Outline:

1. Electric and Magnetic Fields
2. The Wave Nature of Light
3. The Electromagnetic Spectrum
4. Spectra
5. Blackbody Radiation
6. Doppler Shifts

Invisible forces in physics:

We learned in the last lecture about force of gravity and the gravitational fields that are produced by all objects with mass.

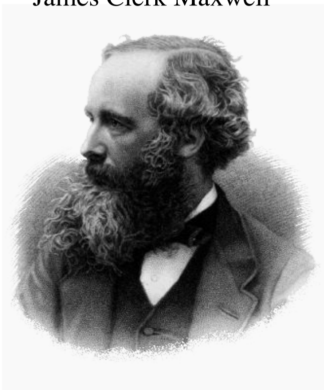
The understanding of light required an understanding of the electric and magnetic fields:

Electric fields: hold atoms together, cause electrons to move through wires (electricity), create lightening.

Magnetic fields: cause attraction/repulsion of magnets, causes compass needle to align with Earth's magnetic field.

Michael Faraday

James Clerk Maxwell



1791 - 1867

1831-1879

Faraday and the discovery of the induction of electric currents.

http://micro.magnet.fsu.edu/electromag/java/compass/index.html

http://micro.magnet.fsu.edu/electromag/java/faraday2/

Magnetic and electric fields are related: magnetic fields can generate electric fields and electric fields can generate magnetic fields.

We now consider these unified into a single force.

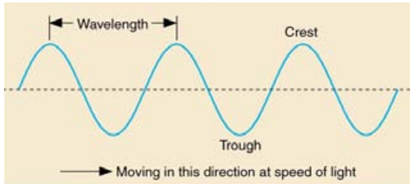
Maxwell's Equation

$$\begin{aligned} \nabla \cdot \mathbf{E} &= 4\pi\rho \\ \nabla \times \mathbf{E} &= -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{B} &= \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}, \end{aligned}$$

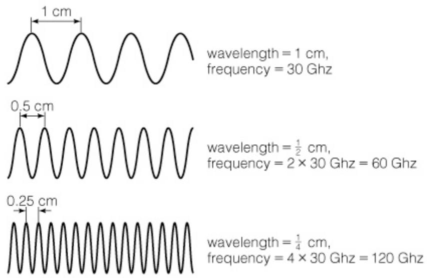
Maxwell derived that electromagnetic waves travel at the speed of light: *We can scarcely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena*.

Waves

- Wavelength (λ)
  - Distance between crests (or troughs)
- Frequency (f)
  - How often it repeats (wiggles up and down)
    - Measured in Hertz (Hz)
      - number of times per sec



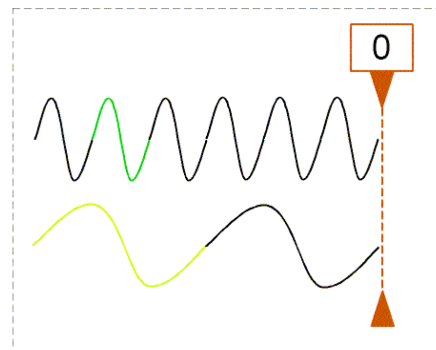
Wavelength and Frequency



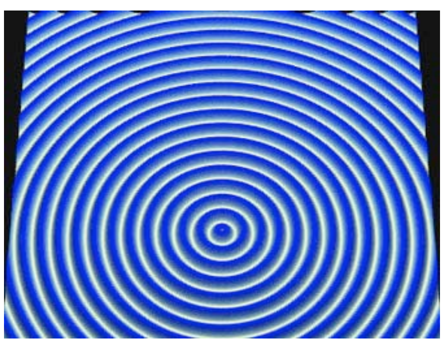
wavelength x frequency = speed of light = constant

For visible light, the color of the light depends on its wavelength. Blue light has the shortest wavelength, and red light has the longest wavelength.

Frequency: number of per unit time
Example 1:



Frequency: number of per unit time
Example 1:



What is Light?

- Newton
  - Prism shows white light contains all colors
  - Light made of particles (photons)
- Maxwell
  - Theory of electricity & magnetism
  - Light is electromagnetic waves
    - Produced by wiggling electrons
    - Radiation = production of light
- Quantum Mechanics
  - Light is both: particle and wave

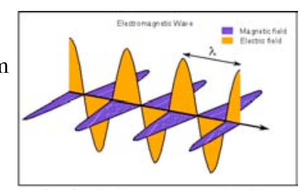
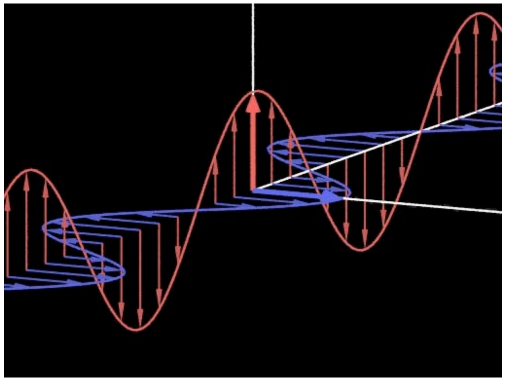


Figure from: http://www.astronomynotes.com/light/s3.htm

Light: Electromagnetic Waves

- A light wave is a vibration of electric and magnetic fields
- Light interacts with charged particles through these electric and magnetic fields

Light is composed of oscillating electrical and magnetic fields



http://rt210.sl.psu.edu/phys_anim/PA.html

The speed of light in a Vacuum is a fundamental constant of nature.

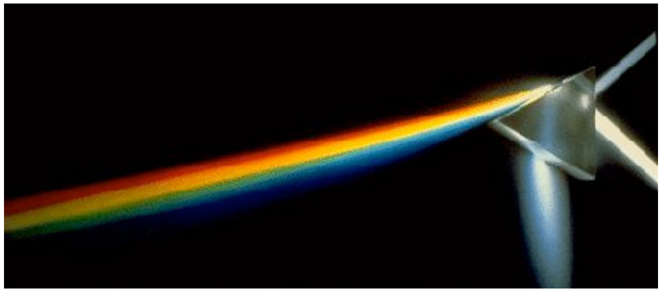
The speed of light relates the wavelength to the frequency of light.

$$\lambda \times f = c$$

λ = wavelength (m) , f = frequency (Hz)

c = 3.00×10^8 m/s = speed of light

Colors of Visible Light



Prisms disperse light and separate white light into its constituent colors.

Image: Wikipedia

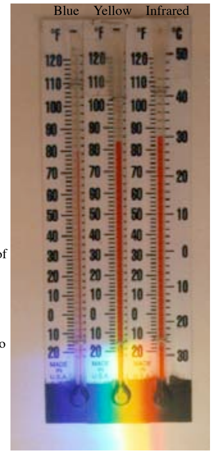
Extending the Spectrum: The Discovery of the Infrared

Homemade version of Herschell's experiment (prism, sunlight, cardboard box, and three thermometers).

In 1800, the German astronomer William Herschell tried to measure the amount of heat associated with different wavelengths of light.

He used a prism to disperse light into its constituent colors. He then projected the colors onto a series of thermometers to see which color would heat the a thermometer to the highest temperature.

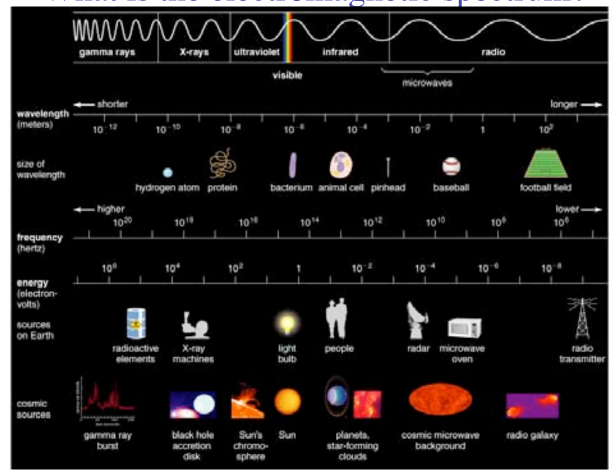
To his surprise, he found the highest temperature was beyond the red, where his eye did not see any light. This was due to infrared light heating the thermometer, which is invisible to the human eye.



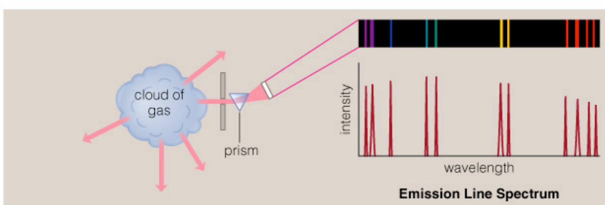
The result of the homemade experiment - the infrared wins)

Cool cosmos: Spitzer Science Center http://coolcosmos.ipac.caltech.edu/

What is the electromagnetic spectrum?

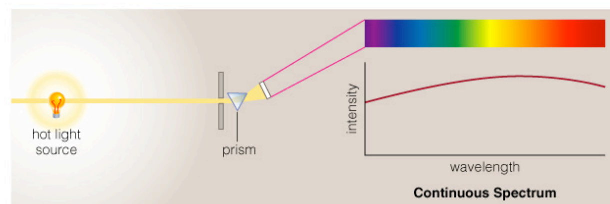


Emission Line Spectrum



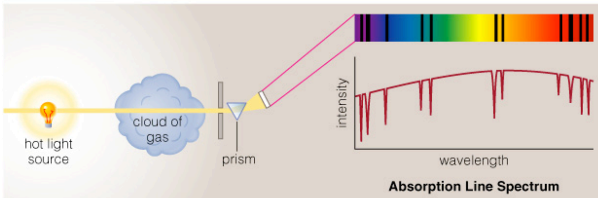
- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines

Continuous Spectrum



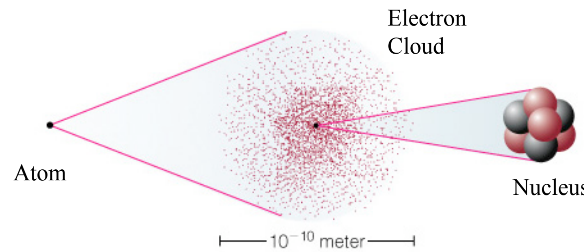
- The spectrum of a common (incandescent) light bulb spans all visible wavelengths, without interruption

Absorption Line Spectrum



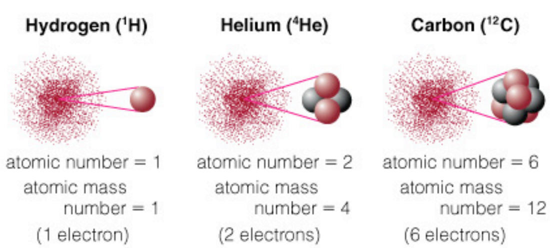
- A cloud of gas between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum

What is the structure of matter?



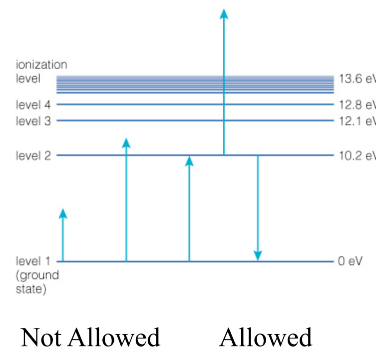
Atomic Terminology

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



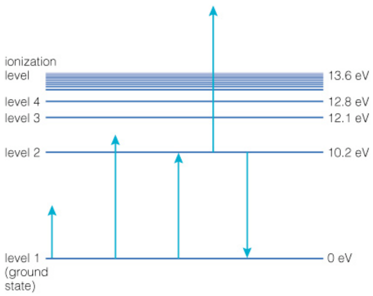
- Molecules: consist of two or more atoms (H_2O, CO_2)

Energy Level Transitions



- The only allowed changes in energy are those corresponding to a transition between energy levels

How is energy stored in atoms?



Excited States

Ground State

- Electrons in atoms are restricted to particular energy levels

Wavelength, Frequency, and Energy

$\lambda \times f = c$

λ = wavelength (m) , f = frequency (Hz)

c = 3.00 x 10^8 m/s = speed of light

$E = h \times f$ = photon energy

$h = 6.626 \times 10^{-34}$ joule x s = photon energy (joules)

Light: Particle or Wave?

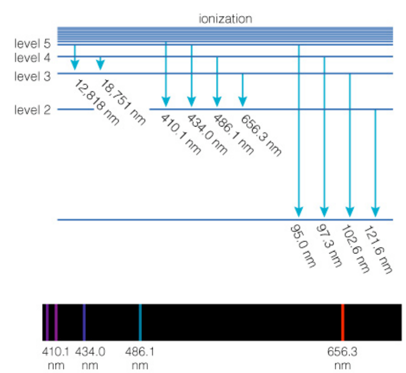
Light has properties of both a wave and a particle.

It can be described as a electromagnetic wave moving at the 3 x 10^5 km s^{-1}. It has all the characteristics of a wave: wavelength, frequency, polarization (see last slides), constructive and destructive interference.

However, it only be emitted or absorbed in discrete amounts called photons, where the photon energy is given by $E = h \times f$. In this sense, light acts as a particle.

Thus, the light that is coming from this powerpoint slide can be thought as both waves and bundles of many photons.

Chemical Fingerprints

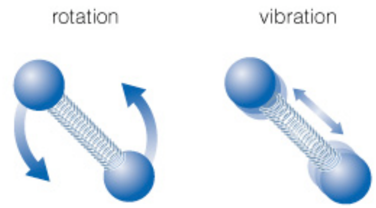


- Downward transitions produce a unique pattern of emission lines

Chemical Fingerprints

- Each type of atom has a unique spectral fingerprint

Energy Levels of Molecules



- Molecules have additional energy levels because they can vibrate and rotate

Energy Levels of Molecules

Spectrum of Molecular Hydrogen

- The large numbers of vibrational and rotational energy levels can make the spectra of molecules very complicated
- Many of these molecular transitions are in the infrared part of the spectrum

Blackbodies

Blackbody - an object which absorbs all incident light at all wavelengths of light.

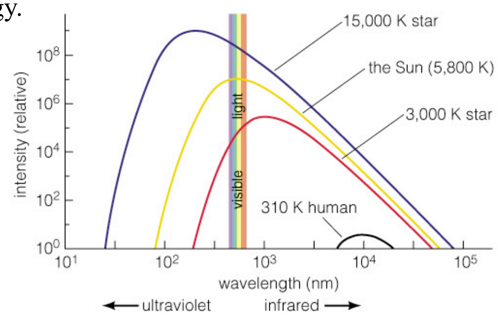
In reality, there is no perfect blackbody, but for many objects, a blackbody is a good approximation.

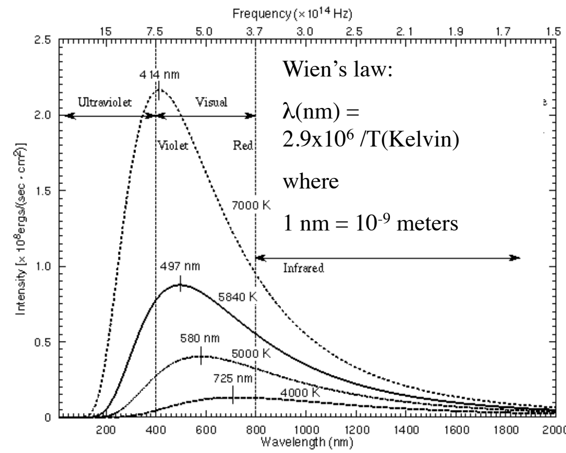
Greybody - an objects which absorbs a constant fraction of the incident light at all wavelengths.

Again, there are no perfect blackbodies.

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.





Wien's law:

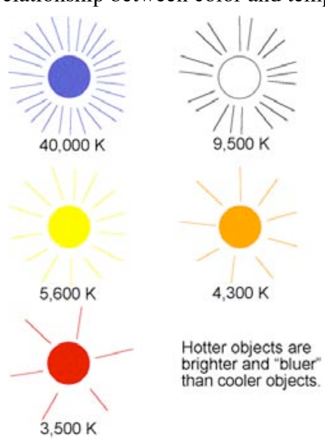
λ(nm) = 2.9x10^6 /T(Kelvin)

where

1 nm = 10^{-9} meters

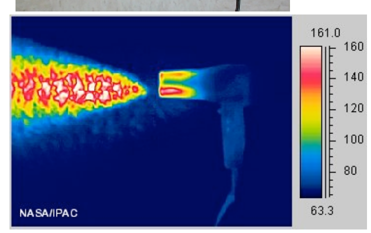
Picture from Nick Strobel's astronomy notes: www.astronomynotes.com

The relationship between color and temperature



Picture from Nick Strobel's astronomy notes: www.astronomynotes.com

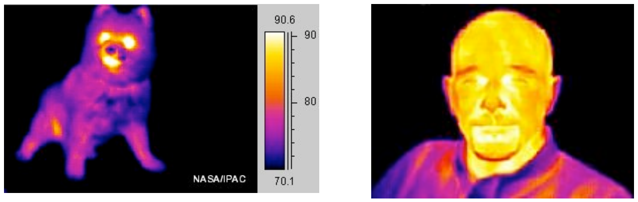
Visible Light (scattered)



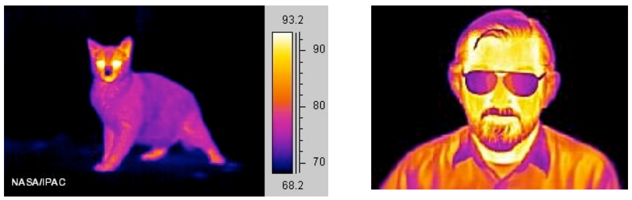
Infrared Light (emitted by hot plastic and the hot air)

Cool cosmos: Spitzer Science Center http://coolcosmos.ipac.caltech.edu/

People and animals glow: infrared (10000 nm) images

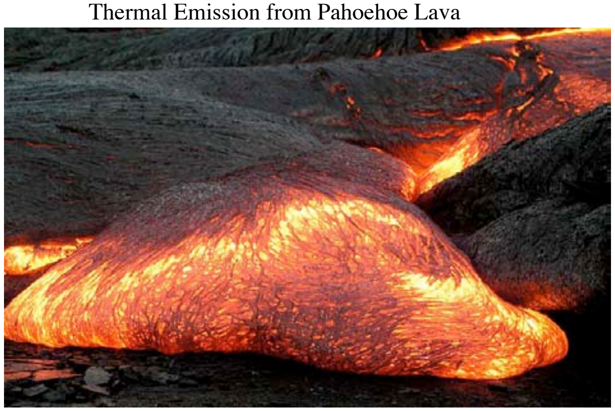


Human body has a temperature of 310 K => peak wavelength = 9400 nm



Cool cosmos: Spitzer Science Center http://coolcosmos.ipac.caltech.edu/

Thermal Emission from Pahoehoe Lava



As a hot object radiates, it cools (conservation of energy)

Image: Wikipedia

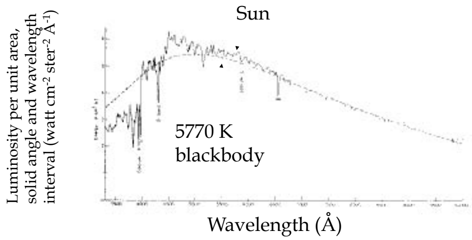
Thermal Emission from Pahoehoe Lava

As a hot object radiates, it cools (conservation of energy)

Cool cosmos: Spitzer Science Center http://coolcosmos.ipac.caltech.edu/

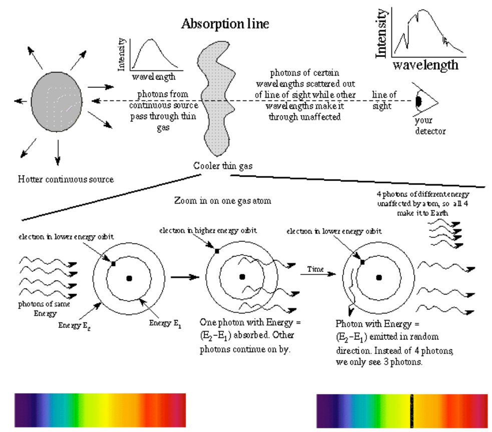
Stars are Blackbodies (sort of)

- One reason the effective temperature comes close to the relevant physical temperature is that the spectrum of the Sun resembles the spectrum of a blackbody.



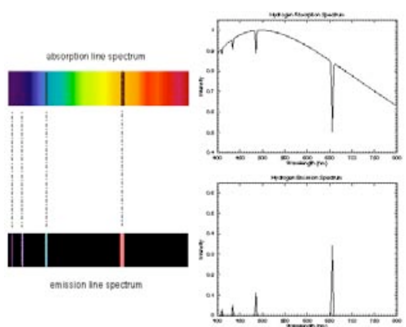
(from Carroll and Ostlie, *Modern astrophysics*)

Slide: courtesy of Dan Watson



Picture from Nick Strobel's astronomy notes: www.astronomynotes.com

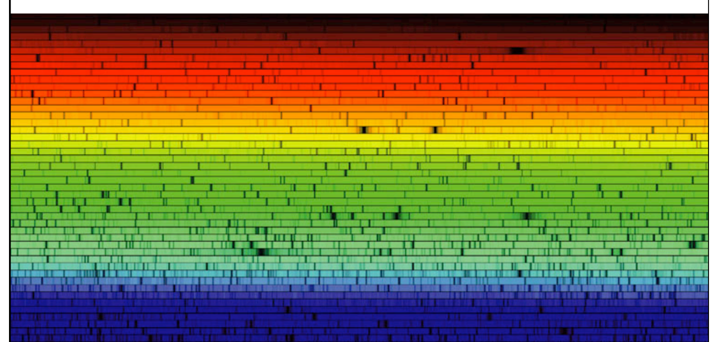
Absorption Line Spectrum



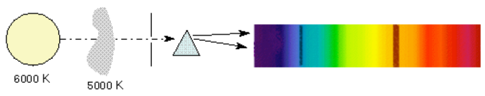
Two ways of showing the same spectra: on the **left** are pictures of the dispersed light and on the **right** are plots of the intensity vs. wavelength. Notice that the pattern of spectral lines in the absorption and emission line spectra are the **same** since the gas is the same.

Picture from Nick Strobel's astronomy notes: www.astronomynotes.com

Example: Solar Spectrum

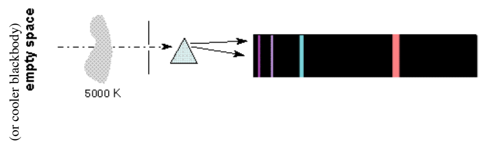


Kirchoff Laws



Foreground gas cooler, absorption

Type of spectrum seen depends on the temperature of the thin gas **relative to** the background. TOP: thin gas is *cooler* so **absorption lines** are seen. BOTTOM: thin gas is *hotter* so **emission lines** are seen.

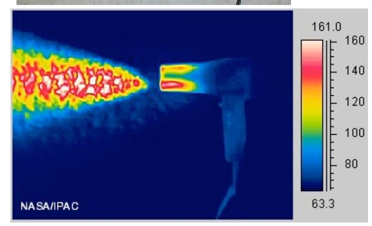


Absorbing gas hotter, emission lines (and blackbody)

If foreground gas and emitting blackbody the same temperature: perfect blackbody (no lines)

Picture from Nick Strobel's astronomy notes: www.astronomynotes.com

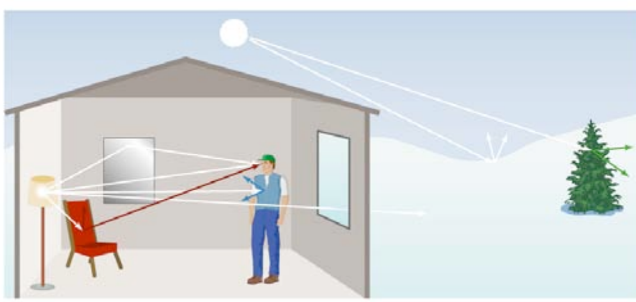
Visible Light (scattered)



Infrared Light (emitted by hot plastic and the hot air)

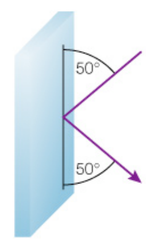
Cool cosmos: Spitzer Science Center http://coolcosmos.ipac.caltech.edu/

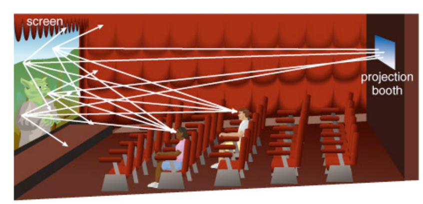
Reflected and Scattered Light



Most light we see is generated by a few hot sources (the Sun, heated filament in light bulb), and then scattered and reflected to light up our environment.

Reflection and Scattering





Mirror reflects light in a particular direction

Movie screen scatters light in all directions

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.

Thought Question
Why is a rose red?

a) The rose absorbs red light.
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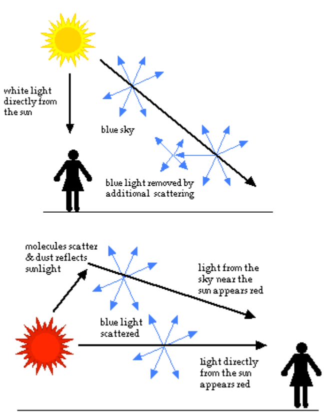
Why is the Sky Blue?



1. Molecules in atmosphere mainly (N_2 and O_2) can scatter light.
2. Some of the sunlight passing through the atmosphere is scattered.
3. Molecules scatter blue light much more efficiently than green or red light.
4. Looking away from Sun, we see the scattered light.
5. Scattering makes the Sun appear redder - this is most apparent at sunset. Why?

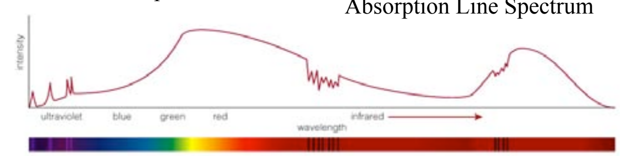
Do astronauts in the space shuttle see a blue sky?

What are the three basic types of spectra?

Continuous Spectrum

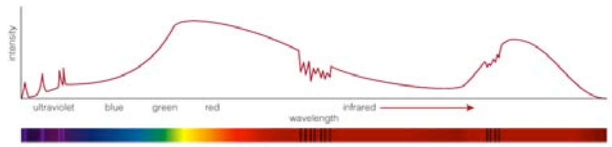
Emission Line Spectrum

Absorption Line Spectrum



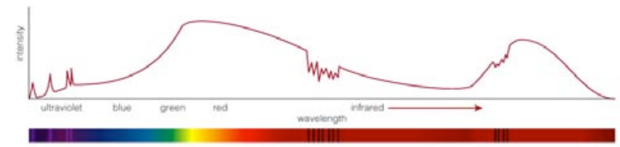
Spectra of astrophysical objects are usually combinations of these three basic types

How do we interpret an actual spectrum?



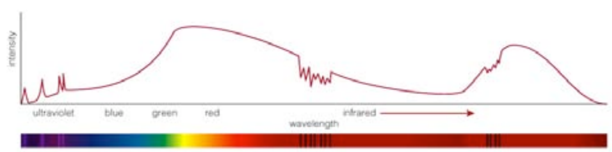
- By carefully studying the features in a spectrum, we can learn a great deal about the object that created it.

What is this object?



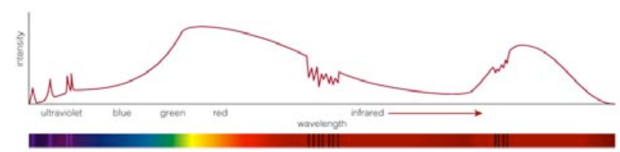
Reflected Sunlight:
Continuous spectrum of visible light is like the Sun's except that some of the blue light has been absorbed - object must look red

What is this object?



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

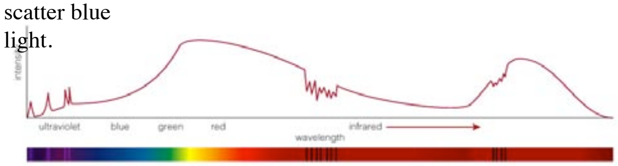
What is this object?



Ultraviolet Emission Lines:
Indicate a hot upper atmosphere

Oxygen and Nitrogen in Atmosphere scatter blue light.

What is this object?



Reflected Sunlight

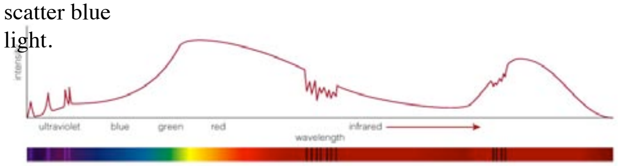
Thermal Emission from ground

Very hot gas in the outer reaches of our atmosphere (we'll learn about this later)

Gas in atmosphere absorbing infrared radiation.

Oxygen and Nitrogen in Atmosphere scatter blue light.

This is the Earth!



Reflected Sunlight

Thermal Emission from ground

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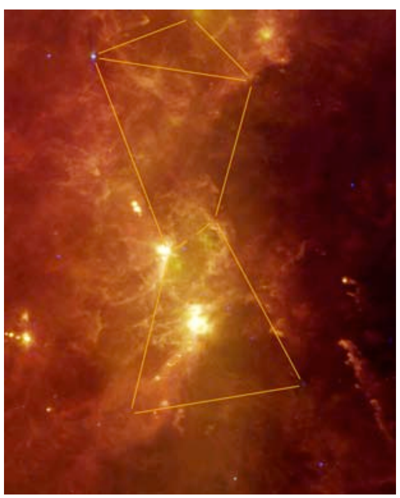


The Orion constellation
At visible and infrared wavelengths

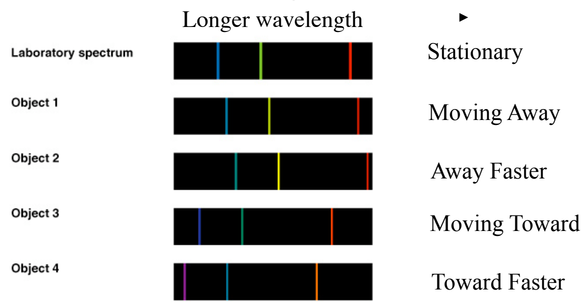
Visible wavelength:
(400 - 700 nm)

Infrared wavelength:
(24000 nm)

Special Topic 1: The Doppler Shift

http://www.astro.ubc.ca/~scharein/a311/Sim.html#Doppler

Measuring the Shift



Change in wavelength = wavelength x velocity / speed of light

$d\lambda$ (nm) = λ (nm) x v (km s-1)/3x10^5 km s^{-1}

Things to know:

1. Light as a electromagnetic wave
2. The wavelength range of visible light, radio waves, infrared light (in nm)
3. The energy of a photon (discrete quanta of light)
4. The discrete nature of atomic and molecular spectra.
5. A blackbody spectrum.
6. Wien's law
7. When do you get emission lines or absorption lines?
8. The doppler shift

Special Topic 2: Polarized Sunglasses

- **Polarization** describes the direction in which a light wave is vibrating
- Light consists of bundles of waves with many different polarizations.
- Polarized sunglasses block all one polarization, and let the other polarization through - thus reducing light in half.
- Reflection can change the polarization of light
- Polarized sunglasses block light that reflects off of horizontal surfaces