The Nature of Light and the Structure of Matter

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Light Speed! A Key Property

- Obviously, using and understanding light is important to the astronomer (we need it in order to “see” anything!)

- The speed of light is not infinity: it takes time for light to travel from a source emitting it to an observer
  - This fact was discovered in 1676 by Ole Rømer: Jovian moon Io passing in and out of Jupiter’s shadow utilized
  - Recall first lecture: 299,792,458 m/s (~186,300 mps)
  - When we cover special relativity we will understand why no object and no information can travel faster than it
  - Speed above defined for vacuum \( c \); different materials can slow light (looks ~3/4 as fast in water -- direction changes)
  - Looking out into space means peering into the past!

Light always “flies” along straight lines (directional changes are sharp): we’ll learn about tricky exception later

It’s electrically neutral: that means you can’t attract it with a charge (charged particle) or bend it with a magnet
A 19th century English scientist, Thomas Young, conducted the famous double slit experiment which “proved” that light is clearly a wavelike phenomenon.

Different light waves have characteristic “wavelengths”

The distance or length between identical points in the wave: peak to peak or trough to trough.

Distinct wavelengths = colors

Waves of light “interfere” with each other just like waves in water do: overlapping either constructively or destructively.

http://www.daviddarling.info/encyclopedia/I/interference.html
Penetrates Earth's Atmosphere?

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Microwave</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Infrared</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Visible</td>
<td>$0.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>X-ray</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Gamma ray</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>

Approximate Scale of Wavelength

- Buildings
- Humans
- Butterflies
- Needle Point
- Protozoans
- Molecules
- Atoms
- Atomic Nuclei

Frequency (Hz)

- $10^4$
- $10^8$
- $10^{12}$
- $10^{15}$
- $10^{16}$
- $10^{18}$
- $10^{20}$

Temperature of objects at which this radiation is the most intense wavelength emitted

- $1 \text{ K}$: $-272 ^\circ \text{C}$
- $100 \text{ K}$: $-173 ^\circ \text{C}$
- $10,000 \text{ K}$: $9,727 ^\circ \text{C}$
- $10,000,000 \text{ K}$: $\sim10,000,000 ^\circ \text{C}$

Sources

- AM Radio
- FM Radio
- Microwave Oven
- Radar
- People
- Light Bulb
- The ALS
- X-Ray Machines
- Radioactive Elements

Energy of one photon (electron volts)

- $10^{-9}$
- $10^{-8}$
- $10^{-7}$
- $10^{-6}$
- $10^{-5}$
- $10^{-4}$
- $10^{-3}$
- $10^{-2}$
- $10^{-1}$
- $10^{1}$
- $10^{2}$
- $10^{3}$
- $10^{4}$
- $10^{5}$
- $10^{6}$
simplified version of the EM spectrum

<table>
<thead>
<tr>
<th>Gamma Rays</th>
<th>X-Rays</th>
<th>Ultraviolet Rays</th>
<th>Infrared Rays</th>
<th>Radar</th>
<th>FM</th>
<th>TV</th>
<th>Shortwave</th>
<th>AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 10^{-14}</td>
<td>1 x 10^{-12}</td>
<td>1 x 10^{-8}</td>
<td>1 x 10^{-4}</td>
<td>1 x 10^{-2}</td>
<td>1 x 10^2</td>
<td>1 x 10^4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Wavelength (in meters)

Visible Light

Wavelength (in meters)

High Energy

Low Energy

zoom in on the rainbow

Electricity and magnetism (E&M) were unified by 19\textsuperscript{th} century physicist James Clerk Maxwell by means of his famous equations. When compiling them he discovered they were telling us that electromagnetic waves all propagate (travel) at the same, constant speed.

Surprisingly, the speed of moving EM fields turned out to be almost the same as the measured speed of light!

A time-varying electric field leads to a new field, a magnetic one, and vice versa. What “waves” are the fields’ magnitudes?
Waves Need a Medium

Light cannot be using air in order to propagate because it has no trouble getting from the sun to the earth across the vacuum of outer space. (Sound definitely uses air e.g.)

A mysterious fluid called the luminiferous aether (or ether) was hypothesized to permeate the universe, with light being waves in the aether like ripples on a pond.

The famous 1887 Michelson-Morley “failed” (null-result) experiment demonstrated that light did not seem to change speed when “swimming” with versus against the aether.

Difference caused by the earth’s motion (rotation and revolution) should have been observed. A result hotly debated, doubted by M&M.
Light can interact with matter to liberate electrons from atoms, producing electricity.

- Number of electrons released jumps in discrete steps, and there is a minimum energy (i.e., maximum wavelength).
- Einstein eventually won the Nobel Prize, not for relativity, but for his 1905 explanation of this: photoelectric effect.

Albert’s theory: light is not a wave but a particle (ZERO mass)! But wait, didn’t we just say that it was conclusively shown to be a wave?

- The smallest, indivisible unit (or quantum) of light is the “photon”

BOTH explanations are true/correct. Light is some third thing that is neither wave nor particle (also true of particles that make up matter: even atoms exhibit wavelike properties): NOT a wave of particles, though maybe of probabilities of localization (no medium needed).
All the Ways γ* Behaves

- **Reflection** (this and other phenomena below a lot like sound, heat,..)
  - Specular (same angle, like mirror) and diffuse (random angle back out)
  - “Total internal” (TIR): light trapped. External substance has smaller ‘n’

- **Refraction**: there is a useful quantity called “index of refraction”
  - $n = 1$ light at max speed; for $n > 1$ light slows and bends (Snell’s Law)
  - For x-rays in certain materials, $n < 1$ (anomalous dispersion)
  - $n >> 1$ (slow light) and $n = \infty$ effectively (stopped light) possible
  - $n < 0$ refers to meta-materials, around which photons slip past

- **Diffraction**: spread around obstacles much smaller than $\lambda$ (waves, p. 3)

- **Scattering** (off stuff less than or equal in $\lambda$): sample of a few kinds
  - Compton: high-energy γ-rays scatter off charged particle, like electron
  - Thomson: the low-energy limit (approximation) of the above
  - Rayleigh: visible photons off objects smaller than $\lambda$ (atoms, molecules)
  - Mie: wavelength about the same, and off spherical things in particular

- **Absorption** (imaginary# part of ‘n’): gone after penetrating too deep
Final Thoughts on Photons

What is different about laser (Light Amplification by Stimulated Emission of Radiation) light, compared to (typical) natural photon production?

- Coherent: very little spatial spread in the beam, as opposed to the isotropic (equal probability in all angles) emission of a standard light bulb or LED, or the broad cone of a flashlight

- Only a very specific color, unlike the white (broad spectrum) light of the sun for instance, which contains all of the colors of the rainbow

- Generally only spot where it hits an opaque surface is visible (taking shortest time & distance), not whole beam. Scattering, such as from dust, is what makes for the pretty pictures

- Fun factoid: today lasers get bounced off a mirror left behind on the moon

Images credit: NASA
Activity: Seeing Further

If you had to build a device to see something far away how would you do it? What items and materials would you need and why, and how would you put them together?

What key properties of light that you learned from this lecture and readings would you rely on? Can you “MacGyver” it together with household items or only things you have on hand?
The Matter Connection

Astronomy about BIG, but is interdisciplinary. Can’t avoid talking about the small to at least some degree (today: photons) but we can keep it brief

- The early universe: when it was only free particles
- Nuclei + subatomic particles streaming from space
- Fusion that powers stars, and spectral lines in star/sunlight: need some atomic and nuclear physics

Matter all around made up of tiny particles, atoms

- Consist of a nucleus (core) of (heavy compared to electrons) protons and neutrons, which are in turn comprised of different quarks (u, d) held together by gluons, which transmit the “strong nuclear force”
- The negatively-charged electrons are very far away from the nucleus (compared to the overall size of an atom), but are bound to the positively-charged protons by the electromagnetic force (neutrons are neutral as name implies): positions not well-defined
- Unique elements have different numbers of protons (same number electrons to balance electric charge)
- Ions: atoms which have lost or gained electron(s), with the outermost or valence (highest energy levels a.k.a. shells or orbitals) easiest to get knocked out

Isotope: different number of neutrons (same element still), allotrope: same element, same isotopic composition but different chemical structure (carbon: diamond, graphite/graphene, buckyballs, nanotubes, etc.)
Quantum Mechanics

Connecting matter and light: Everything you have always thought of and been taught as having a particle nature (like the electron) can also behave like a wave, complete with wavelength and other associated key properties. Can also “bend rules” for short periods

Remember the double-slit experiment from the beginning of today’s lecture? Well, even a single photon, a single electron, etc. can act as though it has passed through *both slits* at the same time! Our world is seriously strange. Observations/measurements (people, instruments) lead to a “collapse” into a definite state

Example of Schrödinger’s cat: dead and alive at same time?
Einstein disliked this: QM is all about probabilities, determinism gone

We will come back to interpretations of what this means in future lectures, but for now most important take-away message is that the world around you is “quantized,” composed of fundamental building blocks, which carry energy, and what can happen must...

These are particles but also waves in nature, or in other words, the concepts of both “a particle,” and “a wave” can apply as models i.e. analogies of the more fundamental underlying reality

Can’t measure position and speed of to same precision at once (Heisenberg uncertainty principle), can “teleport” across barriers
I will love the light for it shows me the way, yet I will endure the darkness because it shows me the stars.

Og Mandino, American Author

Homework (Reading, plus quiz based upon upcoming, Wednesday, lecture)

Take Quiz #3. NO excuses for a late submission.

It is due at 11:59 pm tomorrow Tues. January 30