LIGHT

Question

Until very recently, the study of ALL astronomical objects, outside of the Solar System, has been with telescopes observing **light**.

What kind of information can we get from light?

Light

Light has wave-like characteristics.

The motion of a light source affects wavelengths.

Emitted light depends upon the object's temperature.

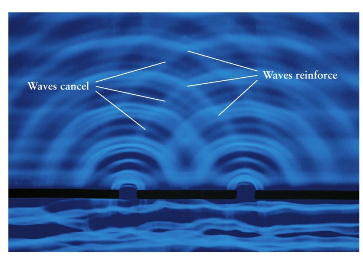
Light has particle-like characteristics.

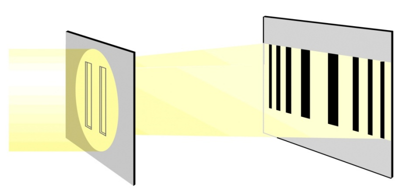
The structure of atoms explains why each chemical element emits and absorbs light at specific wavelengths.

Interference

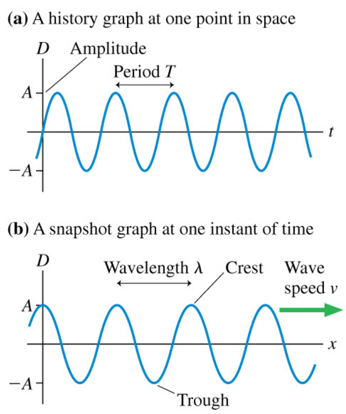
Wave-like Characteristics

Proof:
Double Slit Interference





Wave-like Characteristics



Wavelength: Distance between successive crests (λ).

$1 \text{ nm} = 10^{-9} \text{ m}$

Frequency: Number of crests that pass a specific point in one second (ν *or* f).

Speed: Frequency times Wavelength (c)

$c = \lambda \nu = 3 \times 10^5 \text{ km/s}$

$= 3 \times 10^8 \text{ m/s}$

Example

WREK Radio

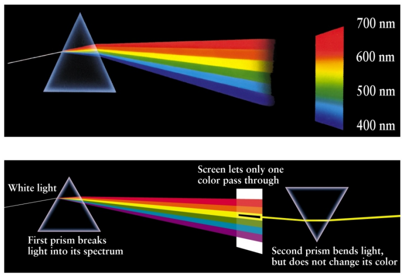
$\nu = 91.1 \text{ MHz} = 91.1 \times 10^6 \text{ /s}$

$c = \nu \lambda$ so $\lambda = c / \nu$

$= (3 \times 10^8 \text{ m/s}) / (91.1 \times 10^6 \text{ /s}) = 3.3 \text{ m}$

(Not visible to the human eye)

Visible Light



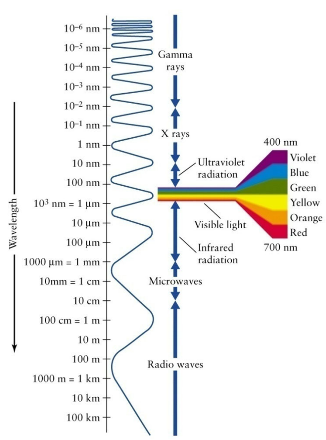
Universe by Freedman, Geller, and Kaufmann

Visible or Optical Light

700 nm (Red) to 400 nm (Violet)

White light is a combination of these colors. Newton's experiment proved that prisms do not add color.

Electromagnetic Spectrum

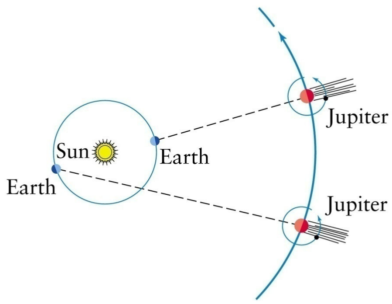


Universe by Freedman, Geller, and Kaufmann

Wavelength Ranges

Gamma	0.01 nm
X-rays	0.01 to 20 nm
Ultraviolet	20 to 400 nm
Visible	400 to 700 nm
Infrared	700 nm to mm
Microwave	mm to cm
Radio wave	cm to km

Measuring the Speed of Light



Universe by Freedman, Geller, and Kaufmann

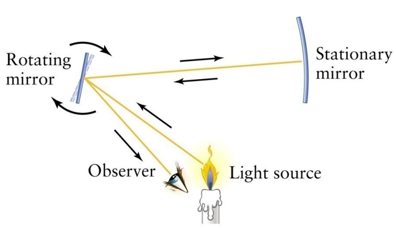
Olaus Roemer (1675) timed when moons disappeared into Jupiter's shadow.

Eclipses were retarded when Earth was far away.

Showed light did not travel infinitely fast.

He did not know the Earth-Sun distance, so he could not compute the speed of light.

Measuring the Speed of Light



Universe by Freedman, Geller, and Kaufmann

Jean Foucault (1850) used a very rapidly rotating mirror.

One must measure the deflection angle and know the speed of the rotating mirror.

Accuracy was better than 1%.

Modern Value
c = 299,792.458 km/s

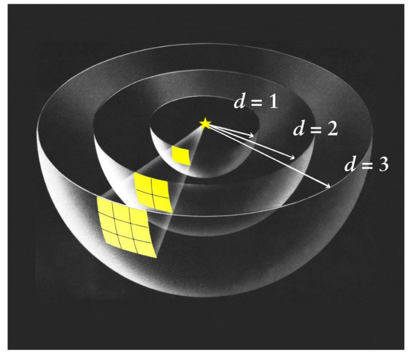
Propagation of Light

Apparent Brightness

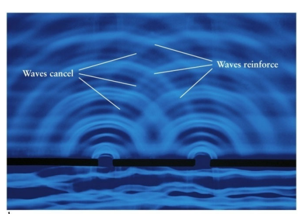
Flux = Luminosity / $4 \pi d^2$

Inverse Square Law

$$\frac{Flux_1}{Flux_2} = \frac{4 \pi d_2^2}{4 \pi d_1^2} = \frac{d_2^2}{d_1^2}$$



Light's Medium



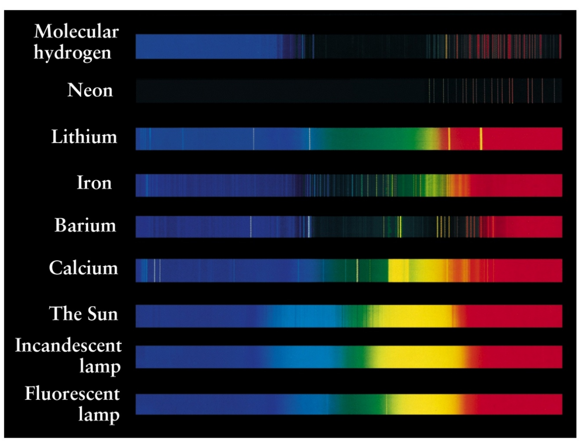
Universe by Freedman, Geller, and Kaufmann

For a water wave, the wave is in the water.
So if Light is a wave, what is waving?
What is Light moving through?
Scientists once believed there existed The Ether!

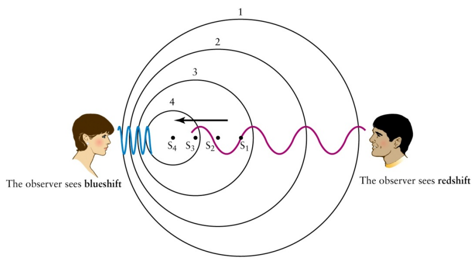
Light

Light has wave-like characteristics.
The motion of a light source affects wavelengths.

Spectra of Different Elements



Doppler Shift



Universe by Freedman, Geller, and Kaufmann

If a light source is approaching or receding from the observer, the light waves will be, respectively, crowded closer together or spread out. The Doppler effect is only produced by **radial velocities**.

$$(\lambda_{obs} - \lambda_o)/ \lambda_o = \Delta \lambda / \lambda_o = v / c$$

$$v = c \, \Delta\lambda / \lambda_o$$

where λ_{obs} is the observed wavelength and λ_o is the rest wavelength.

Doppler Shift Example #1

The revolution of the Earth around the Sun produces a Doppler Shift. Assume one is observing a star while we are moving directly toward it.

The Earth's v = –30 km/s. Let's use λ_{rest} = 600 nm (yellow light). Calculate $\Delta\lambda$ and the observed λ.

$$\boldsymbol{\Delta \lambda / \lambda = v / c}$$

$$\Delta\lambda = (600 \text{ nm}) (-30 \text{ km/s}) / (3 \times 10^5 \text{ km/s})$$

$$\Delta\lambda = -0.06 \text{ nm} = \lambda_{observed} - \lambda_{rest}$$

$$\lambda_{observed} = -0.06 \text{ nm} + \lambda_{rest} = 599.94 \text{ nm}$$

Doppler Shift Example #2

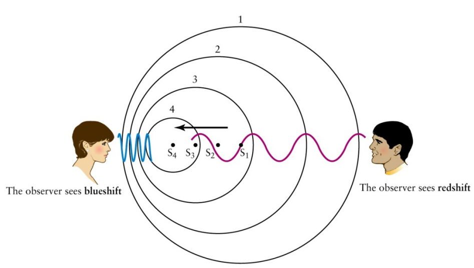
λ = **500 nm** = 500 x 10^{-9} m λ_{obs} = **510 nm** = 510 x 10^{-9} m

v = c $\Delta\lambda$ / λ = (3 x 10^8 m/s) [(510 x 10^{-9}) – (500 x 10^{-9})] / (500 x 10^{-9} m)

= (3 x 10^8 m/s) [(10 x 10^{-9} m)] / (500 x 10^{-9} m)

= 6 x 10^6 m/s = **6000 km/s**

Doppler Shift



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LIGHT

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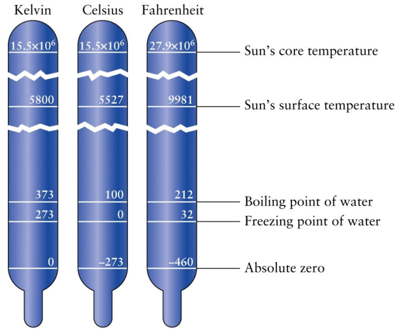
Emitted light depends upon the object's temperature.

Temperature Scales



Universe by Freedman, Geller, and Kaufmann

Kelvin Temperature Scale

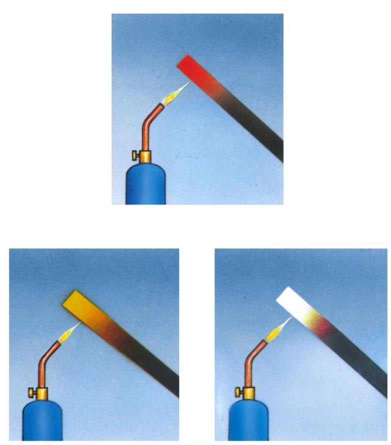
- Coldest theoretically possible Temperature = 0 K
- No negative temperatures
- No degree symbol – just K

Temperature Effects

1. Temperature is a measure of the average **motion or speed** of the gas molecules.

2. Electromagnetic radiation is emitted when electric charges **accelerate** – that is, whenever they either **change the speed or the direction** of their motion. Each collision results in the emission of radiation.

➡ **Temperature** determines the type of electromagnetic radiation emitted!



Universe by Freedman, Geller, and Kaufmann

Color Indicates Temperature

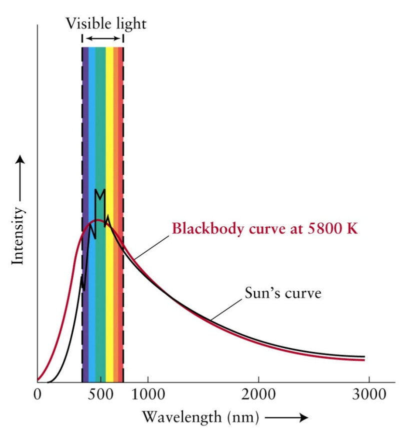
Blackbodies

A **blackbody** is an idealized object that absorbs all the light that hits it.

It is in **thermal equilibrium.**

(It absorbs the entire energy incident upon it and emits energy at the same rate that it is being absorbed).

Are stars blackbodies?



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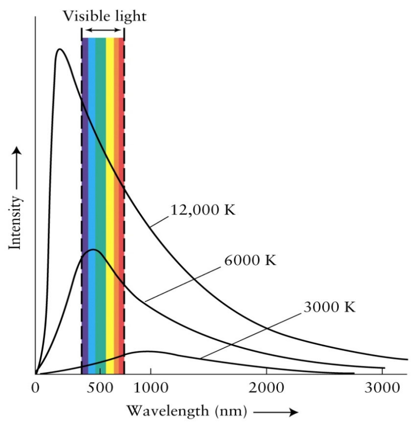
Blackbody Radiation



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A blackbody with a temperature higher than absolute zero emits some *energy in all wavelengths*.

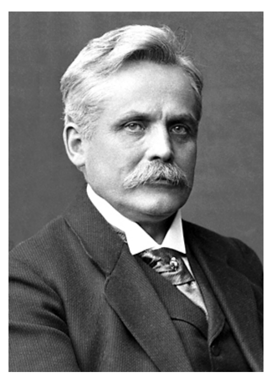
A blackbody at a **higher temperature** emits *more energy at all wavelengths* than does a cooler one.

The **higher the temperature**, the *shorter the wavelength* at which the maximum energy is emitted.

Wien's Displacement Law

The wavelength of maximum energy is given by **Wien's Law**

$$\lambda_{max} T = 0.0029 \ \ (\text{m K})$$



Wilhelm Wien
Nobel Laureat 1912

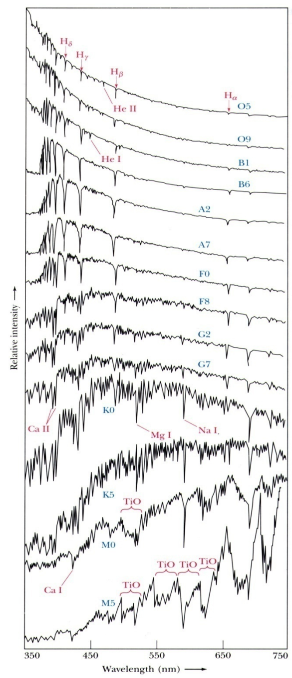
Examples

Sun λ_{max} = 500 nm = 5.0 x 10^{-7} m

T = 0.0029 m K / 5.0 x 10^{-7} m = **5,800 K**

Rigel (Orion) λ_{max} = 240 nm = 2.4 x 10^{-7} m

T = 0.0029 m K / 2.4 x 10^{-7} m = **12,000 K**



Stefan-Boltzmann Law

Total energy is provided by the **Stefan-Boltzmann Law:**

$$E = \sigma A T^4$$

For a sphere

$$L = E = 4 \pi R^2 \sigma T^4$$

(σ is equal to 5.670×10^{-8} J/m^2/K^4)

Stefan-Boltzmann Law

$L = E = 4 \pi R^2 \sigma T^4$

Example

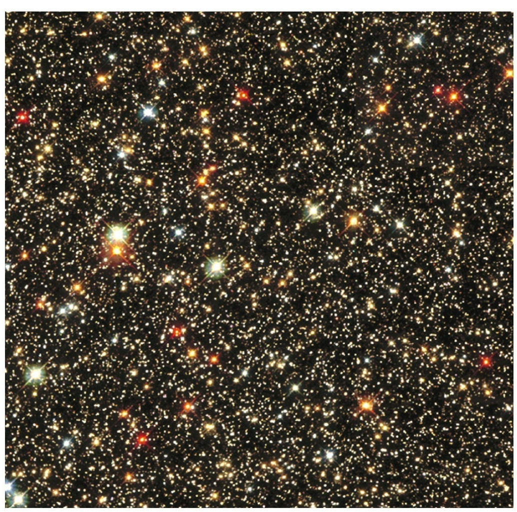
$L_{Rigel} / L_{Sun} = (R_{Rigel} / R_{Sun})^2 (T_{Rigel} / T_{Sun})^4$

$90{,}000 = (R_{Rigel} / R_{Sun})^2 (12{,}000 / 5{,}800)^4$

$R_{Rigel} / R_{Sun} = \text{sqrt}(90{,}000)\ (5{,}800 / 12{,}000)^2$

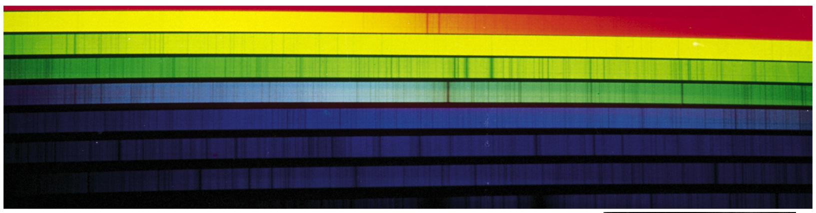
$R_{Rigel} / R_{Sun} = \mathbf{75}$

LIGHT



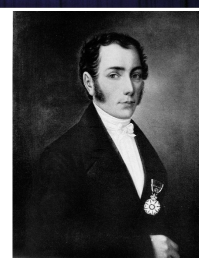
Solar Spectrum

What do we learn if we disperse sun light?



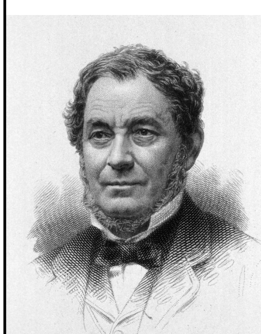
Fraunhofer (1814)
Highly magnified spectrum

➡ He counted ~600 dark lines (Fraunhofer lines).



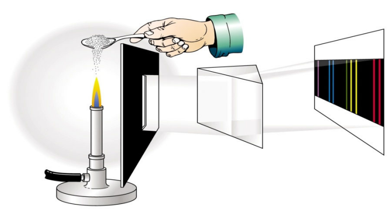
Joseph von Fraunhofer

Spectral Analysis



Robert Bunsen

Bunsen (1857) Invented the gas burner that has no color of its own for flame tests.



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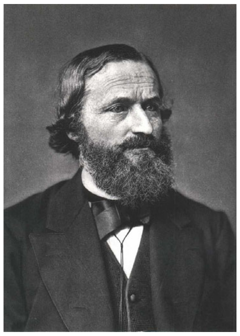
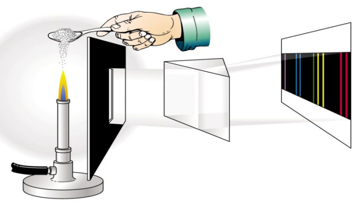
Spectral Analysis



Gustav Kirchhoff

Bunsen (1857) Invented the gas burner that has no color of its own for flame tests.



Universe by Freedman, Geller, and Kaufmann

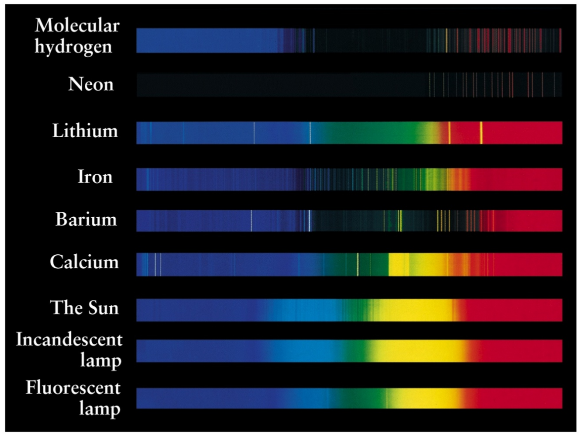
Kirchhoff (1860) Suggested that the flame tests should be studied through a prism. They created a spectrograph and developed “Spectral Analysis”. They cataloged lines, found new lines, and recognized new elements of cesium, rubidium, and helium.

Periodic Table of the Elements

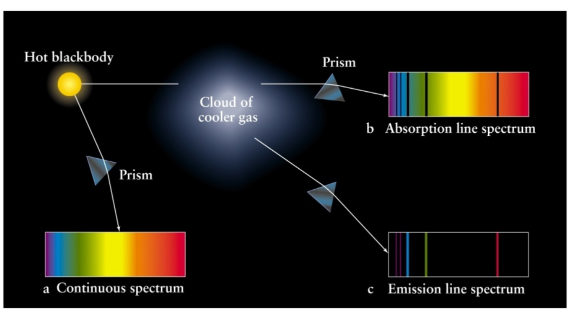
1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Kryton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantaium	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110	111	112	113	114	115	116	117	118
				57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium
				89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium

Universe by Freedman, Geller, and Kaufmann

Spectra of Different Elements



Types of Spectra



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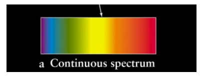
Depends upon Point-of-View

- Continuous Spectrum
- Absorption-Line Spectrum
- Emission-line Spectrum

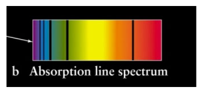
Kirchhoff's Laws

(of spectroscopy)

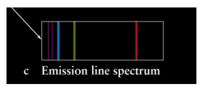
1. A **hot, opaque body**, such as a hot dense gas, produces a **continuous** spectrum – a complete rainbow.



2. A **cool, transparent gas** in front of a source of continuous spectrum produces an **absorption line** spectrum – a series of dark spectral lines among a continuous spectrum.



3. A **hot, transparent gas** in front of dark space produces an **emission line** spectrum – a series of bright spectral lines against a dark background.



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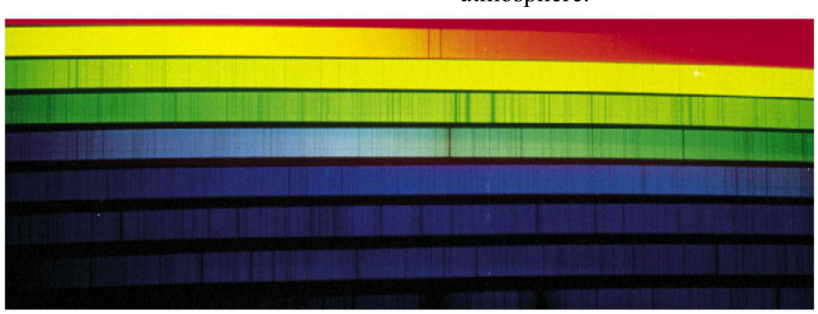
Sun's Spectrum

You see that the Sun's spectrum is an absorption spectrum. So, where is the "cool gas"?

1) In the Sun.
2) Floating between the Sun and the Earth.
3) The "cool gas" is the Earth's atmosphere.



LIGHT

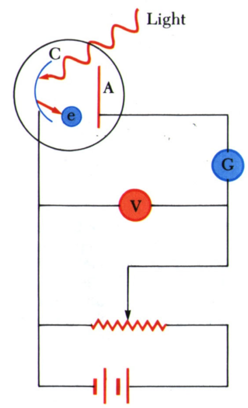
Light

Light has wave-like characteristics.
The motion of a light source affects wavelengths.
Emitted light depends upon the object’s temperature.
Light has particle-like characteristics.

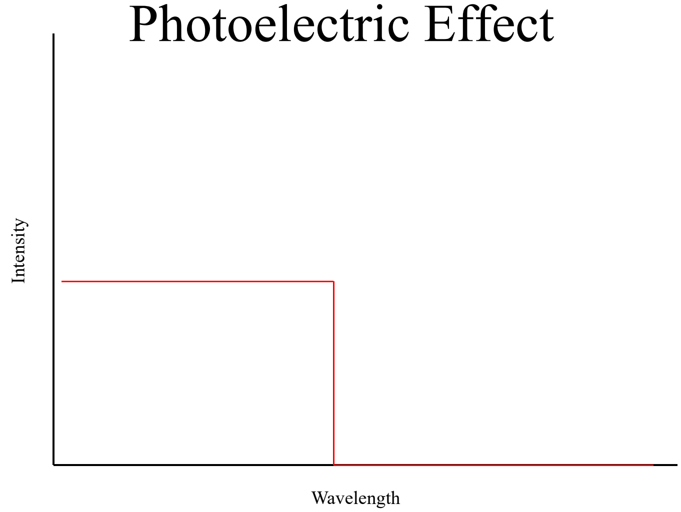
An Observation

Illuminating a metal surface, in an electric potential, with light causes the emission of electrons.

But this only occurs at specific wavelengths.



Photoelectric Effect



Photoelectric Effect

Features that could not be explained with Classical Physics:

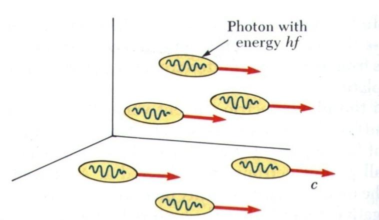
1. No electrons are emitted if the incident light wavelength was longer than some cutoff wavelength, λ_c.

2. If the light wavelength is shorter than the cutoff wavelength, a photo-electric effect is observed and the number of photo-electrons emitted is proportional to the light intensity.

3. The maximum kinetic energy of the photo-electrons increases with shorter light wavelength.

4. Electrons are emitted almost instantaneously.

Photoelectric Effect

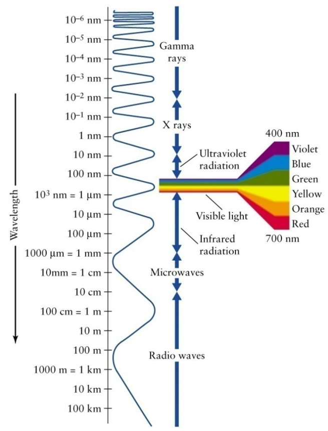


Einstein (1905) analyzed the Photoelectric Effect. He assumed that light can be considered a stream of photons. Each photon has an energy equal to:

$$E = h\nu = hc/\lambda$$

$$h = 6.625 \times 10^{-34}\ \text{J s}$$

Electromagnetic Spectrum



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Wavelength Ranges

Shortest λ, greatest energy

Gamma	0.01 nm
X-rays	0.01 to 20 nm
Ultraviolet	20 to 400 nm
Visible	400 to 700 nm
Infrared	700 nm to mm
Microwave	mm to cm
Radio wave	cm to km

Longest λ, lowest energy

Photoelectric Effect Example

1) $\lambda = 500 \text{ nm} = 500 \times 10^{-9} \text{ m}$

$$\mathbf{E = hc/\lambda} = (6.625 \times 10^{-34} \text{ Js})(3 \times 10^{8} \text{ m/s}) / (500 \times 10^{-9} \text{ m})$$

$$= 3.975 \times 10^{-19} \text{ J} \;\; (\,/\, 1.6 \times 10^{-19} \text{ J/eV}) = 2.5 \text{ eV}$$

Photoelectric Effect Examples

1) $\lambda = 500\text{ nm} = 500 \times 10^{-9}\text{ m}$

$\mathbf{E = h\,c / \lambda} = (6.625 \times 10^{-34}\text{ Js})(3 \times 10^{8}\text{ m/s}) / (500 \times 10^{-9}\text{ m})$

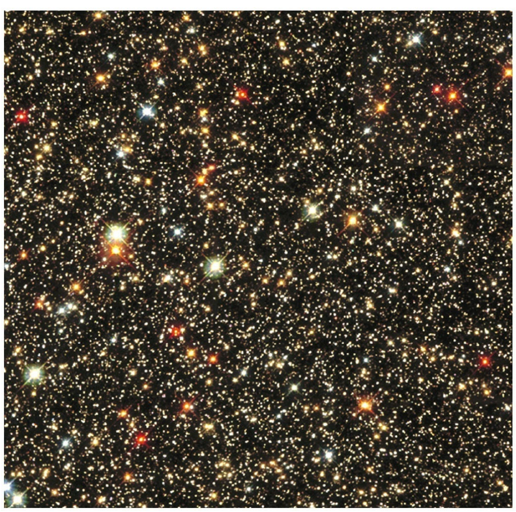
$= 3.975 \times 10^{-19}\text{ J} \;(\,/\,1.6 \times 10^{-19}\text{ J/eV}) = 2.5\text{ eV}$

2) $\lambda = 0.2\text{ nm} = 0.2 \times 10^{-9}\text{ m}$

$\mathbf{E = h\,c / \lambda} = (6.625 \times 10^{-34}\text{ Js})(3 \times 10^{8}\text{ m/s}) / (0.2 \times 10^{-9}\text{ m})$

$= 9.938 \times 10^{-19}\text{ J} \;(\,/\,1.6 \times 10^{-19}\text{ J/eV}) = 6211\text{ eV}$

LIGHT



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Emitted light depends upon the object's temperature.

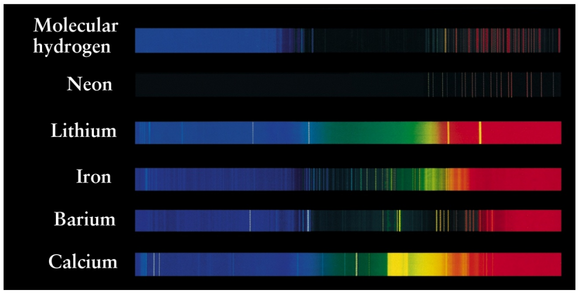
Light has particle-like characteristics.

The structure of atoms explains why each chemical element emits and absorbs light at specific wavelengths.

Atomic Structure

What do spectral lines tell us about the structure of atoms?

After all, each element has its own unique set of spectral lines.



The Electron

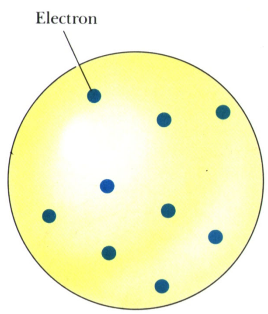


Figure 42.1 Thomson's plum-pudding model of the atom.

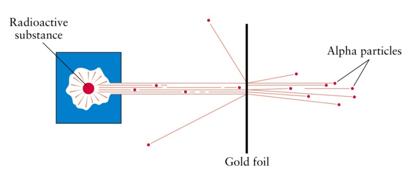
J.J. Thompson (1897)

Usually considered the discoverer of the electron.

Worked on deflections of cathode rays (electrons) in an electric field.

Suggested a model of the atom as a volume of positive charge with electrons embedded throughout.

Atomic Nucleus



Rutherford (1910)

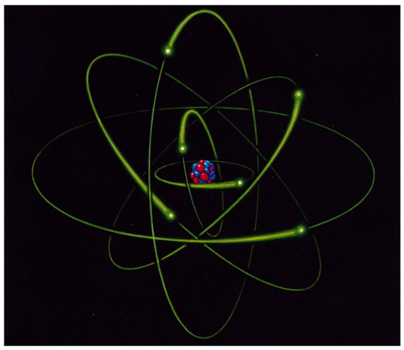
Bombarded gold foil with alpha particles (now known to be He nuclei).

Most passed through the foil without deviating.

A few reflected off straight back!

Concluded that the nucleus is small but massive.

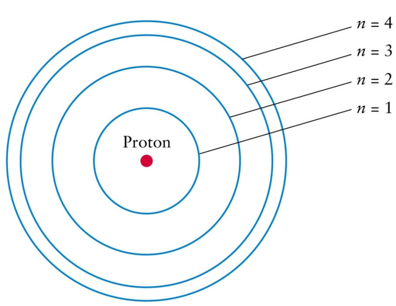
Atomic Structure



Universe by Freedman, Geller, and Kaufmann

One must use the new quantum theories to describe the structure of atoms.

Bohr Model of the Atom



Universe by Freedman, Geller, and Kaufmann

Niels Bohr (1913)

Simple but Bold, New Ideas

Assume electrons move in circular orbits about the protons – even though Classical Mechanics does Not allow it.

Assume a few, certain orbits are stable.

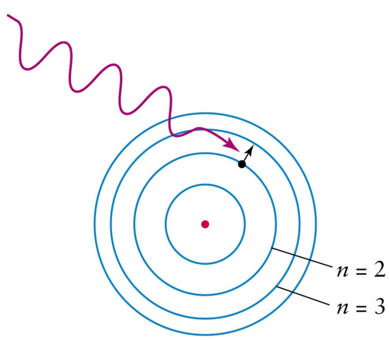
Radiation is emitted or absorbed when an electron moves from one orbit to another.

More Bold Assumptions

The electrons **emit or absorb energy** in discrete units of light energy called quanta (now photons) by "jumping" or "falling" from one orbit (or state or level) to another. Energy of a photon is equal to the energy difference between two quantum states

$$\Delta E = h f = h c / \lambda$$

Absorption



Absorption

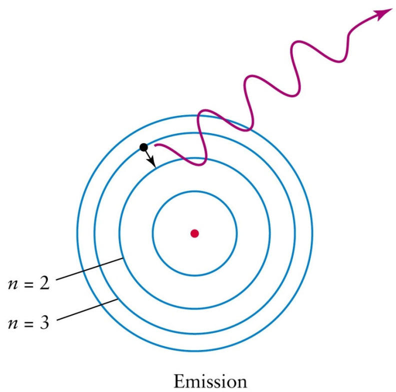
Universe by Freedman, Geller, and Kaufmann

In order for an electron to move up to a higher level, it requires energy.

This energy is provided by a photon of exactly the right wavelength (and, hence, energy) getting absorbed.

Energy must be Conserved!

Emission

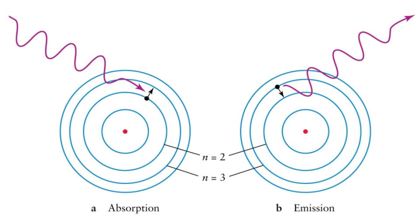


Universe by Freedman, Geller, and Kaufmann

In order for an electron to move down to a lower level, it must lose (or give up) energy.

This energy is given off as a photon that has exactly the right wavelength (energy) so that the electron can move down ("fall") exactly on a lower state.

Energy Level Transitions

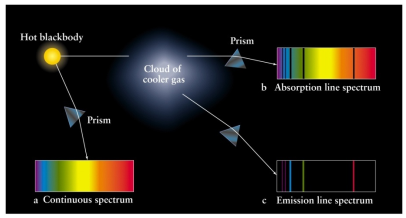


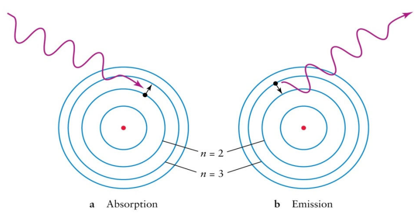
Universe by Freedman, Geller, and Kaufmann

Absorption of a photon produces an absorption-line spectrum.
(It blocks the stream of continuous radiation.)

Emission of a photon produces an emission-line spectrum.
(Can be emitted in any direction.)

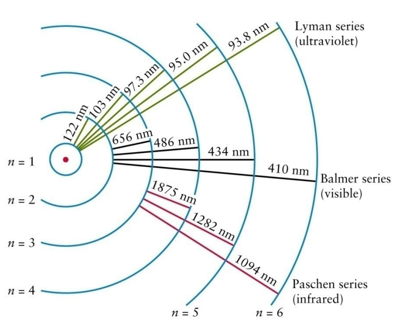
Spectral Types Explained

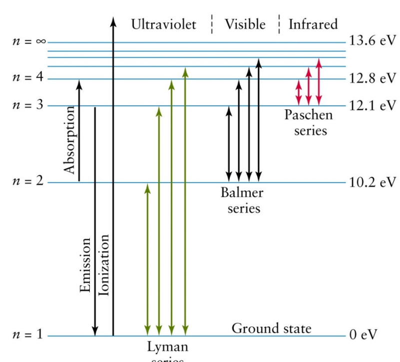




Universe by Freedman, Geller, and Kaufmann

Hydrogen Series





$E_n = 13.6\,(1 - 1/n^2)$ [in eV]

Universe by Freedman, Geller, and Kaufmann