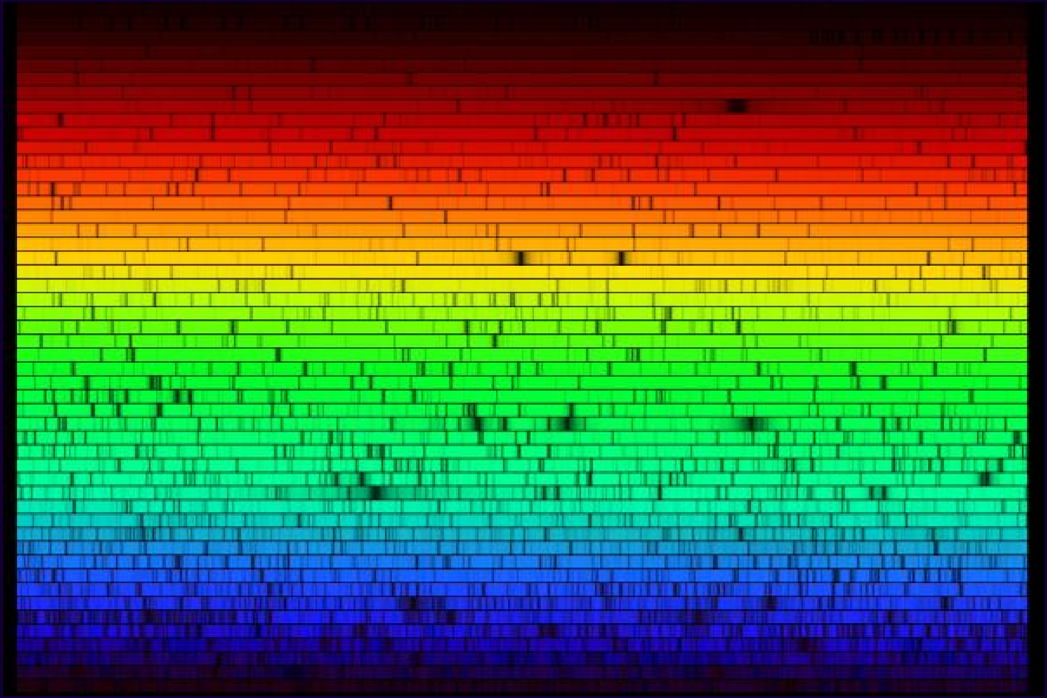
Light

Astronomy 101
Syracuse University, Fall 2021
Walter Freeman

October 21, 2021



This is a "picture" of the Sun. What can we learn from it?

Announcements

- Homework 5 will be posted tonight.
- Prelab 7 will be posted tonight. (You will do it electronically.)
- Blackboard reflects your grades from Quiz 2, but *not* the retake.

- If you're worried about quiz scores, come talk to me tomorrow morning
  - Office hours: 9am-11pm tomorrow
  - Held in room 112 as always

Paper 2

- Paper 2's assignment is posted. (It will be modified slightly tonight.)
- It is due two weeks from tomorrow.

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- This paper is an argumentative paper:
  - You're telling us that someone else is wrong
  - You can be bold in making these claims, as long as you argue your point well!

How much of the light in this room can you see?

A: All of it
B: Most of it
C: Around a quarter of it
D: Not much of it at all

How much of the sound in this room can you hear?

A: All of it

B: Most of it

C: Around a quarter of it

D: Not much of it at all

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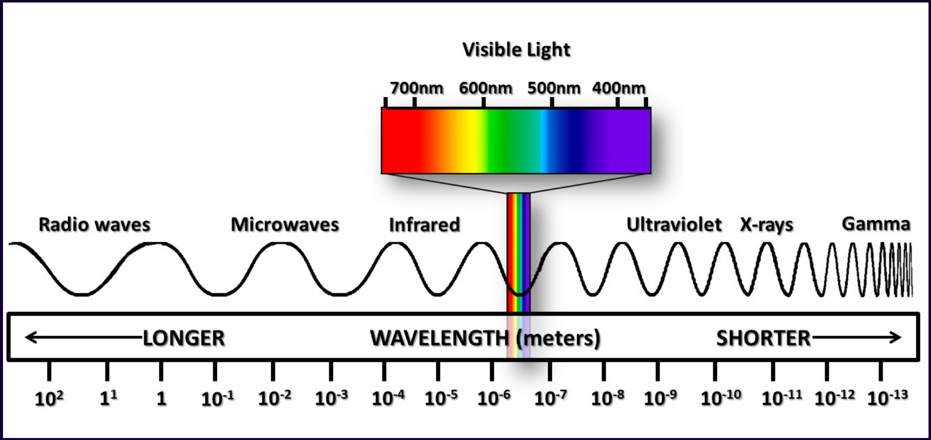
In the same way *light* has a spectrum of frequencies/wavelengths, and our eyes only perceive a tiny fraction of that spectrum.

When we say "light", we mean *all* wavelengths, not just the ones we can see!

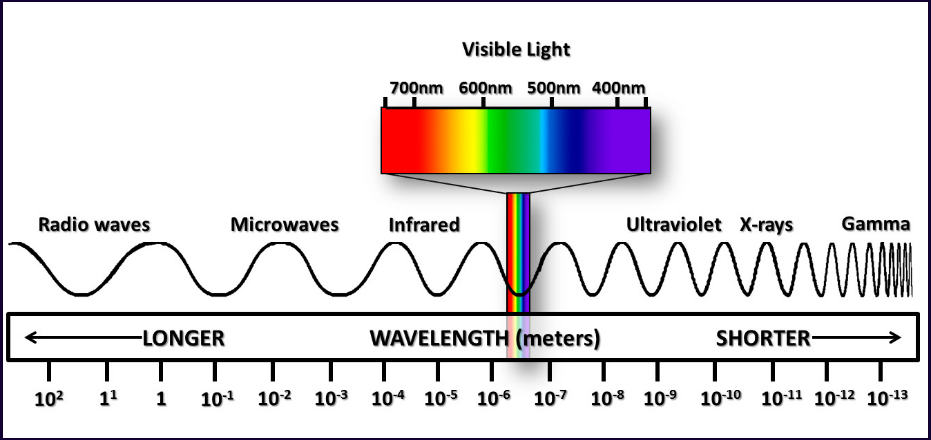
The electromagnetic spectrum



There is an enormous range of "colors" of light out there!

What's this "sound" like?

The electromagnetic spectrum



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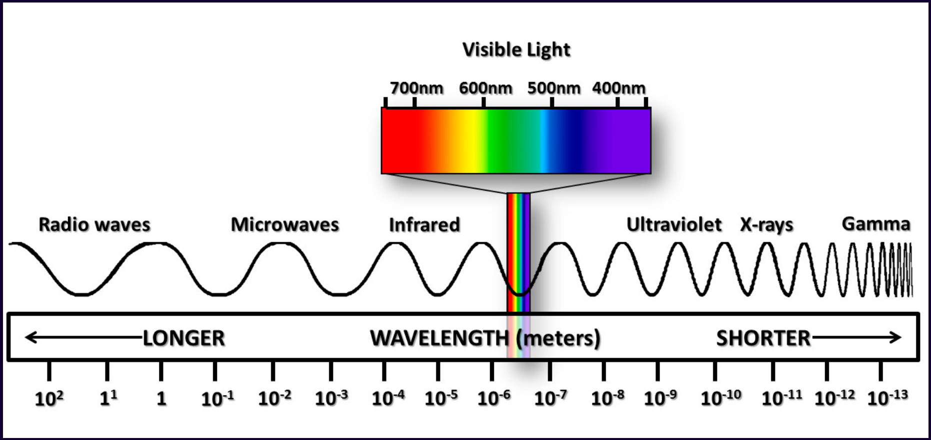

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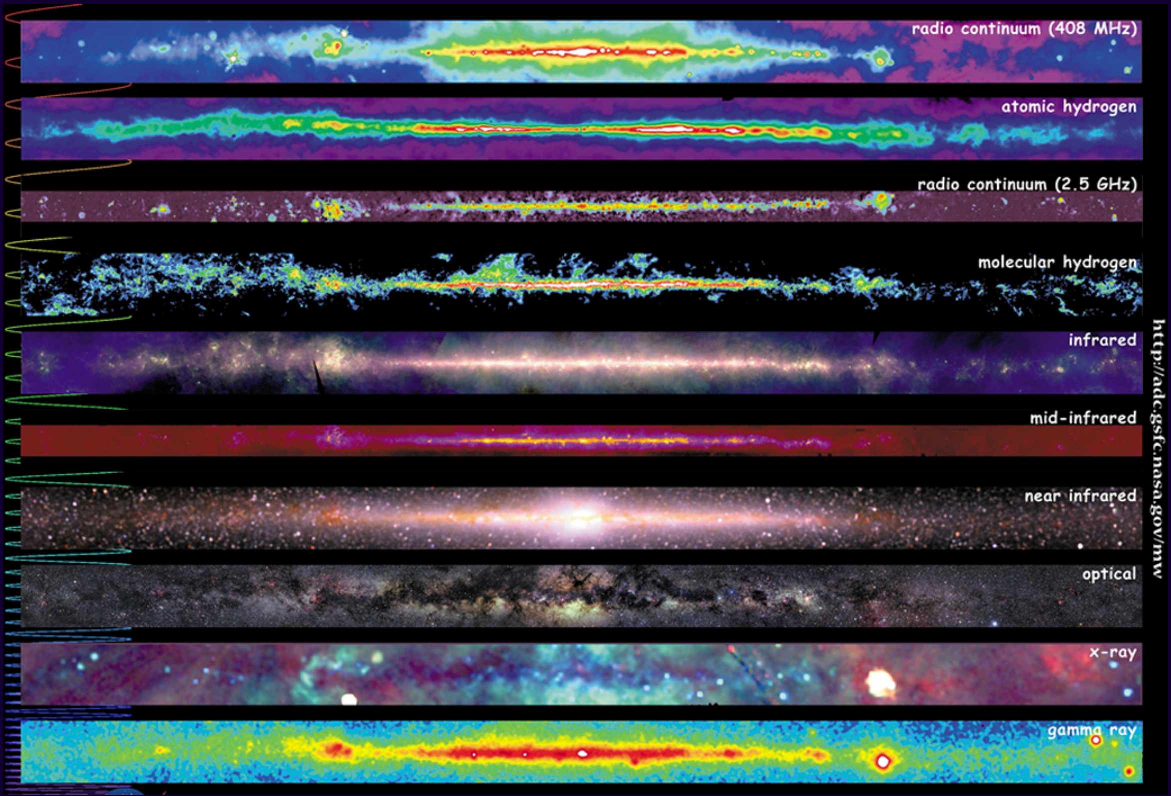
Music: "The Blood of Cu Chulainn", from the soundtrack to *Boondock Saints* (Jeff Danna, 1999)

We can learn far more about what's going on in the orchestra if we have the whole spectrum, rather than just a piece!


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw

An illuminating story

In the late 19th century, the laws of electromagnetism looked like this:

- Electric fields exert a force on electric charges
- Magnetic fields exert a force on *moving* electric charges

We know this thanks in large part to the work of Michael Faraday, who famously wasn't good at algebra and drew pictures of fields.

Where do these fields come from?

- Electric charges make electric fields
- Moving electric charges make magnetic fields
- Changing magnetic fields make electric fields

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- ... which makes an electric field further away ...

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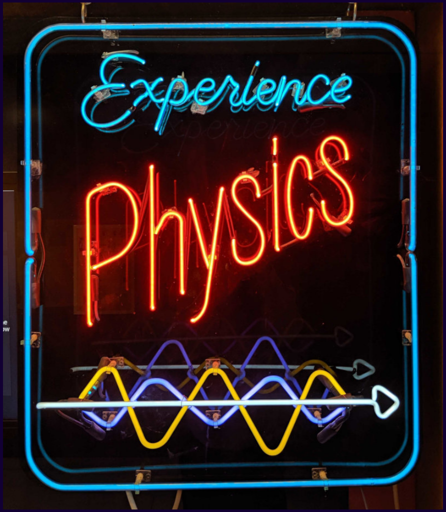
- Moving electric charges make magnetic fields
- Changing magnetic fields make electric fields
- Changing electric fields make magnetic fields

Last law added by James Clerk Maxwell in the 1860's, and it has a surprising consequence:

- Changing electric field makes a magnetic field
- ... which makes a magnetic field ...
- ... which makes an electric field further away ...
- This leads to a traveling electromagnetic disturbance: an *electromagnetic wave.*



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Independently, light had been measured to travel at 300 million meters per second some years prior.

So ... if this electromagnetic wave travels at the speed of light, perhaps it *is* light?

In the history of science, sometimes theory gets ahead of experiment – like in the discovery of the nature of light.

The properties of waves

Light is a traveling *electromagnetic wave*. This means:

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- ... it moves through space at some speed: the speed of light, $c = 3 \times 10^8$ m/s.
- ... these waves have a wavelength: the distance from peak to peak of the electric field. We use the letter λ for wavelength.
- ... and, as an observer holds still, a certain number of waves pass that observer per second. This is called the frequency, f.

How are these things related? Let's look at a simulation...

Three basic wave properties:

- Wave speed: c
- Wavelength: λ
- Frequency: f

If I keep c constant and increase f, then λ will ______________...

If I keep c constant and decrease f, then λ will ______________...

If I keep λ constant and increase c, then f will ______________...

This leads us to the basic relation:

$$c = f\lambda$$

Or in words:

$$(\text{speed of light}) = (\text{frequency}) \times (\text{wavelength})$$

This is easy to remember by thinking about how each quantity is measured:

$$\frac{\text{meters}}{\text{second}} = \frac{\text{waves}}{\text{second}} \times \frac{\text{meters}}{\text{wave}}$$

This means:

- Shorter wavelengths have higher frequency
- Longer wavelengths have lower frequency

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Maxwell deduced that it was a wave, and experiments confirmed that.

You should know:

- Energy per photon is *proportional* to the frequency of the light
- Energy per photon is *inversely proportional* to its wavelength
- Wavelength is inversely proportional to frequency

... but later experiments (which we'll see soon) showed that it had to come in discrete chunks! What gives?

Is light a wave, or is it a bunch of little particles?

It turns out that, in quantum mechanics, it can be *both*, and everyone gets to be right!

The quantum nature of light

Light has both particle properties and wave properties:

- Particle properties: it comes in discrete chunks called *photons*, each carrying a certain energy.
- Wave properties: it has a wavelength λ and frequency f

It turns out that shorter-wavelength, higher-frequency light has higher energy per photon. The relationship is:

$$E = hf = hc/\lambda$$

This value h is called Planck's constant. It is baked into the fabric of the Universe, like G and c:

- G, the universal gravitational constant: tells us how strong gravity is
- c, the speed of light: tells us how fast light goes

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- G, the universal gravitational constant: tells us how strong gravity is
- c, the speed of light: tells us how fast light goes
- h, Planck's constant: tells us how "lumpy" light is: how much energy do photons of a given frequency have?

Things you should know:

Light is both a particle and a wave.

- All light travels at the same speed, $c = 300$ million m/s, in vacuum
- Light comes in little lumps called *photons*
- Energy per photon is *proportional* to the frequency of the light
- Energy per photon is *inversely proportional* to its wavelength
- Wavelength is inversely proportional to frequency

Types of light

As you go down the table:

- Wavelength decreases
- Frequency increases (not shown)
- Energy per photon increases

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- Wavelength decreases
- Frequency increases (not shown)
- Energy per photon increases
- These are just names – all light is really the same kind of thing

	Wavelength	Energy	Application
Radio waves	100 meters - 1 meter		Long distance communication
Microwaves	1 meter - 1 cm	Too small to matter	Short distance communication
"Far infrared"	1 cm - 10 μ m	Thousandths of an eV	Radiated by room temp objects
"Near infrared"	750 nm - 10000 nm	Tenths of an eV - 1.6 eV	"Invisible light"
Visible light	380-750 nm	1.6 eV - 3.2 eV	Eyeballs!
Near ultraviolet	100-380 nm	3.2 eV - 10 eV	"Invisible light"
Extreme ultraviolet	1 nm - 100 nm	10 eV - 1000 eV	Etching computer chips
X-rays	Trillionths of a meter	1000 eV - 1 million eV	Medical imaging
Gamma rays	Smaller than that	Millions of eV	Nuclear transitions

We have lots of names for different sorts of light.

They differ only in wavelength/energy/frequency, and the other things they interact with.

- Radio waves: used to communicate over long distances
- Microwaves: used to communicate over short distances
- "Far infrared": associated with objects with temperatures close to ours
- "Near infrared": much like light, but we can't see it
- Visible light (only a very narrow range!)
- Ultraviolet: enough energy to disrupt atoms
- X-rays: enough energy to penetrate human tissue
- Gamma rays: enough energy to disrupt atomic nuclei!

All of these are “types of light”.

They differ only in wavelength/frequency/energy!