Astronomy 122

<u>This Class (Lecture 8):</u>

Light and Telescopes

Homework #3 due Fri at 11:59pm!

<u>Next Class:</u>

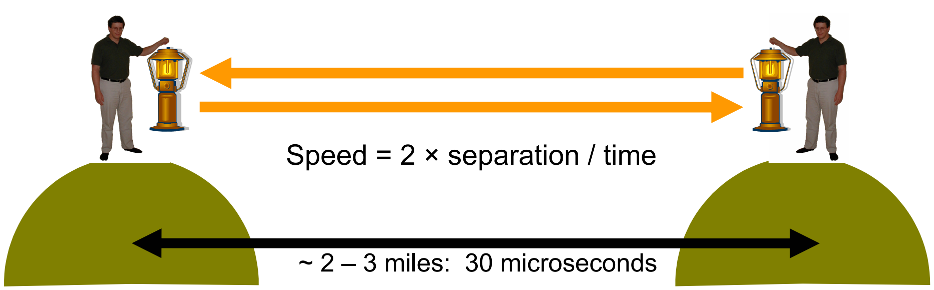
The Origin of the Solar System

Music: *What's the Frequency Kenneth?* – REM

Outline

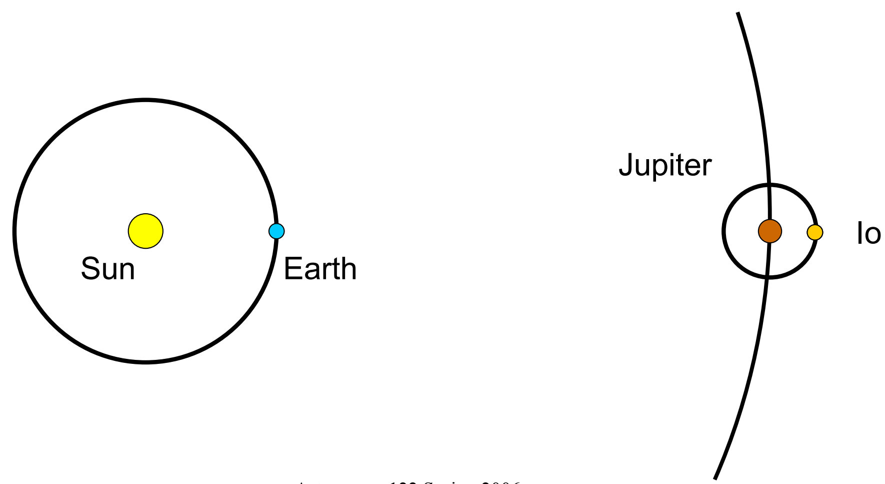
The Speed of Light

- The ancient Greeks believed speed of light was infinite
- In the 1600s Galileo realized that "very fast" is not the same as "infinite"
  - First to suggest an experiment to measure speed of light
- Maxwell theorized that light waves travel at the same speed, ***regardless of wavelength***



Light travels with a finite speed

First actual measurement by Ole Roemer in 1675 using Jupiter's moon Io – eclipses by Jupiter delayed by several minutes (16 mins) every six months because of extra light travel distance



How Fast is Light?

- Measured in 1675 at 8¼ minutes per AU
- Today, we know the speed of light to be **c = 3×10^8 m/s** (186,000 miles per second)!
- How fast is that?
  - Around the Earth over 7 times in a second
  - From Earth to the Moon in under 2 seconds (it took the astronauts 2 weeks)
  - From the Sun to the Earth in a little over 8 minutes
  - From the Sun to Pluto in about 5½ hours
  - From the nearest star to Earth, about 4 years

A Light Year

The **light-year**
- Distance that light travels in one year
- Speed of light: $\approx 3.00\times10^5$ km/sec
- Seconds in one year:

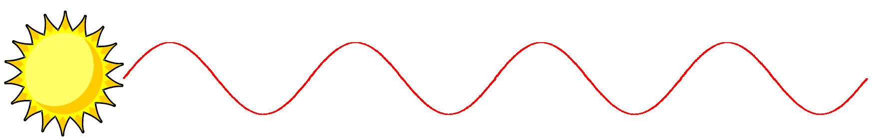
$$\left(60\,\frac{\text{sec}}{\text{min}}\right)\times\left(60\,\frac{\text{min}}{\text{hour}}\right)\times\left(24\,\frac{\text{hour}}{\text{day}}\right)\times\left(365\,\frac{\text{days}}{\text{year}}\right)=3.16\times10^7\,\text{sec}$$

so 1 light year = (3.00×10^5 km/sec) × (3.16×10^7 sec) = 9.42×10^{12} km

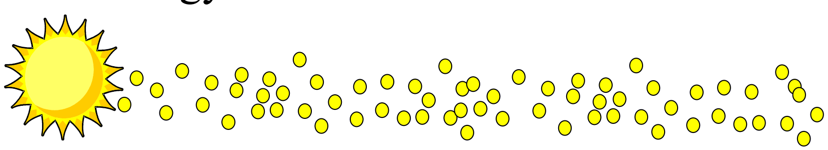
- Nearest star (Proxima Centauri) is about 4.2 light years away.
- Analogous to saying: Chicago is about 2 hours away.

Particle or Wave?

- So, how does light behave?



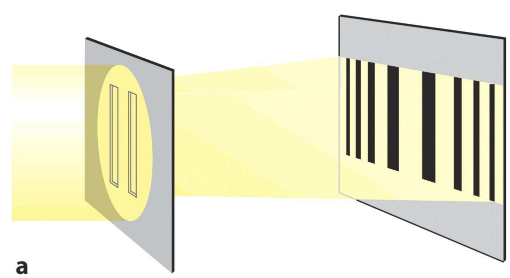
- **Huygens:** light travels in the form of waves of energy



- **Newton:** light is composed of a large number of particles

Light is a Wave!

- In 1801, an English physicist demonstrated that light travels as a wave
- When a single color of light is passed through a double slit, a pattern light and dark bands is produced
- Can only be explained by wave-like behavior



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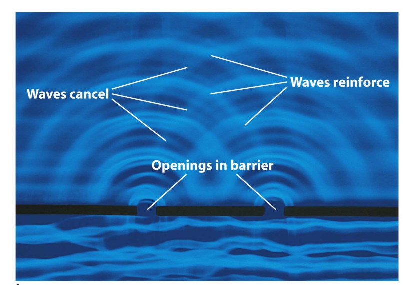

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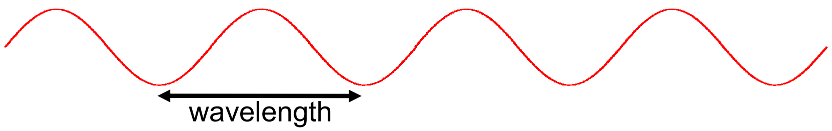
Light as a Wave

- The fundamental properties of a wave are its *wavelength* and *frequency*

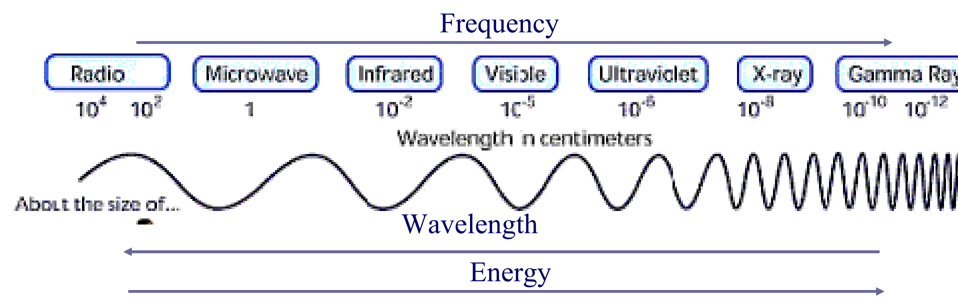


- **Wavelength** (λ) is the distance between successive crests of a wave
- **Frequency** (ν) the number of wave crests that pass by an observer per second (1/period)
- **Frequency = the speed of a wave / Wavelength**

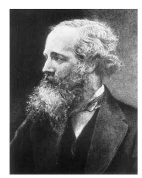
$$\upsilon = \frac{c}{\lambda}$$

What's the Frequency?

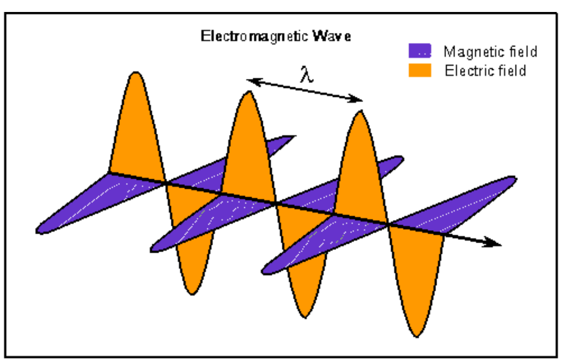
- The frequency of light depends on its color.
- The unit is Hertz, equivalent to 1 cycle a second.
- For radio waves, we normally use larger units
  - 1 kHz = 1000 Hz
  - 1 MHz = 10^6 Hz
  - 1 GHz = 10^9 Hz



Electromagnetic Radiation

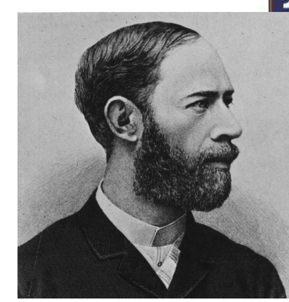


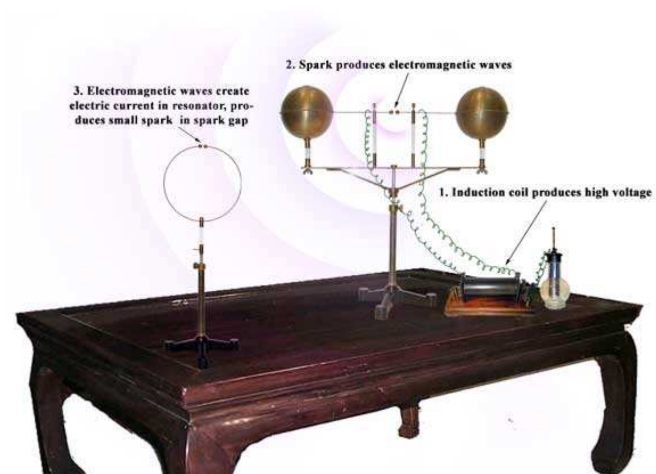
- In the 1860s, a Scottish physicist named Maxwell created new theories of electricity and magnetism
- Suggested that light is traveling electric and magnetic energy
- Geek speak for light – *electromagnetic radiation*
- Predicted "invisible" light!



The discovery of radio waves

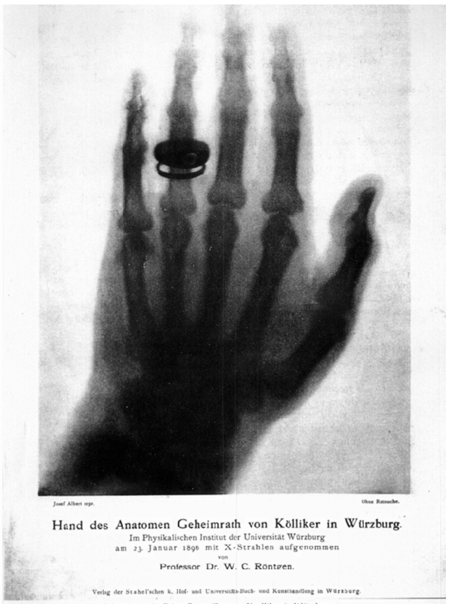
Heinrich Hertz's experiment (1885)





The discovery of X-rays

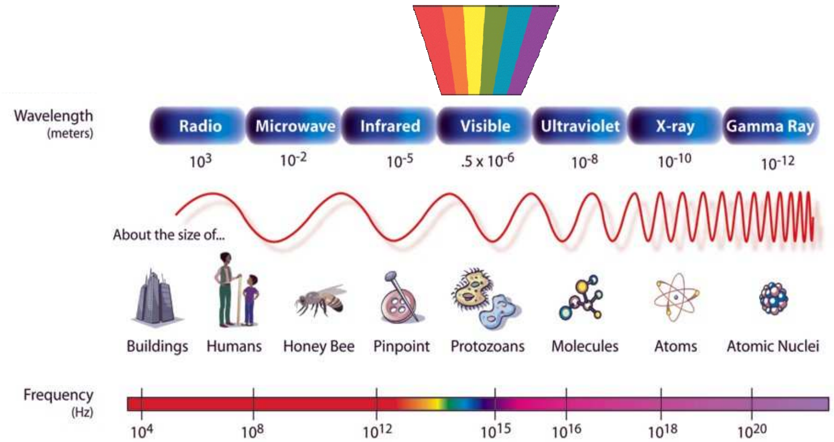
Wilhelm Roentgen (1895)



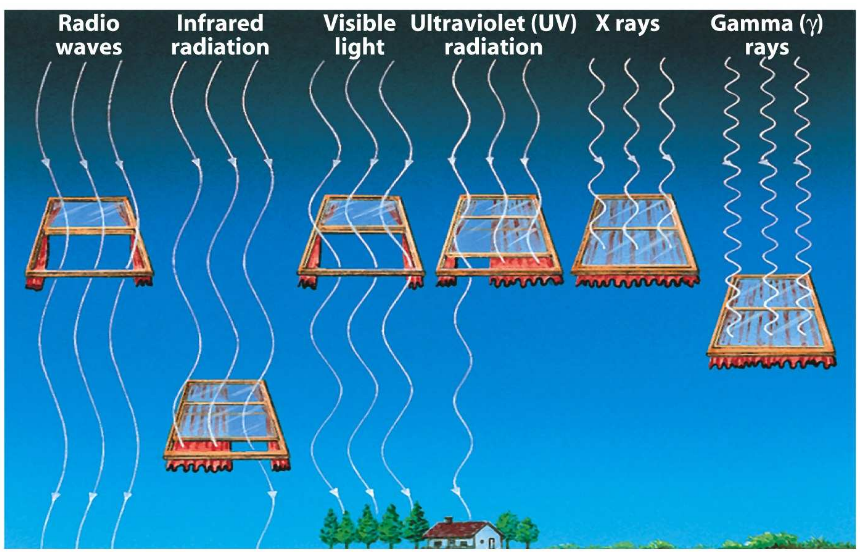
Radiograph of the hand of the anatomist Privy Councillor von Koelliker in Würzburg, taken by W.C. Röntgen in Würzburg on January 23, 1896

The electromagnetic spectrum

- Visible light is only a tiny portion of the full electromagnetic spectrum
- Red light has longer wavelength/lower frequency/lower energy than blue light
- Divisions between regions are really only from biology or technologies.



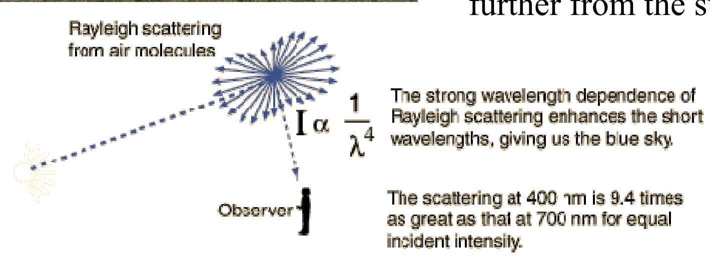
The atmosphere absorbs some wavelengths and not others



Why is the Sky Blue?

Atmospheric nitrogen and oxygen scatter the blue part of the spectrum via Rayleigh scattering (when molecules are up to $\lambda/10$).

Note that the blue of the sky is more saturated when you look further from the sun.



http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html#c2

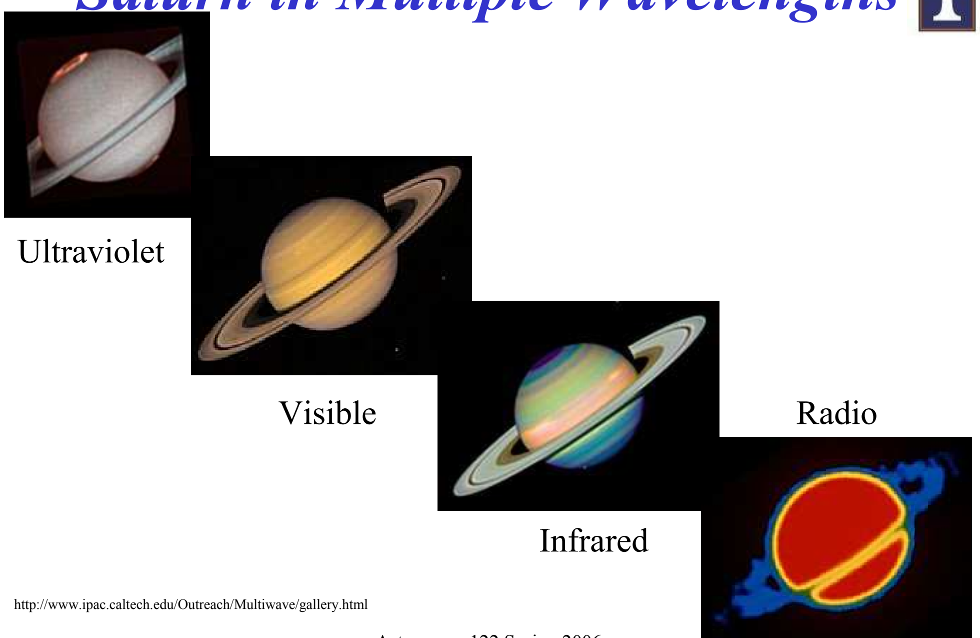
Light is also a Particle!

- In 1905, Einstein showed that light also behaves as a particle
- Light particles are called ***photons (symbol γ)***
- The energy of a photon increases as the frequency of the light increases (and the wavelength decreases)

$$E = h\nu$$

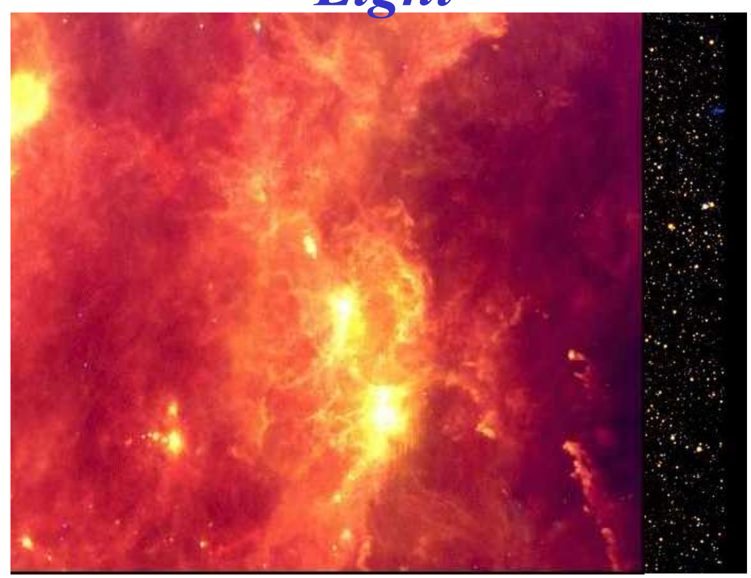
- Planck's constant ($h = 6.63 \times 10^{-34}$ J s)
- That means that a 100-watt light bulb emits 3×10^{20} photons per second!
- What does this mean for a laser pointer?

Saturn in Multiple Wavelengths

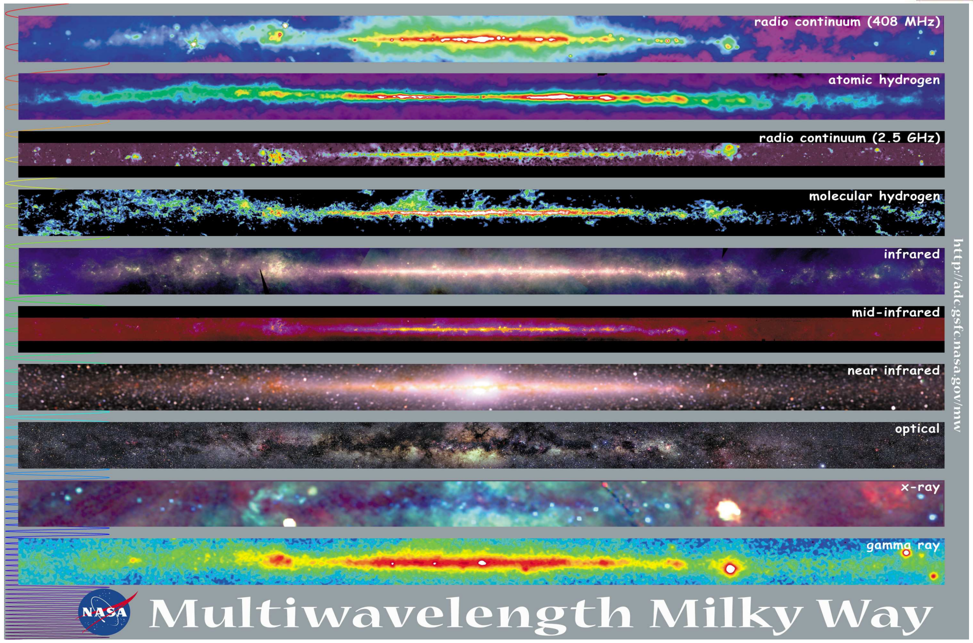


http://www.ipac.caltech.edu/Outreach/Multiwave/gallery.html

Orion in Visible and Infrared Light



Multi-Wavelength Galaxy

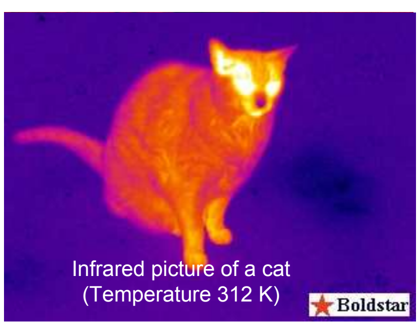


The Big Picture

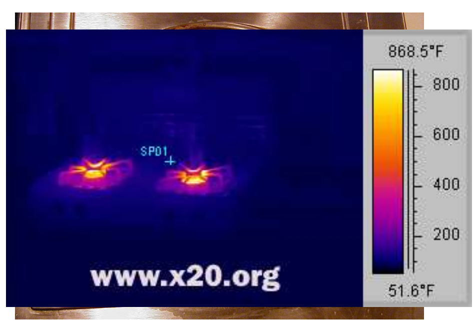
- Today, we can observe in almost every part of the electromagnetic spectrum
- Only 100 years ago, we were blind to the big picture of the Universe
- As we begin to piece together the big picture, our understanding of the cosmos grows

Blackbody Radiation

- Light that objects emit because of their temperature is called **blackbody radiation**
- Blackbody radiation is composed of a continuous spectrum of wavelengths
- The **hotter** an object gets, the **more intense** and **shorter wavelength** (blue-er) its blackbody radiation becomes



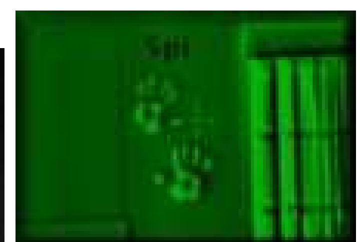
Infrared picture of a cat (Temperature 312 K)



Visible-light picture of a stove element (Temperature ~ 400 K)

Glowing Bodies

- So, everything we know is in fact giving off light– as long as it has a temperature (T > 0 K), it is glowing.
- The higher the temperature the shorter the wavelength it glows in– compare the person on the right (in the near infrared) and a light bulb (in the visible).



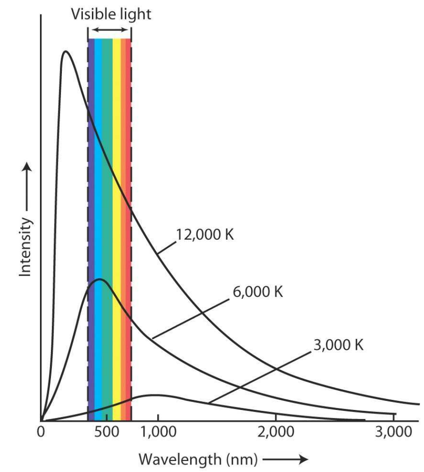
http://www.x20.org/thermal/thermal_weapon_sight_TIWS320.htm

Define Blackbody

- A perfect absorber of light
- It re-emits radiation according to its temperature
- Therefore, “blackbody radiation" = thermal radiation
- Usually, most familiar objects are well approximated as blackbody radiators
- A clear exception is a laser pointer.
  - Why?
- The spectrum of this ideal, only depends on its temperature!

The Spectrum of Blackbody Radiation

- Brightness is > 0 for all λ
- For higher temperature the maximum occurs at shorter wavelengths.
- For lower temperatures the maximum occurs at longer wavelengths.



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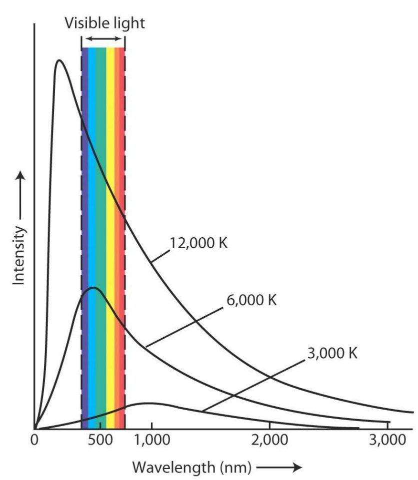
- For higher temperature the maximum occurs at shorter wavelengths.
- For lower temperatures the maximum occurs at longer wavelengths.

Wein's Law

$$\lambda_{\max} = \frac{0.0029}{T} \text{ meters}$$

(if T is in Kelvin)



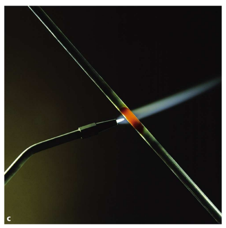
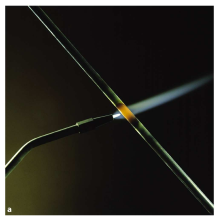
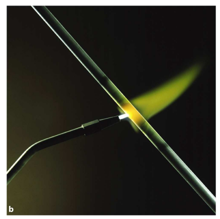
Think

Which star is hotter?
- Vega (blue)
- Capella (yellow)
- Antares (red)

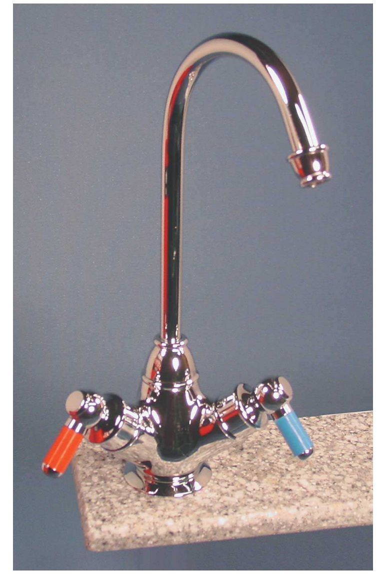
- Note: It doesn’t matter how far away the star is!

Red Hot?

- Actually Red hot is not too hot.
- Blue hot is hot.
- White hot is even hotter.

Common Error?



The Spectrum of Blackbody Radiation

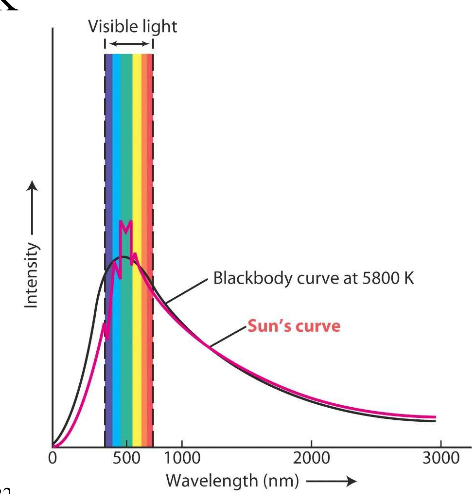
Sun's maximum is at $\cong 500$ nm

$$\text{So, } T \approx \frac{2.9\times10^{-3}\text{ m K}}{500\times10^{-9}\text{ m}} = 5800\text{ K}$$

The Sun's spectrum looks almost like a 5800 K blackbody.

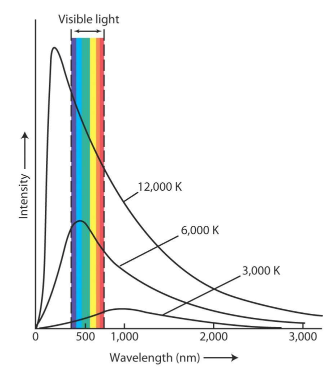
This is a very powerful tool! We can find the temperature by the light shape (spectrum).

Color $\Leftrightarrow$ Temperature!



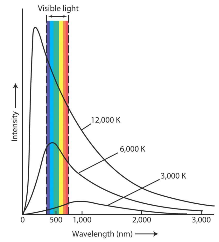
Blackbody Flux-ed

- Flux is the energy flow, or how rapidly energy flows out of the blackbody.
- The total flux from a blackbody is adding up the intensity in the spectrum.
- Do you think it depends on temperature?



- Strongly dependent on temperature.
  - $F = \sigma T^4$ energy per per unit area per unit time

Blackbody Flux-ed



- Strongly dependent on temperature.
  - $F = \sigma T^4$ energy per per unit area per unit time

$$\sigma = 5.67 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2 K^4} \text{ Stefan - Boltzmann}$$

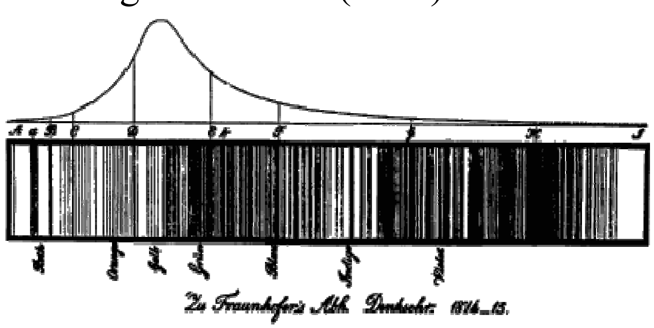
Stephan-Boltzmann Law

- If the Sun, suddenly became twice as hot, it would be

1. ¼ times dimmer
2. ½ times dimmer
3. 1/16 times dimmer
4. 1/32 times dimmer
5. 2 times as bright
6. 4 times brighter
7. 16 times brighter
8. 32 times brighter

Spectral Lines

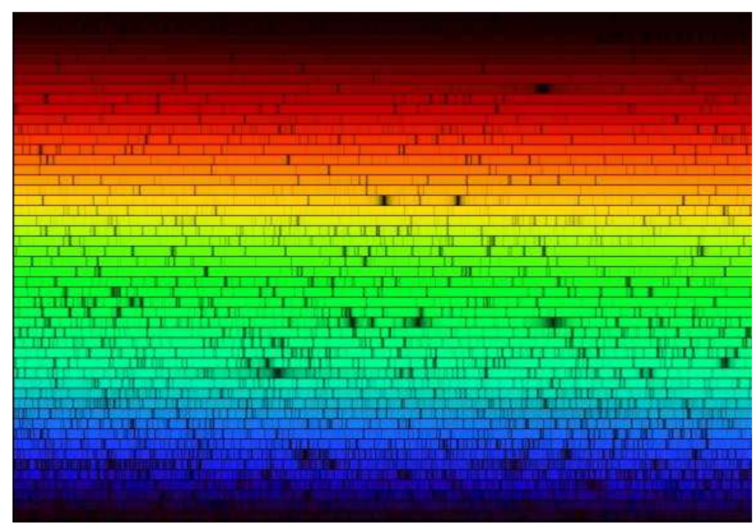
- Fraunhofer discovered that Sun's spectrum contained narrow gaps (absorption lines) when viewed at high resolution (1814)



Joseph von Fraunhofer (1787-1826)

Prism spectrograph

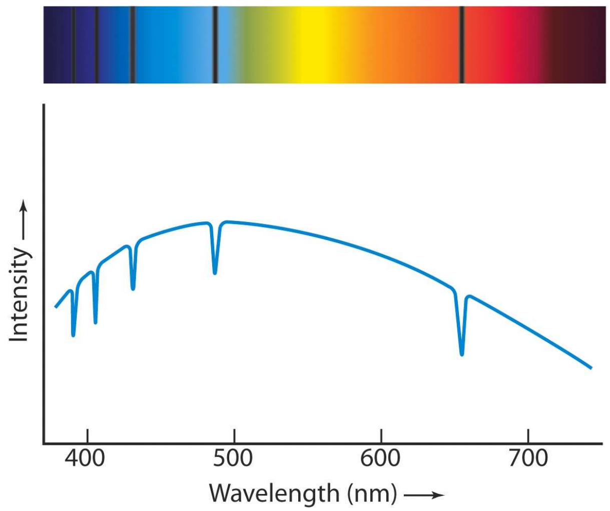
What Color is Sunlight?



http://antwrp.gsfc.nasa.gov/apod/ap000815.html

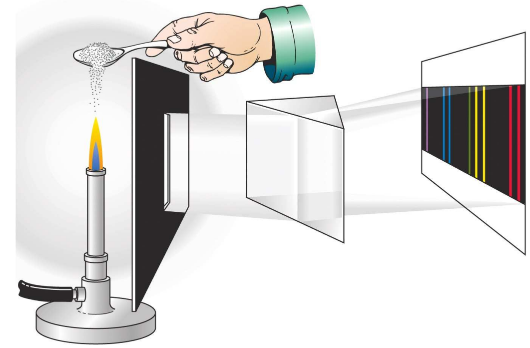
Spectrum Lines

- When astronomers looked at the spectra of the Sun and stars, they saw **gaps**
- Not a perfect blackbody spectrum!
- Called *dark spectrum lines*



In the Laboratory

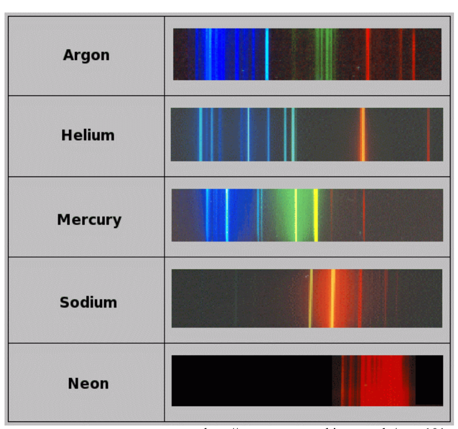
- Bright spectrum lines were produced and studied in the laboratory in the mid-1800s
- Discovered that burning different chemical elements produced different patterns of lines



Spectrum Lines = Fingerprints

The pattern of spectrum lines produced by a gas depends on its chemical composition

Or a barcode!

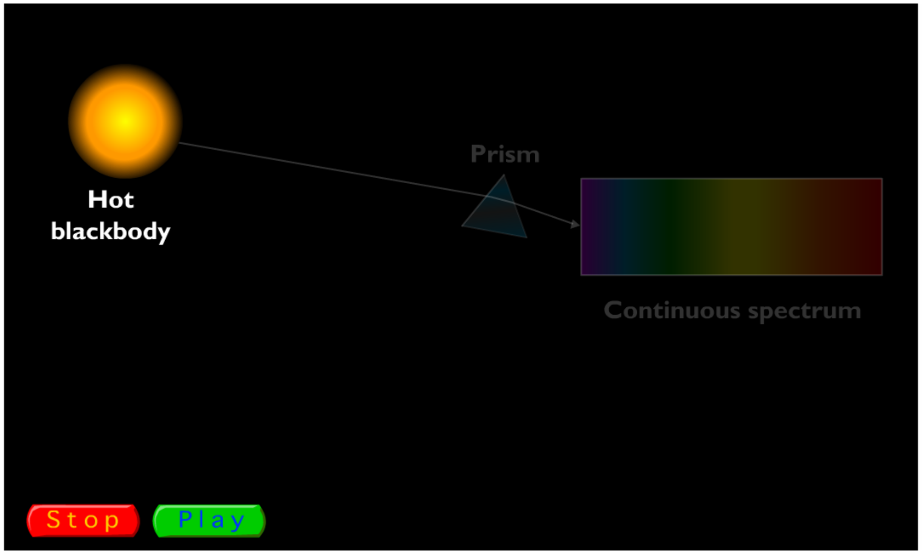


http://www.astro.washington.edu/astro101v

Kirchoff's Laws

- Law 1: A hot opaque body, such as a blackbody or a hot dense gas, produces a continuous spectrum– a rainbow of colors.
- Law 2: A hot transparent gas will produces emission line spectrum– a series of bright spectral lines with a dark background.
- Law 3: A cool, transparent gas in front of a blackbody, produces an absorption line spectrum– it removes the light at the same colors as the gas would emit if it was hot (Law #2)

Kirchoff's Laws



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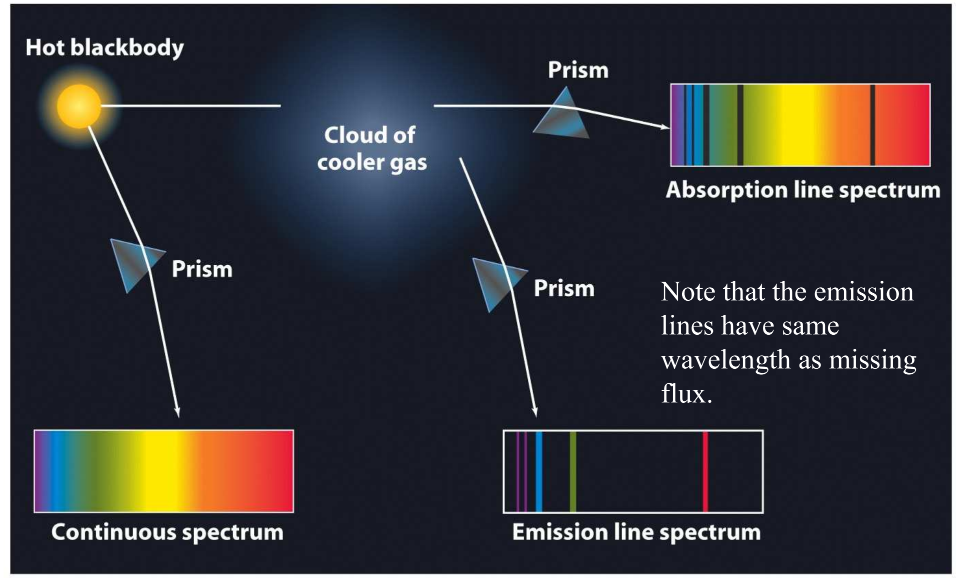

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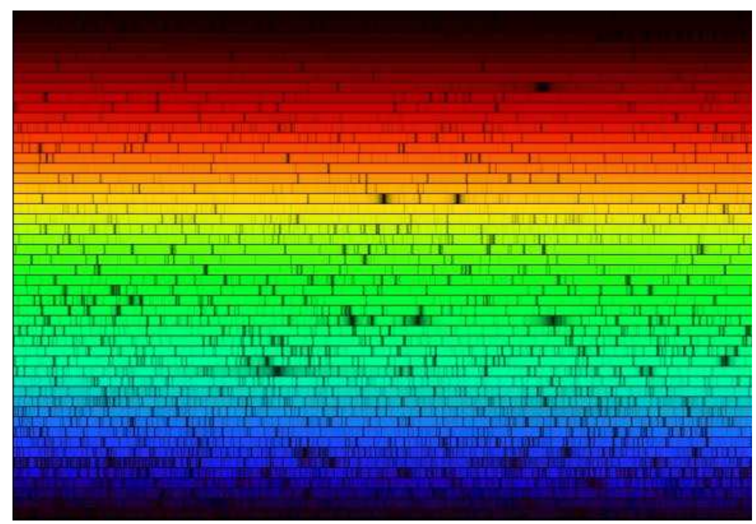
What Color is Sunlight?

Sun is a hot, dense object

So, there must be a cooler, less dense solar atmosphere surrounding it.



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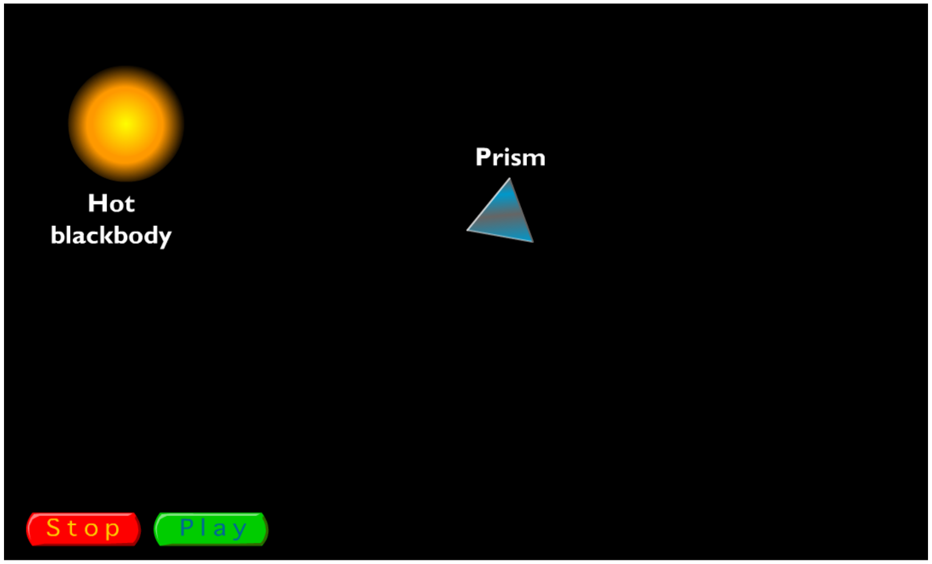

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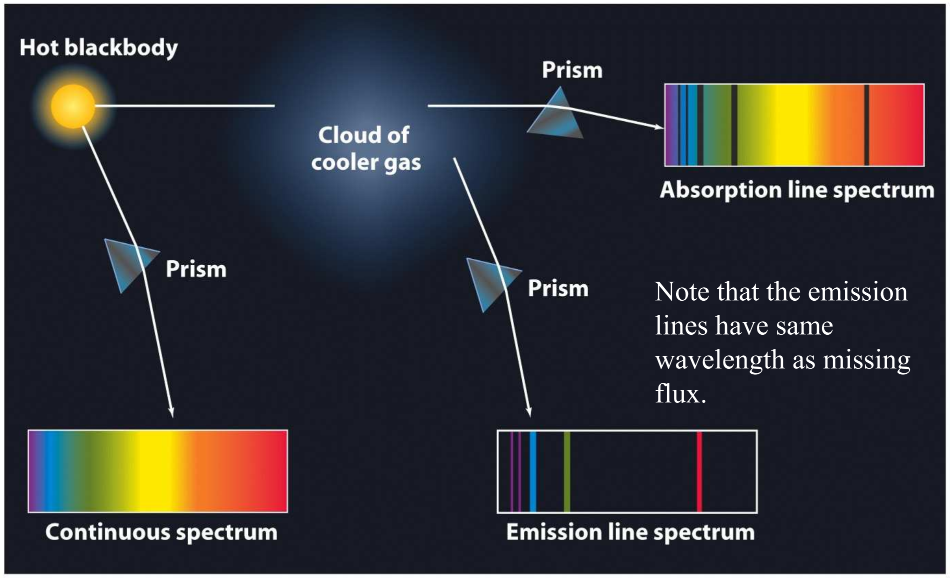

Note that the emission lines have same wavelength as missing flux.