How to Make Light (part 1)
Light is a changing electric and magnetic field - electromagnetic radiation.

Changing electric field, e.g. by accelerating electrons

We discuss two major mechanisms:
- Thermal blackbody Radiation
- Spectral Line Emission
Heat and Temperature

- The hotness or coldness of an object is characterized by its temperature.
- Temperature refers to the degree of agitation, or the speed with which the particles move.
Temperature

- In science, temperature is measured in K (degree Kelvin).

- All atoms are vibrating unless at absolute zero temperature ($T = 0 \text{ K} = -459.7 \text{ F}$).

- Water freezes at 273 K and boils at 373 K.

- Heat refers to the amount of energy stored in a body.
Spectrum: photon distribution according to energy (or wavelength or frequency)

Blackbody: perfect absorber (roughly a very thick or solid object)
Animation
The Difference Between Black and White

- “White” light – contains all the frequencies of the visible part of the spectrum.

- White paint – diffusely scatters all frequencies of the visible part of the spectrum equally.

- Black paint – absorbs all frequencies of the visible part of the spectrum equally.

- “Blackbody” – emits and absorbs radiation over a specific set of frequencies.
Discussion Question

Why does NASA paint spacecraft white?

Absorption Spectrum of Black Paint

Absorption Spectrum of White Paint

Absorption

Frequency

Infrared

Visible
Hotter objects emit photons with a higher average energy.

- **Wien’s Law**
  - The peak of the blackbody emission spectrum is given by

\[ \lambda_{\text{max}} = \frac{2.9 \times 10^6}{T(\text{Kelvin})} \text{ nm} \]

The higher the temperature, the shorter the wavelength, i.e. the bluer
WAVELENGTH

Note: degrees Kelvin (K) = degrees Celsius (C) + 273
Blackbody Radiation

- 15,000 K star
- The Sun (5,800 K)
- 3,000 K star
- 310 K human

Intensity (relative) vs. wavelength (nm)

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The graph below shows the blackbody spectra of three different stars. Which of the stars is at the highest temperature?
Stefan-Boltzmann Law:
Emitted power per unit area = $\sigma T^4$

$\sigma = 5.7 \times 10^{-8} \text{ W/(m}^2\text{K}^4)$
You are gradually heating up a rock in an oven to an extremely high temperature. As it heats up, the rock emits nearly perfect theoretical blackbody radiation – meaning that it is brightest when hottest. is bluer when hotter. is both is neither
For star: $L = A \sigma T^4$, $A$ is its surface area.

Luminosity is proportional to fourth power of temperature.

- Sun: $6000\,\text{K}$, $L = 1$
- $12,000\,\text{K}$, $L = 16$\;\quad \left(\frac{12,000}{6000}\right)^4 = 2^4$
- $2000\,\text{K}$, $L = \frac{1}{81}$\;\quad \left(\frac{2000}{6000}\right)^4 = (1/3)^4$
Campfires are blue on the bottom, orange in the middle, and red on top.

Which parts of the fire are the hottest? the coolest?

As atoms get hotter, they wiggle faster and collide to each other harder ---> more light they emit and more wiggle per second = frequency goes up = wavelength goes down. Thus bluer.

Thus, as temperature goes up light gets stronger and gets blue.
Thermal Radiation

- Every object with a temperature greater than absolute zero emits radiation.
- Hotter objects emit more total radiation per unit area.
- Hotter objects emit photons with a higher average energy.
How to Make Light (Part 2)

- Structure of atoms
- Energy levels and transitions
- Emission and absorption lines
- Light scattering
Atoms

Atoms are made of electrons, protons, and neutrons.

The bounding force: the attractive Coulomb (electrical) force between the positively charged nucleus and the negatively charged electrons.
Electrons can be in different orbits of certain energies, called energy levels.

Different atoms have different energy levels, set by quantum physics.

Quantum means discrete!
Excitation of Atoms

- To change its energy levels, an electron must either absorb or emit a photon that has the same amount of energy as the difference between the energy levels.
- \( E = h\nu \) --- Larger energy difference means higher frequency.
- Different jumps in energy levels means different frequencies of light absorbed.
If a photon of exactly the right energy is absorbed by an electron in an atom, the electron will gain the energy of the photon and jump to an outer, higher energy orbit.

A photon of the same energy is emitted when the electron falls back down to its original orbit.
No thanks. Wrong energy.

Aha!

Ah.

Oops.
Collisions (like in a hot gas) can also provide electrons with enough energy to change energy levels.

A photon of the same energy is emitted when the electron falls back down to its original orbit.
Different allowed “orbits” or energy levels in a hydrogen atom.

Emission line spectrum

Absorption line spectrum
Spectral Lines of Some Elements

Argon
Helium
Mercury
Sodium
Neon

Spectral lines are like a cosmic barcode system for elements.
Atoms of different elements have unique spectral lines because each element

- has atoms of a unique color
- has a unique set of neutrons
- has a unique set of electron orbits
- has unique photons
Blackbody radiation

Gas atoms

Telescope

Spectrograph

Absorption spectrum
There are similar absorption lines in the other regions of the electromagnetic spectrum. Each line exactly corresponds to chemical elements in the stars.
Reflection nebula

Emission nebula
Encoded in an object’s spectrum is information about the emitter/absorber. This is how we learn what the Universe is made of!
There are three basic aspects of the light from an object that we can study from the Earth.

- **Intensity** (spatial distribution of the light)
- **Spectra** (composition of the object and the object’s velocity)
- **Variability** (change with time)
The Doppler Effect:
other information contained in spectrum

- A moving light or sound source emits a different frequency in the forward direction than in the reverse direction.

- Take a look at the police car to see how this works.
In general ...

- The “native” frequency at which an object is emitting is called the rest frequency.

- You will see/hear frequencies higher than the rest frequency from objects moving towards you.

- You will see/hear frequencies lower than the rest frequency from objects moving away from you.
The first crest travels out in circle from the original position of the plane.

At a later time, a second crest is emitted from the plane's new position, but the old crest keeps moving out in a circle from the plane's original position.

The same thing happens again at a later time.

Doppler Effect

Shorter wavelength (more blue)

Longer wavelength (more red)
What we actually see in Astronomy

Emission spectrum of hot gas as seen in lab

Emission spectrum of hot gas as seen in rapidly moving object

Is this object moving towards or away from us?
Two identical stars are moving towards the Earth. Star A’s emission lines are observed to be at visible wavelengths. The same emission lines for Star B are observed to be at ultraviolet wavelengths. From these observations you conclude that:

- Both stars are moving away from the Earth
- Star A is moving towards the Earth faster than Star B
- Star B is moving towards the Earth faster than Star A
- Star B is moving away from the Earth while Star A is moving towards the Earth.
A spectral line from star A indicates that star A rotates slowly. This light is slightly blueshifted.

A spectral line from star B indicates that star B rotates rapidly. This light is greatly blueshifted.

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Two otherwise identical stars are rotating at different rates. Star A is rotating slower than Star B. How do Star A’s spectral lines appear with respect to Star B’s lines?

- Star A’s lines are narrower than Star B’s lines.
- Star B’s lines are narrower than Star A’s lines.
- There is no difference in the lines of the two stars.
- Star A’s lines are stronger than Star B’s lines.
The Symphony of Light

- Comparison with sound waves
- See the symphony of the universe with telescopes
<table>
<thead>
<tr>
<th>Spectrum Type</th>
<th>Wavelength Range</th>
<th>Size Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>$1 \times 10^{-3}$</td>
<td>Buildings, Grains of Sugar</td>
</tr>
<tr>
<td>Microwave</td>
<td>$7 \times 10^{-7}$</td>
<td>Protozoans, Bacteria</td>
</tr>
<tr>
<td>Infrared</td>
<td>$4 \times 10^{-7}$</td>
<td>Molecules, Atoms</td>
</tr>
<tr>
<td>Visible</td>
<td>$10^{-8}$ to $10^{-12}$</td>
<td>Atomic Nuclei</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>$10^{-8}$ to $10^{-12}$</td>
<td></td>
</tr>
<tr>
<td>X-ray</td>
<td>$10^{-12}$</td>
<td></td>
</tr>
<tr>
<td>Gamma Ray</td>
<td>$10^{-12}$</td>
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Most kinds of e-m radiation cannot penetrate the Earth's atmosphere
The Five College Radio Astronomy Observatory
Optical Sky
Near-infrared sky
Soft X-ray Sky
The Multi-wavelength Sun

- Radio
- Infrared
- Optical
- X-ray