Light and the Electro-Magnetic spectrum

Koupelis - chapter 4
OpenStax - chapter 5

Today's lecture: Light

- How do we learn about the objects in the Universe? About their properties?
- From their light
- Light is radiation
- So to understand the Universe, we need to we learn about the nature of light/radiation itself

What is the nature of light?

- Useful in the dark
- A kind of electro-magnetic wave, carrying energy
- The only messenger from the Universe available to astronomers

(except meteorites, Moon rocks, cosmic rays, gravitational waves)

Light : what is its nature?

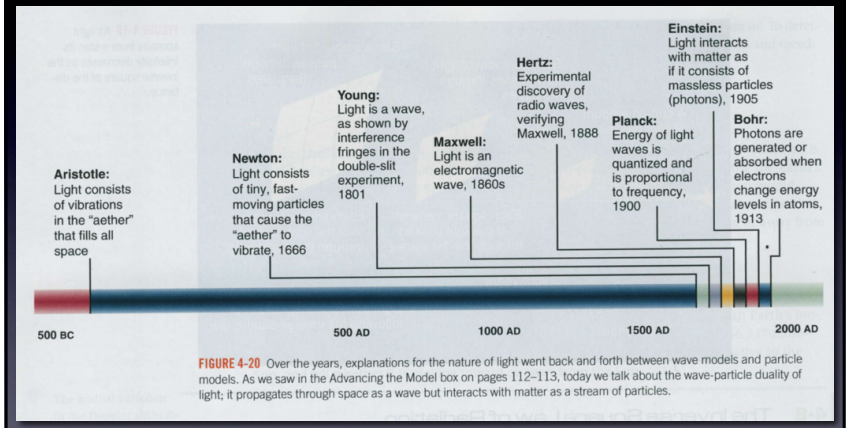
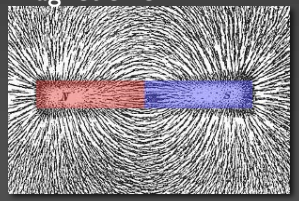


FIGURE 4-20 Over the years, explanations for the nature of light went back and forth between wave models and particle models. As we saw in the Advancing the Model box on pages 112–113, today we talk about the wave-particle duality of light; it propagates through space as a wave but interacts with matter as a stream of particles.

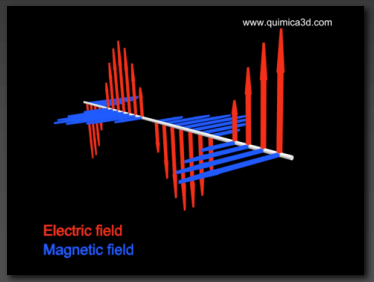
Light as an electro-magnetic wave

Electric field

Magnetic field



A changing electric field
induces
a changing magnetic field,
and vice versa



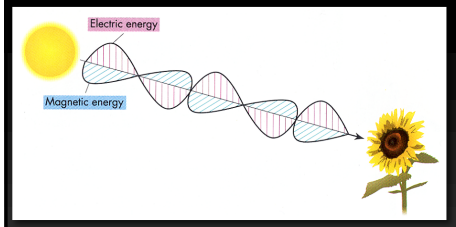
Properties of light

(and electro-magnetic radiation in general)

Properties of light

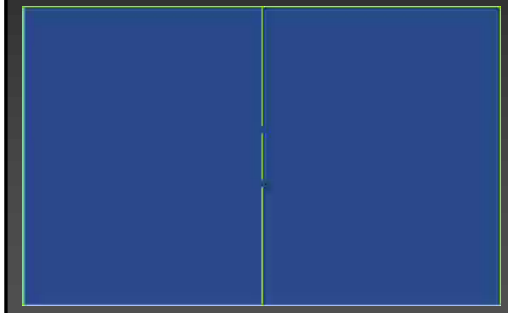
(and electro-magnetic radiation in general)

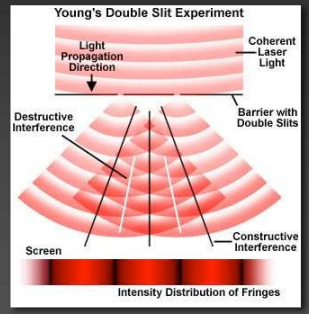
- Light behaves like a ***wave*** (like sound)



Light as a wave

Light propagates through vacuum.





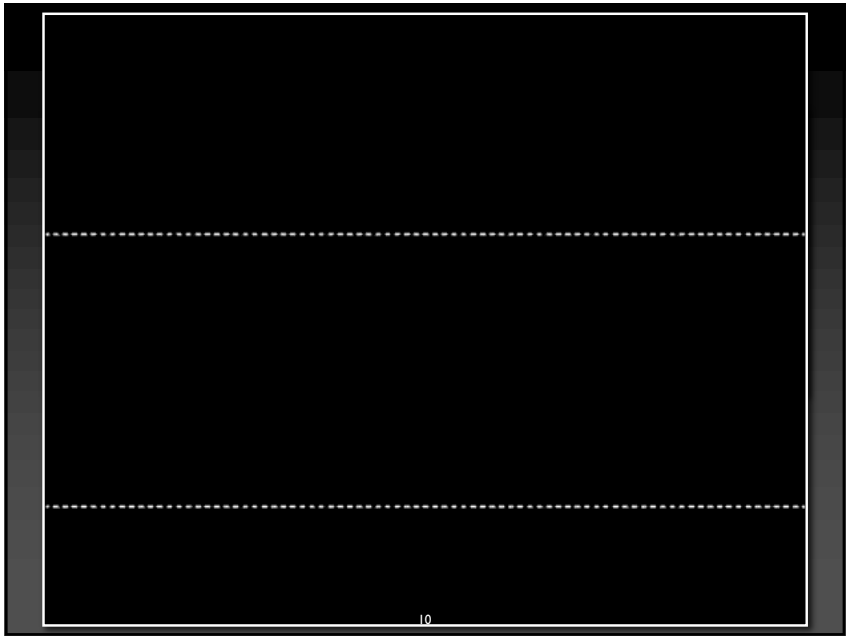
Waves can interfere, so can light.

Light as a wave

A few simple relevant formulas:

$$\text{Frequency} = \frac{\text{speed}}{\text{wavelength}} \qquad \nu = \frac{c}{\lambda}$$

$$\text{Energy} = \text{constant x frequency} \qquad E = h \cdot \nu = h \cdot c / \lambda$$



Which of the waves has higher frequency?

The top one 0%

The bottom one 0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at pollev.com/app

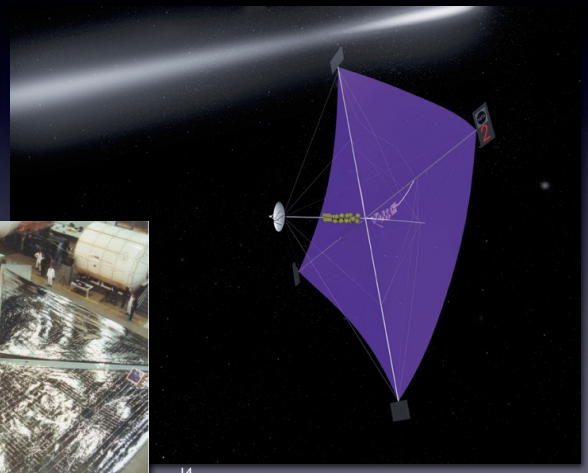
Which of the waves carries more energy? 0

The top one 0%

The bottom one 0%

Start the presentation to see live content. For screen share software, share the entire screen. Get help at pollev.com/app

‘sailing’ with radiation pressure



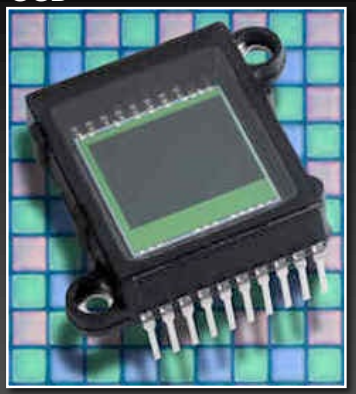
Properties of light

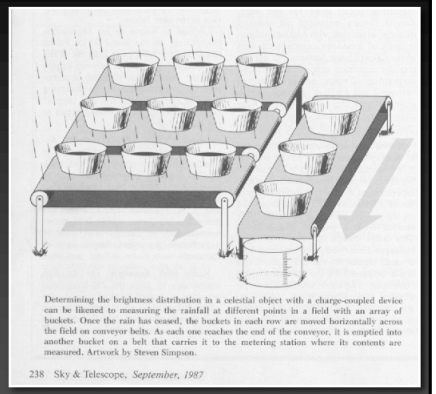
(and electro-magnetic radiation in general)

- Light behaves like a ***wave*** (like sound)
- Light behaves like a ***particle***: photons

Light as a particle

CCD





Determining the brightness distribution in a celestial object with a charge-coupled device can be likened to measuring the rainfall at different points in a field with an array of buckets. Once the rain has ceased, the buckets in each row are moved horizontally across the field on conveyor belts. As each one reaches the end of the conveyor, it is emptied into another bucket on a belt that carries it to the metering station where its contents are measured. Artwork by Steven Simpson.

238 Sky & Telescope, *September, 1987*

A CCD (Charge-Coupled Device) counts photons, part of a digital camera!

Recall : $E = h\nu$

Properties of light

(and electro-magnetic radiation in general)

- Light behaves like a ***wave*** (like sound)

- Light behaves like a ***particle***: photons
- Light transports energy; each photon is an energy 'package'.
- Photons with shorter wavelengths carry more energy.

Properties of light

(and electro-magnetic radiation in general)

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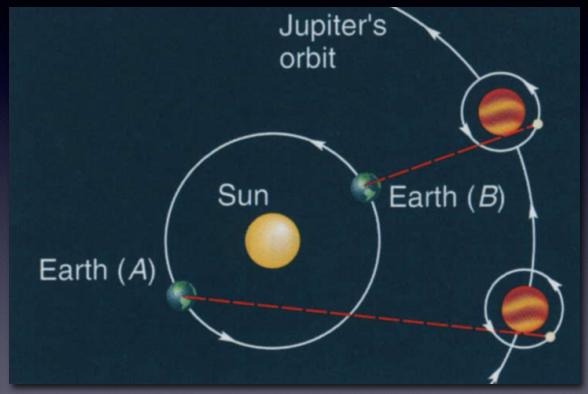
- Light behaves like a ***particle***: photons
- Light transports energy; each photon is an energy 'package'.
- Photons with shorter wavelengths carry more energy.
- Light can propagate in vacuum
- Light moves at the maximum speed (usually indicated by *c*)
  In vacuum: 299.792,458 km/s (roughly 1.08 billion km/hr)
  In other media (air or glass) this speed is slightly lower.

How to measure the speed of light?

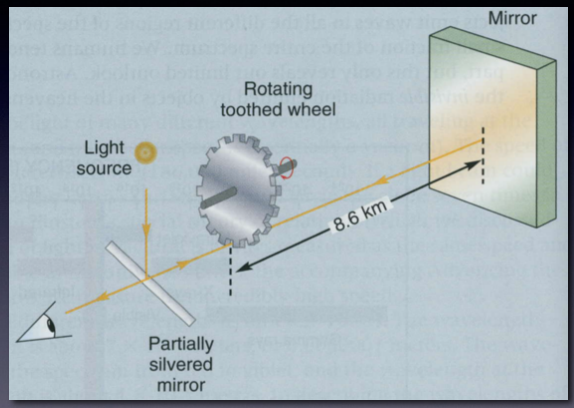
Ole Roemer (1675) : orbital period of Io (1.76 days)



Result : 214.000 km/s (wrong, but almost correct)

How to measure the speed of light?

Armand Fizeau (1849) : double mirror with gear wheel

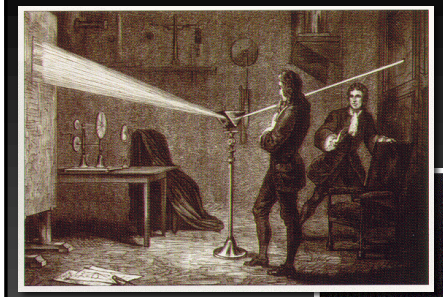


Result : 315.000 km/s (correct to 5%)

The rainbow

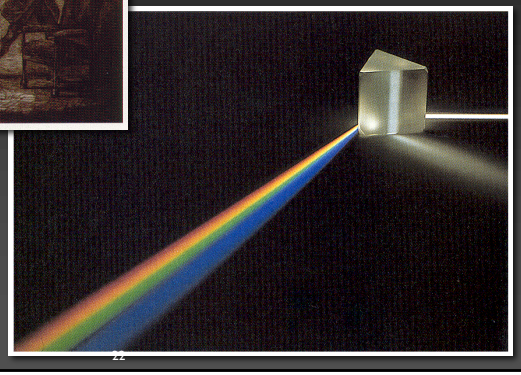
White light consists of a rainbow of colours
A ‘colour’ is light with a specific wavelength

The spectrum



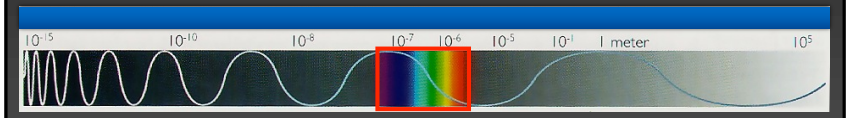
Newton (1666):

“Light consists of small, fast-moving particles”



the electro-magnetic spectrum

Visible light is only a small part of the total electro-magnetic spectrum.



Typical wavelength of 'visible' electro-magnetic radiation:

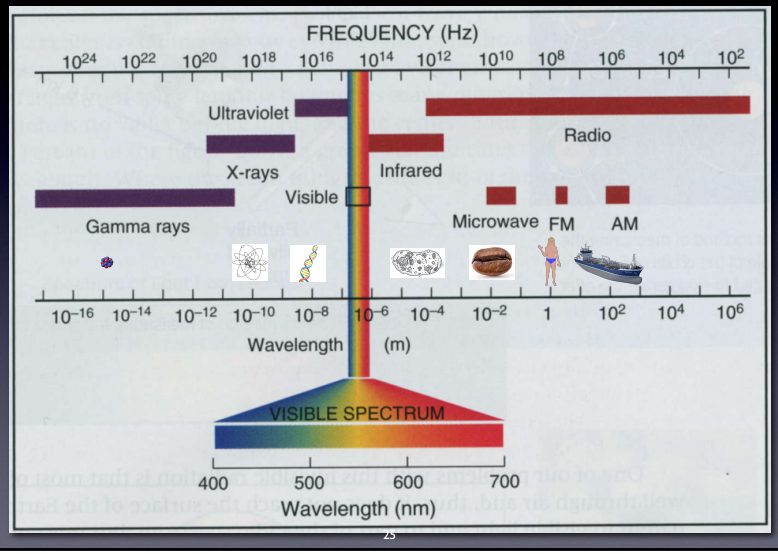
500 nano-meter = 0.0005 millimeter ('green' light)

What other radiation do you know of? Hints: Think of why you use sunscreens; what is used to study broken bones; what to warm a cup of milk; how you can listen to music...

Nobody has responded yet.

Hang tight! Responses are coming in.

The Electro-Magnetic spectrum



Ultra-violet

(±10 – 390 nanometer)

more energetic than visible light

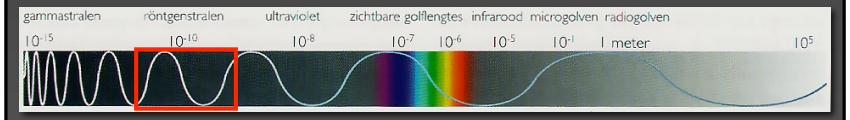
It's usually stopped by the ozone layer

Causes tanning, sun burn, skin cancer

X-rays

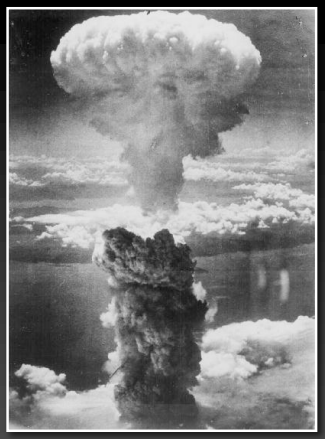
(±0.03 – 3 nanometer)

Penetrates deep into materials.
medical applications
screening luggage

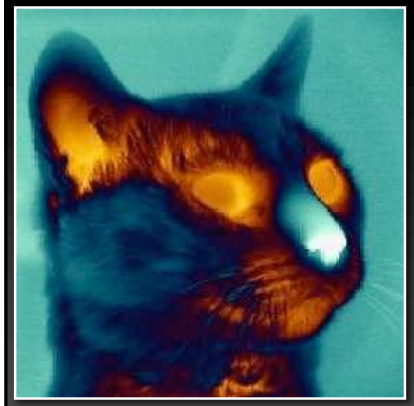


Gamma radiation

(shorter than ±0.03 nanometer)



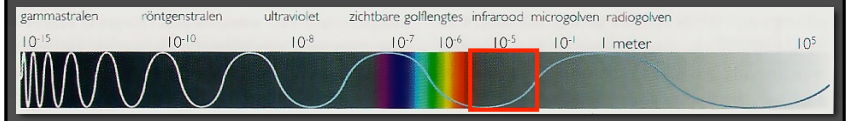
Most energetic radiation
Produced in radioactive decay
Very harmful to life



Infrared

(±720 nanometer –
300 micrometer)

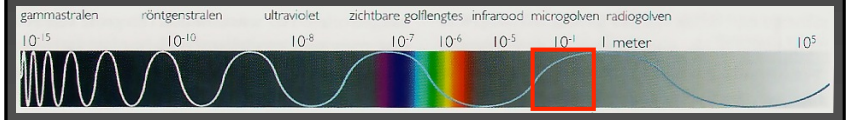
Less energetic than visible light
"heat radiation"
remote controls, security



Microwaves

(±300 micrometer –
1 centimeter)

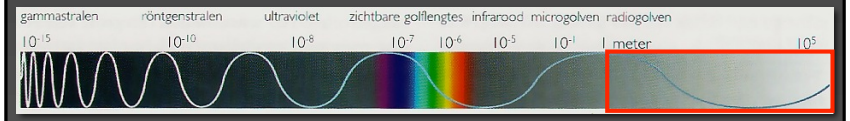
(sub-) millimeter radiation
micro-wave, radar



Radiowaves

(±1 centimeter - kilometers)

Electro-magnetic radiation with the longest wavelengths; radio, WiFi, navigation, radar etc

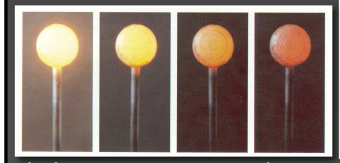


Glowing objects

Hot objects radiate

from glowing red to white hot

metal, lava, stars, etc.



higher temperature lower

Glowing objects

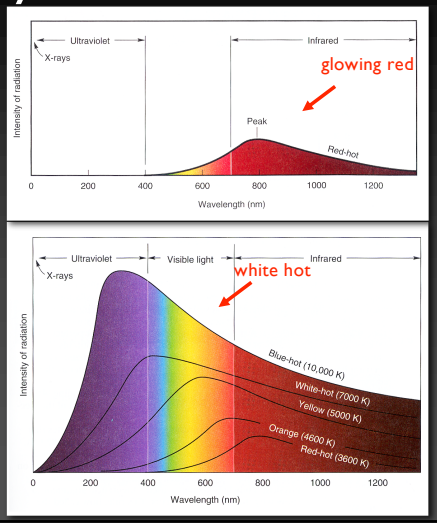
Hot objects radiate, from glowing red to white hot metal, lava, stars, etc.

La Palma, Cumbre Vieja volcano, 1 Nov 2021

Planck curve: blackbody radiation

From colder to hotter (increasing Temp):

- Peak of the spectrum shifts to the blue (shorter wavelengths)
  → Wien's law
- Intensity of the radiation increases at all wavelengths
  → Stefan-Boltzmann's law



Wien's law

$$\text{wavelength of the peak (m)} = \frac{0.003}{\text{Temperature (K)}}$$

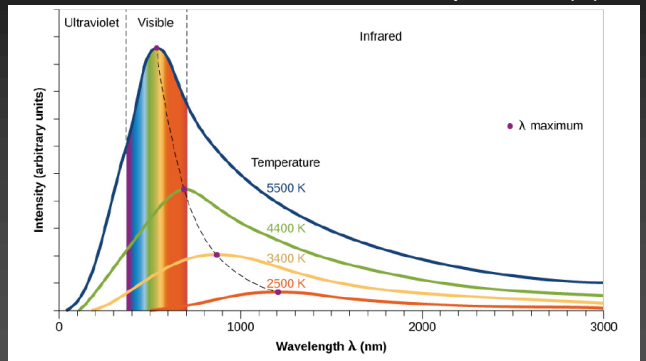
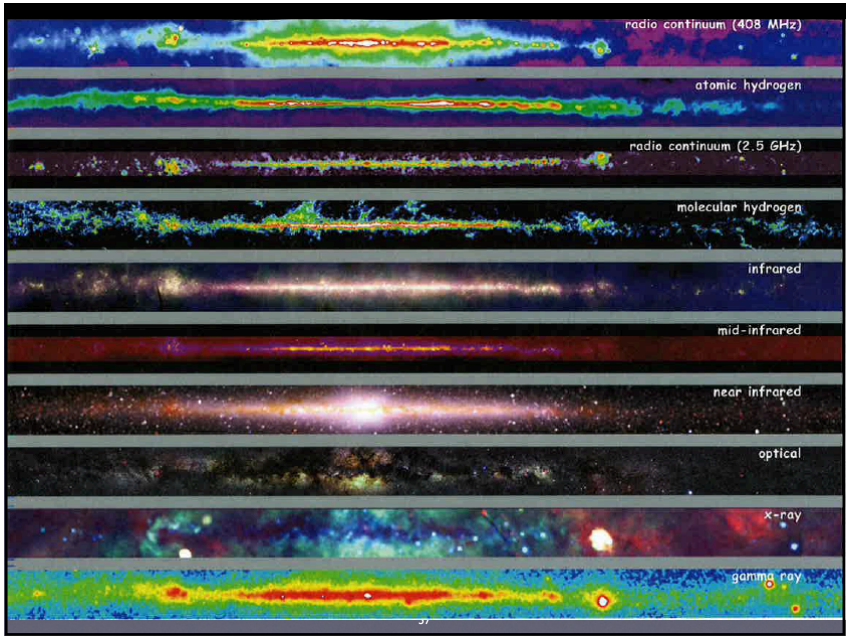


Figure 5.8 Radiation Laws Illustrated. This graph shows in arbitrary units how many photons are given off at each wavelength for objects at four different temperatures. The wavelengths corresponding to visible light are shown by the colored bands. Note that at hotter temperatures, more energy (in the form of photons) is emitted at all wavelengths. The higher the temperature, the shorter the wavelength at which the peak amount of energy is radiated (this is known as Wien's law).

Types of Electromagnetic Radiation

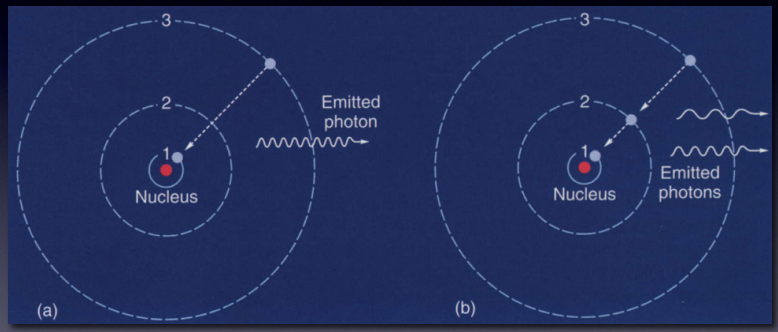
Type of Radiation	Wavelength Range (nm)	Radiated by Objects at This Temperature	Typical Sources
Gamma rays	Less than 0.01	More than 10^8 K	Produced in nuclear reactions; require very high-energy processes
X-rays	0.01–20	10^6–10^8 K	Gas in clusters of galaxies, supernova remnants, solar corona
Ultraviolet	20–400	10^4–10^6 K	Supernova remnants, very hot stars
Visible	400–700	10^3–10^4 K	Stars
Infrared	10^3–10^6	10–10^3 K	Cool clouds of dust and gas, planets, moons
Microwave	10^6–10^9	Less than 10 K	Active galaxies, pulsars, cosmic background radiation
Radio	More than 10^9	Less than 10 K	Supernova remnants, pulsars, cold gas

Table 5.1



The structure of atoms

discrete ‘orbits’ or energy levels of electrons in an atom

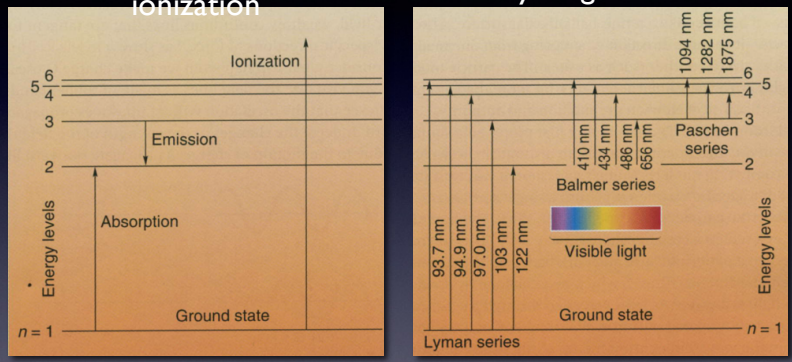


described by quantum-mechanics

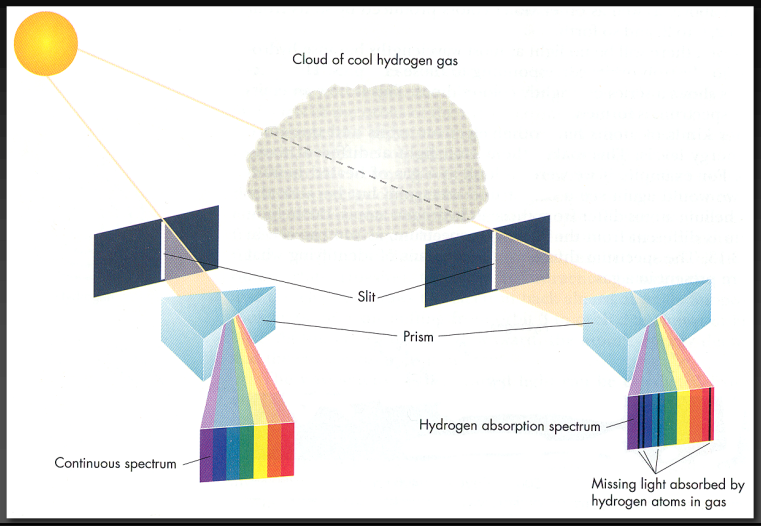
discrete energy levels with regularity

emission, absorption, ionization

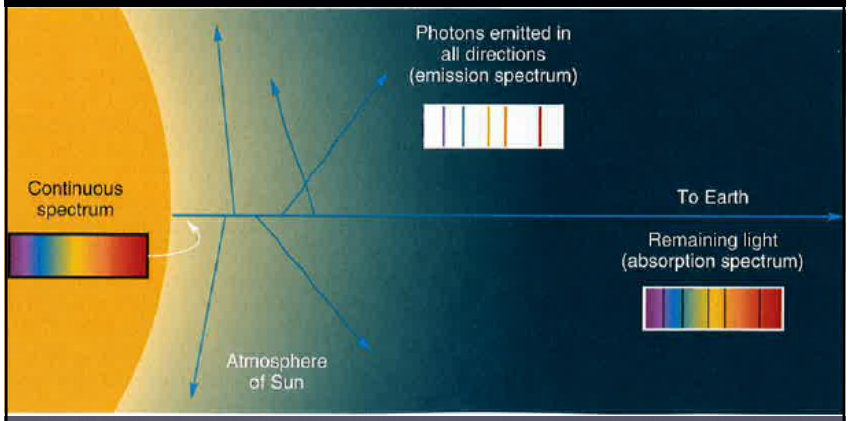
Hydrogen-atom



Absorption

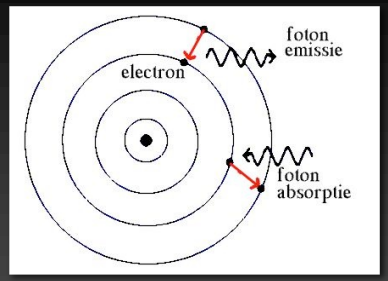


Light from the Sun

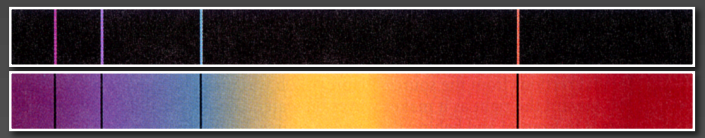


We can measure which atoms are present in the atmosphere of a star!

Emission & Absorption

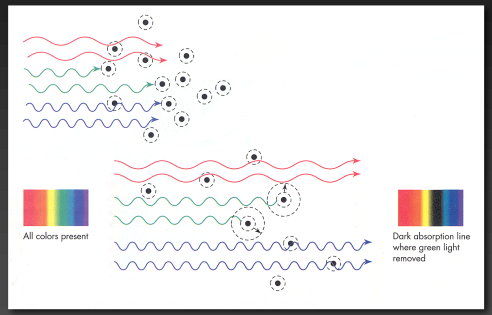


emission lines



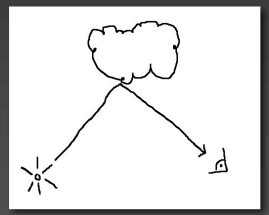
absorption lines

Absorption & Reflection



Transmission

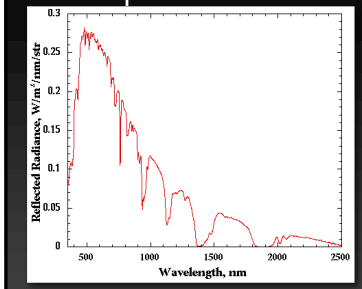
cloud

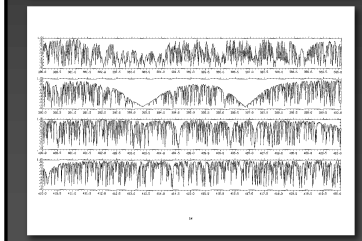


Reflection or scattering

Spectra of astronomical objects

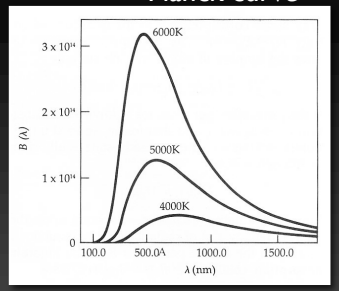
Solar spectrum

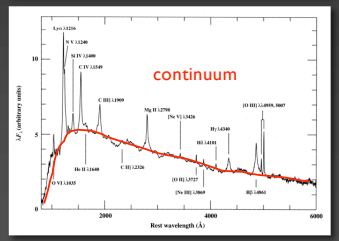




absorption lines

Planck curve

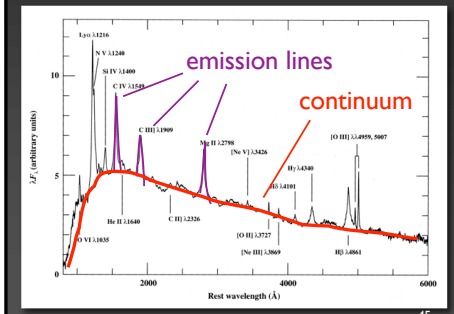


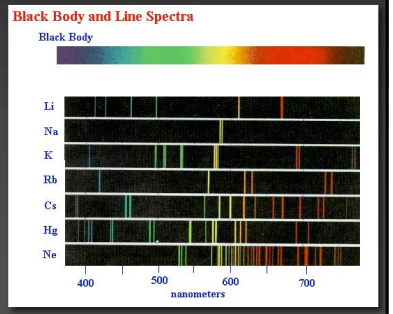


emission lines

Information from the spectrum

- The continuum informs us about:
  - ➢ the temperature of an object (Wien's law)
- Emission & Absorption lines inform us about:
  - ➢ which elements an object is made of
  - ➢ the density & temperature of these elements





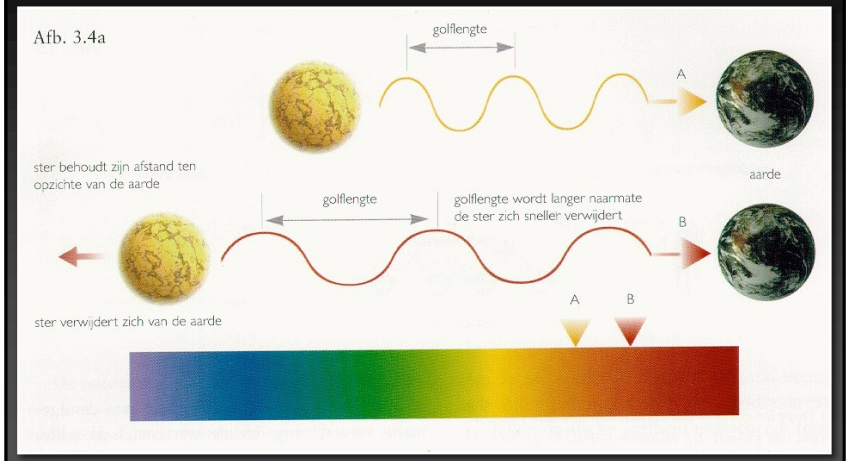
Each element has a 'finger print'

Doppler effect

lower pitched sound

higher pitched sound

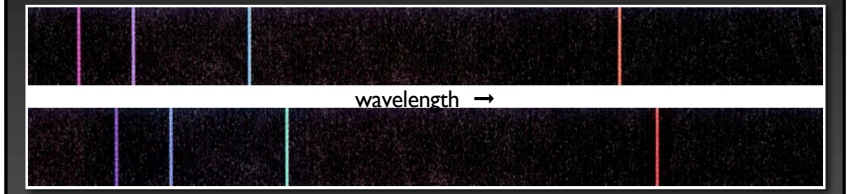
Doppler effect



Doppler effect

We measure the Doppler shift, and thus velocities, using Emission and Absorption lines

Object does not move



Object moves away from us : red shift

Object moves towards us : blue shift

Is it moving towards or away from us?

Away 0%

Towards 0%

It is at rest 0%

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Doppler effect

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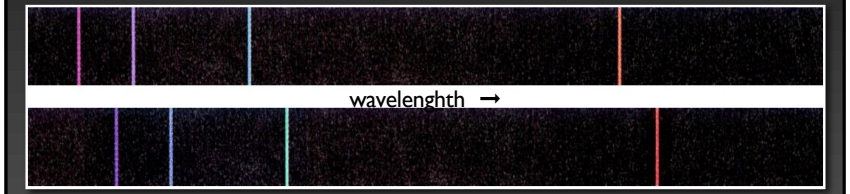
Object does not move

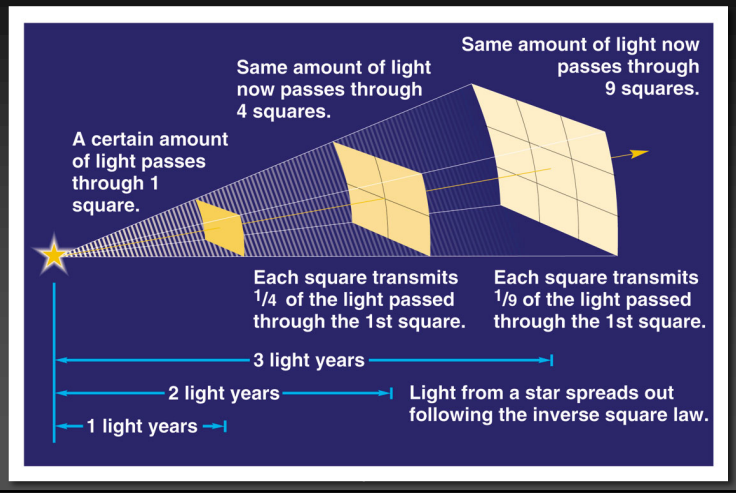


Object moves away from us : red shift

Object moves towards us : blue shift

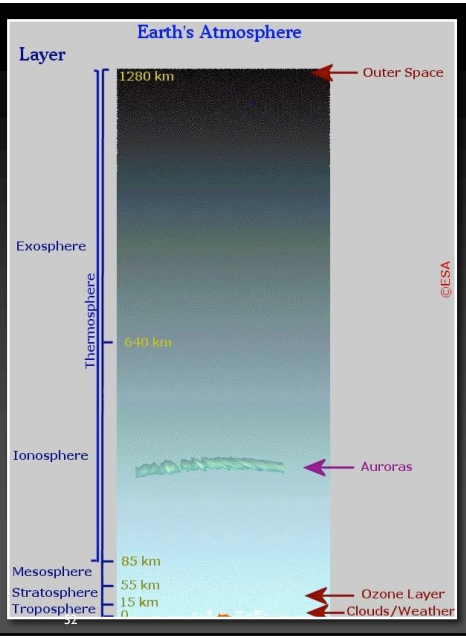
The amount of the shift is proportional to the velocity of the object with respect to us

The "$\frac{I}{R^2}$ - law"



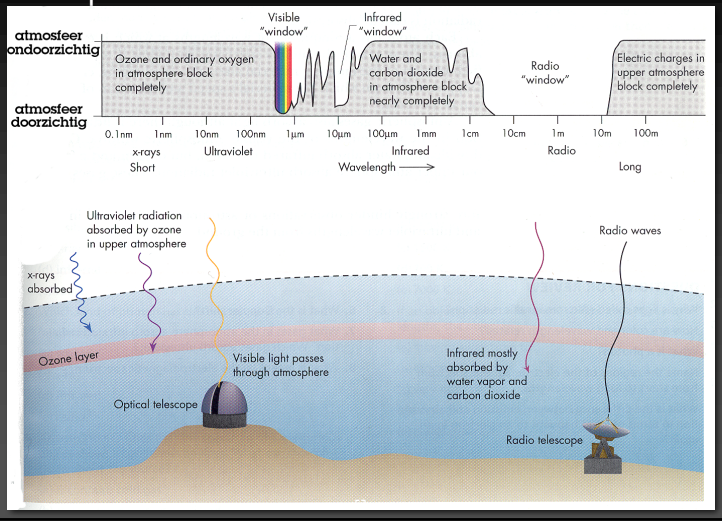
The Earth atmosphere

protects us against harmful radiation from the Universe

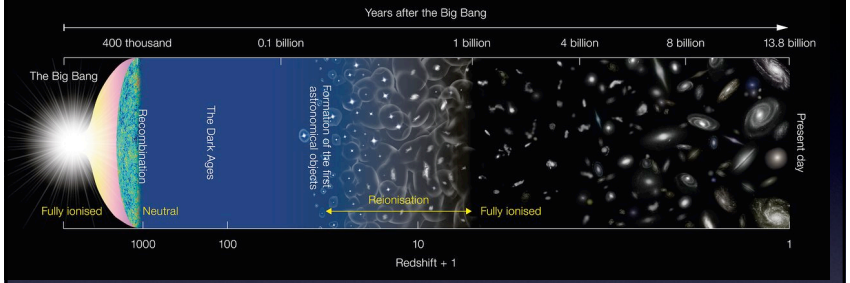


Atmospheric ‘windows’

The ‘optical’ window



Teaser and summary



- We observe objects as they were when their light was emitted (constancy of the speed of light) → we can learn about the past by studying even more distant objects
- From the wavelength at which the maximum intensity is radiated, we can infer the T of a star
- From the absorption/emission lines we learn about the chemical composition and the velocity with respect to us (along the line-of-sight)

The frequency at which a star emits most of its radiation depends on

Distance from us 0%

Intensity 0%

Temperature 0%

Velocity with respect to us 0%

An electron in an atom in a star changes to a higher energy level, will this result in?

absorption line 0%

emission line 0%

continuum 0%

Next lecture:

Telescopes

windows to the universe

Koupelis - chapter 5
OpenStax - chapter 6