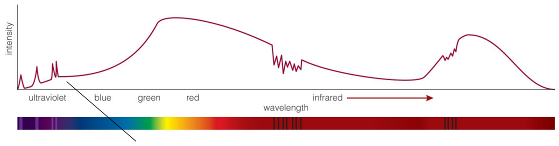
What is this object?



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

55

What is this object?



Ultraviolet emission lines:
Indicate a hot upper atmosphere

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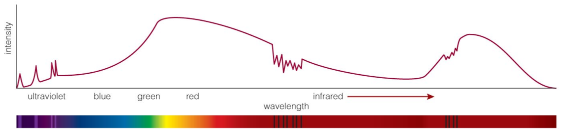
What is this object?



Mars!

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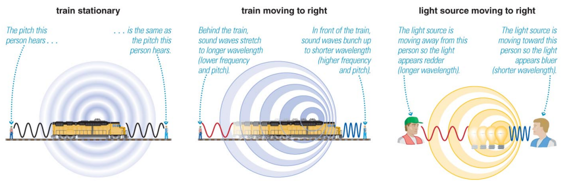
How does light tell us the speed of a distant object?



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

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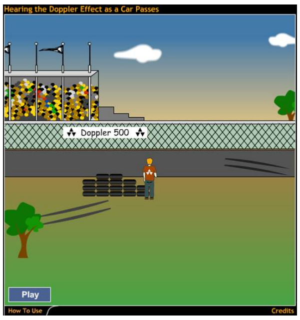
The Doppler Effect



PLAY Hearing the Doppler Effect as a Car Passes

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Explaining the Doppler Effect

PLAY Understanding the Cause of the Doppler Effect

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Same for light

PLAY The Doppler Effect for Visible Light

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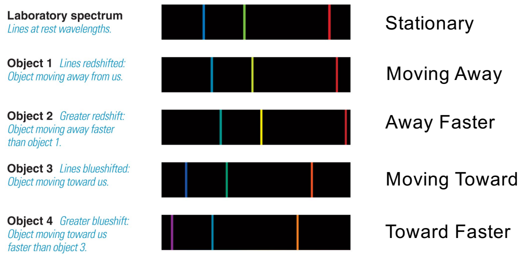
Measuring the Shift



- We generally measure the Doppler effect from shifts in the wavelengths of spectral lines.

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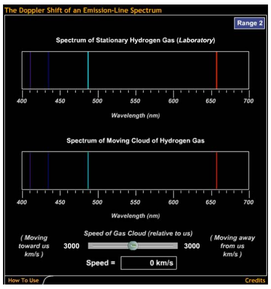
The amount of blue or red shift tells us an object's speed toward or away from us.



PLAY The Doppler Shift of an Emission Line Spectrum

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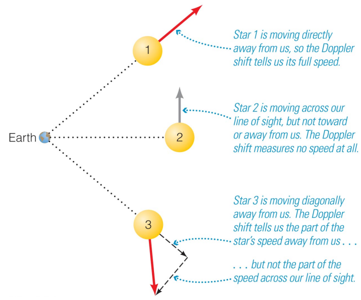
Doppler shift tells us ONLY about the part of an object's motion toward or away from us.



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Thought Question

I measure a line in the lab at 500.7 nm. The same line in a star has wavelength 502.8 nm. What can I say about this star?

A. It is moving away from me.
B. It is moving toward me.
C. It has unusually long spectral lines.

65

Thought Question

I measure a line in the lab at 500.7 nm. The same line in a star has wavelength 502.8 nm. What can I say about this star?

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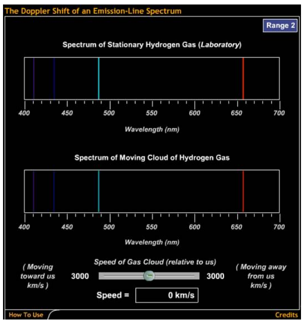
Measuring Redshift



PLAY The Doppler Shift of an Emission Line Spectrum

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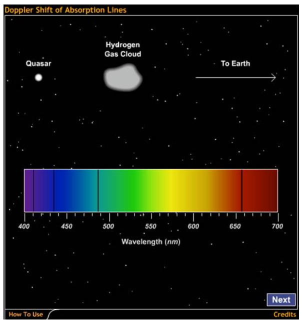
Measuring Redshift



PLAY Doppler Shift of Absorption Lines

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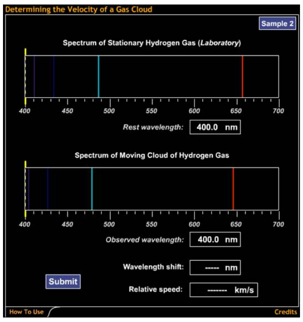
Measuring Velocity



PLAY Determining the Velocity of a Gas Cloud

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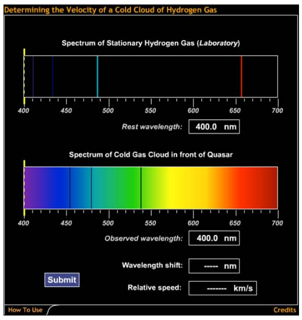
Measuring Velocity



PLAY Determining the Velocity of a Cold Cloud of Hydrogen Gas

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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?

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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)

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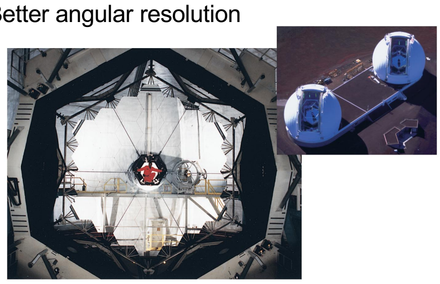
Bigger is better

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



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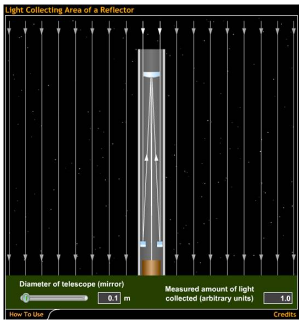
Bigger is better



PLAY Light Collecting Area of a Reflector

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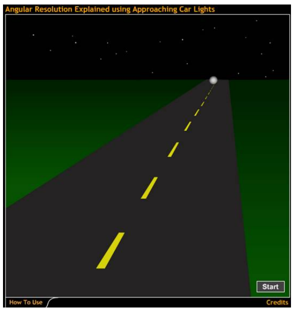
Angular Resolution

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



PLAY Angular Resolution Explained Using Approaching Car Lights

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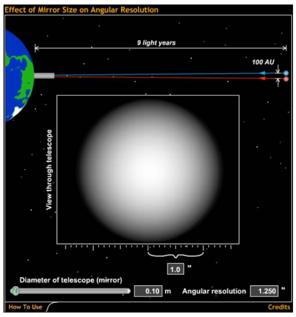
Angular Resolution: Smaller Is Better



PLAY Effect of Mirror Size on Angular Resolution

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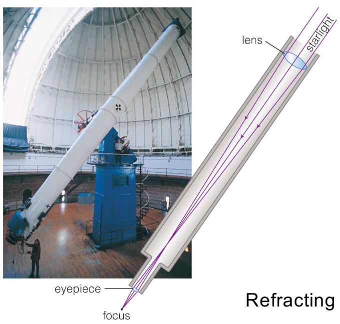
Basic Telescope Design

- Refracting: lenses

Yerkes 1-m refractor



Refracting telescope

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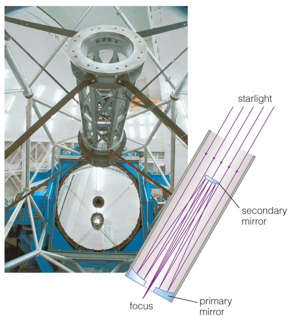
Basic Telescope Design

- Reflecting: mirrors
- Most research telescopes today are reflecting

Gemini North 8-m



Reflecting telescope

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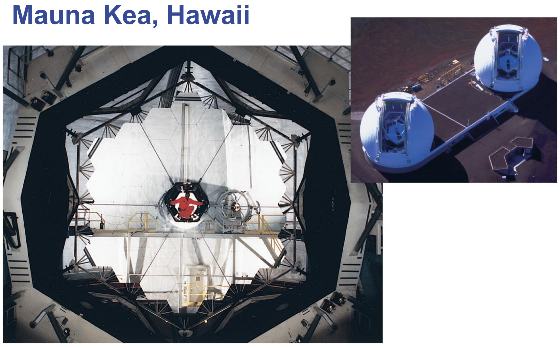
Keck I and Keck II
Mauna Kea, Hawaii



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Mauna Kea, Hawaii

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Different designs for different wavelengths of light

500 meter radio telescope (Guizhou Province, China)

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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

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

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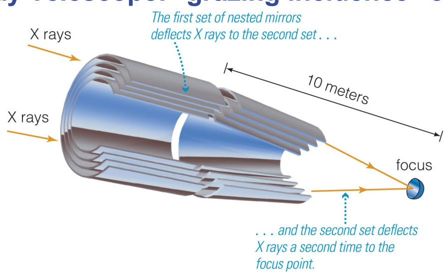
X-ray Telescope: "grazing incidence" optics



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.

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Want to buy your own telescope?

- Buy binoculars first (e.g., 7 x 35) — you get much more for the same amount of money.
- Ignore magnification (sales pitch!).
- Notice: aperture size, optical quality, portability.
- Consumer research: *Astronomy*, *Sky & Telescope*, *Mercury* magazines; astronomy clubs.

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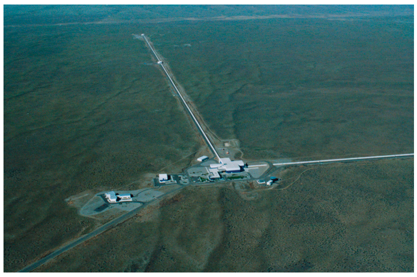
Looking Beyond Light



Shown here is one of the gravitational wave detectors that are part of Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO).

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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

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Observing problems due to Earth's atmosphere

1. Light pollution

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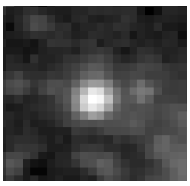
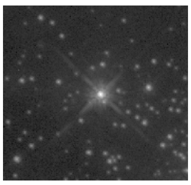
2. Turbulence causes *twinkling* ⇒ blurs images



Star viewed with ground-based telescope



View from Hubble Space Telescope

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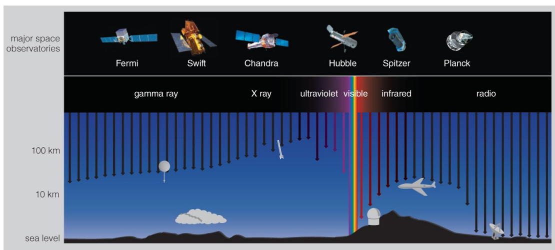
3. Atmosphere absorbs most of EM spectrum, including all UV and X ray and most infrared.



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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.

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

Chandra X-Ray Observatory

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James Webb Space Telescope

The James Webb Space Telescope, a full-scale model of which is shown here, is set to launch in March 2021.

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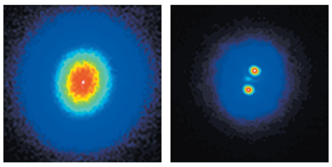
Improvements for ground-based telescopes

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

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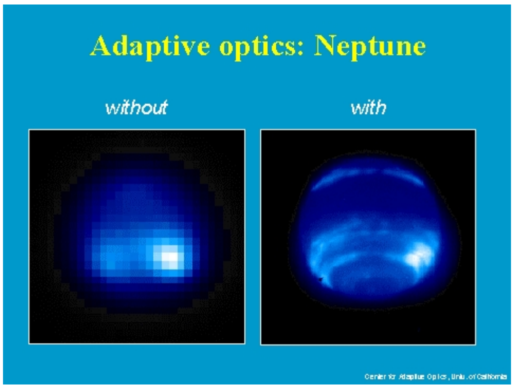

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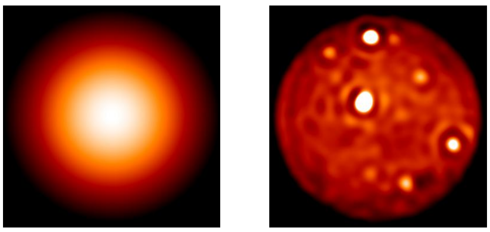
Adaptive Optics

- Jupiter's moon Io observed with the Keck telescope



without adaptive optics | with adaptive optics

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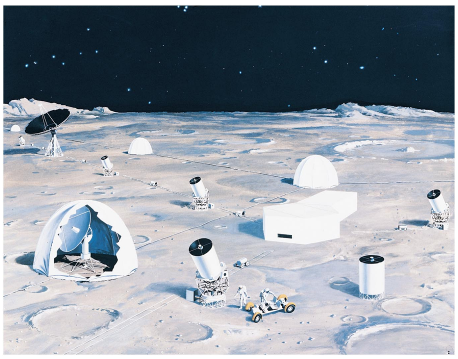

The Moon would be a great spot for an observatory (but at what price?).

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