The Electromagnetic Radiation Spectrum

How to read this chart

- This chart is organized in octaves (frequency doubling/halving) starting at 1Hz and going higher (2,4,8, etc) and lower (1/2, 1/4, etc). The octave is a natural way to represent frequency.
- Frequency increases on the vertical scale in the upward direction.
- The horizontal bars wrap around from far right to far left as the frequency increases upwards.
- There is no limit to either end of this chart, however, due to limited space, only the "known" items have been shown here. A frequency of 0Hz is the lowest possible frequency but the method of depicting octaves used here does not allow for ever reaching 0Hz, only approaching it. Also, by the definition of frequency (Cycles per second), there is no such thing as negative frequency.
- Values on the chart have been labelled with the following colours: Frequency measured in Hertz, Wavelength measured in meters, Energy measured in electronVolts.

Ultraviolet Light

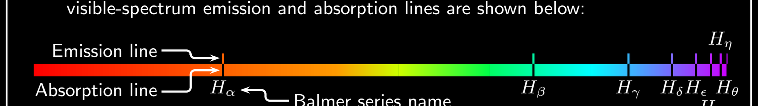
- Ultraviolet light is beyond the range of human vision.
- Physicists have divided ultraviolet light ranges into Vacuum Ultraviolet (VUV), Extreme Ultraviolet (EUV), Far Ultraviolet (FUV), Medium Ultraviolet (MUV), and Near Ultraviolet (NUV).
- UV-A, UV-B and UV-C were introduced in the 1930's by the Commission Internationale de l'Éclairage (CIE, International Commission on Illumination) for photobiological spectral bands.
- Short-term UV-A exposure causes sun-tanning which helps to protect against sunburn. Exposure to UV-B is beneficial to humans by helping the skin produce vitamin D. Excessive UV exposure causes skin damage. UV-C is harmful to humans but is used as a germicide.
- The CIE originally divided UVA and UVB at 315nm, later some photo-dermatologists divided it at 320nm.
- UVA is subdivided into UVA1 and UVA2 for DNA altering effects at 340nm.
- The sun produces a wide range of frequencies including all the ultraviolet light, however, UVB is partially filtered by the ozone layer and UVC is totally filtered out by the earth's atmosphere.
- A bumblebee can see light in the UVA range which helps them identify certain flowers.

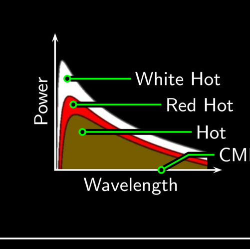
Emission and Absorption

- As EMR passes through elements, certain wavelength bands get absorbed and some new ones get emitted. This absorption and emission produces characteristic spectral lines for each element which are useful in determining the makeup of distant stars. These lines are used to prove the red-shift amount of distant stars.
- When a photon hits an atom it may be absorbed if the energy is just right. The energy level of the electron is raised – essentially holding the radiation. A new photon of specific wavelength is created when the energy is released. The jump in energy is a discrete step and many possible levels of energy exist in an atom.
- Johann Balmer created this formula defining the photon emission wavelength (λ); where m is the initial electron energy level and n is the final electron energy level:

$$\lambda = 364.56nm\left(\frac{m^2}{m^2 - n^2}\right)$$

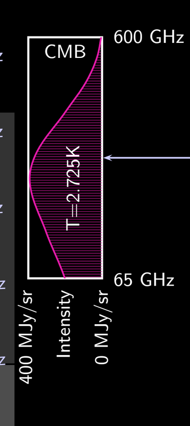
- Much of the interstellar matter is made of the simplest atom hydrogen. The hydrogen visible-spectrum emission and absorption lines are shown below:





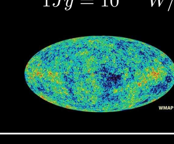
- Max Planck determined the relationship between the temperature of an object and its radiation profile; where R_λ is the radiation power, λ is the wavelength, T is the temperature:

$$R_\lambda = \frac{37418}{\lambda^5 \epsilon\left(\frac{14388}{\lambda T} - 1\right)}$$



Cosmic Microwave Background Radiation

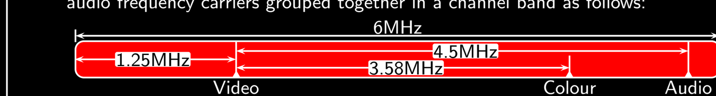
- CMB radiation is the leftover heat from the hot early universe, which last scattered about 400,000 years after the Big Bang.
- CMB permeates the entire universe at a temperature of 2.725 ± 0.001K.
- CMB was predicted in the 1940's by Ralph Alpher, George Gamow and Robert Herman.
- Arno Penzias and Robert Wilson accidentally discovered CMB while working for Bell Telephone Laboratories in 1965.
- The intensity is measured in Mega Jansky (Jy) per steradian. $1Jy = 10^{-26}W/m^2/Hz$



Close examination of slight CMB intensity variations in different parts of the sky help cosmologists study the formation of galaxies.
WMAP photo by NASA

Television

- Terrestrial broadcast TV uses the VHF and UHF ranges (30MHz - 3GHz) 05.
- Satellite television is transmitted in the C-band (4 - 8 GHz) 05 and Ku-band (12 - 18 GHz) ▲ where one of many satellites is shown. To eliminate interference, the stations are broadcast in alternating polarities, for example, Ch 1 is vertical and Ch 2 is horizontal and vice versa on neighbouring satellites.
- TV channels transmitted through cable (CATV) are shown as 05. CATV channels starting with "T-" are channels fed back to the cable TV station (like news feeds).
- Air and cable analog TV stations are broadcast with the separate video, colour, and audio frequency carriers grouped together in a channel band as follows:

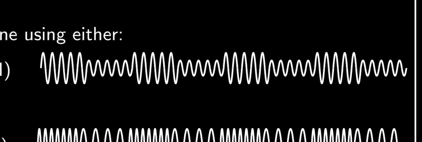


- 15.7 kHz horizontal sweep signal is a common contaminant to VLF listening.
- Digital compression methods are used for HDTV broadcasts in order to pack more channels into the same 6MHz bandwidth as analog TV.

Radio Bands

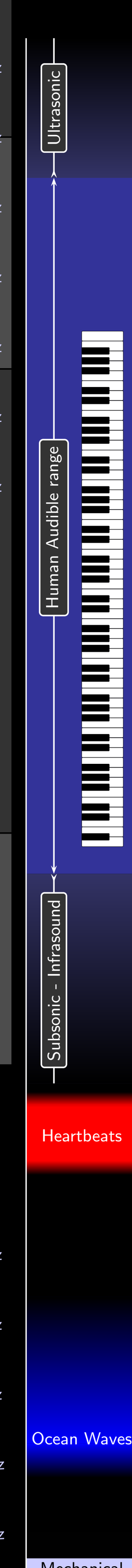
- The radio spectrum (ELF to EHF) is populated by many more items than can be shown on this chart. Only a small sampling of bands used around the world have been shown.
- Communication using EMR is done using either:
  - Amplitude Modulation (AM)

  OR
  - Frequency Modulation (FM)



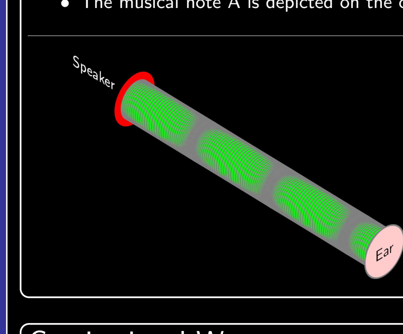
- Each country has its own rules and regulations for allotting bands in this region. Refer to the authority in your area (Ex. FCC in the USA, DOC in Canada).
- Not all references agree on the ULF band range, the HAARP range is used here.
- **RA**dio **D**etecting **A**nd **R**anging (RADAR) uses EMR in the microwave range to detect the distance and speed of objects.
- **C**itizens **B**and Radio (CB) contains 40 stations between 26.965 - 27.405MHz.
- Schumann resonance is produced in the cavity between the Earth and the ionosphere. The resonant peaks are depicted as S
- Hydrogen gas emits radio band EMR at 21cm H
- Some individual frequencies are represented as icons:

xxHz	Submarine communications		Pager
	Time / frequency standards	W	Weather stations
xxm	Ham / international meter bands		Short wave radio
GMRS	General Mobile Radio Service		Wireless Microphone
FRS	Family Radio Service	CP	Cellular Phones
SOS	Distress signal, in Morse code: · · · — — — · · ·		



Sound

- Although sound, ocean waves, and heartbeats are not electromagnetic, they are included on this chart as a frequency reference. Other properties of electromagnetic waves are different from sound waves.
- Sound waves are caused by an oscillating compression of molecules. Sound cannot travel in a vacuum such as outer space.
- The speed of sound in air at sea level is 1240kph (770mph).
- Humans can only hear sound between ≈20Hz to ≈20kHz.
- Infrasound (below 20Hz) can be sensed by internal organs and touch. Frequencies in the 0.2Hz range are often the cause of motion sickness.
- Bats can hear sound up to ≈50kHz.
- The 88 piano keys of the Equal Temperament scale are accurately located on the frequency chart.
- Over the ages people have striven to divide the continuous audio frequency spectrum into individual musical notes that have harmonious relationships. Microtonal musicians study various scales. One recent count lists 4700 different musical scales.
- The musical note A is depicted on the chart as A



This image depicts air being compressed as sound waves in a tube from a speaker and then travelling through the tube towards the ear.

Gravitational Waves

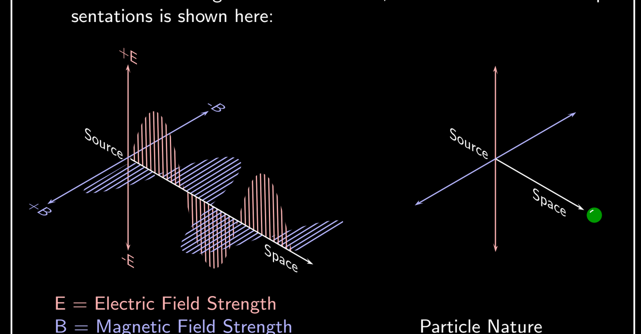
- Gravity is the mysterious force that holds large objects together and binds our planets, stars, and galaxies together. Many people have unsuccessfully theorized about the details of gravity and its relationship to other forces. There have been no links between gravity waves and electromagnetic radiation.
- Gravity is theorized to warp space and time. In fact, gravity is responsible for bending light as observed by the gravity-lens example of distant galaxies.
- "Gravitational waves" would appear as ripples in space-time formed by large objects moving through space that might possibly be detected in the future by very sensitive instruments.
- The speed that gravity propagates through space has been theorized to be the same as the speed of light.

Brain Waves

- By connecting electrodes from the human head to an electroencephalograph (EEG), it is possible to measure very small cyclic electrical signals.
- There has been much study on this topic, but like all effects on humans, the findings are not as sound as the science of materials.
- Generally, lower brain wave frequencies relate to sleep, and the higher frequencies relate to alertness.
- Devices have been made for measuring and stimulating brain waves to achieve a desired state.

Electro**m**agnetic **R**adiation (EMR)

- EMR is emitted in discrete units called photons but has properties of waves as seen by the images below. EMR can be created by the oscillation or acceleration of electrical charge or magnetic field. EMR travels through space at the speed of light (2.997 924 58 $\times 10^8$ m/s). EMR consists of an oscillating electrical and magnetic field which are at right angles to each other and spaced at a particular wavelength. There is some controversy about the phase relationship between the electrical and magnetic fields of EMR, one of the theoretical representations is shown here:



E = Electric Field Strength
B = Magnetic Field Strength
Wave Nature

Particle Nature

- The particle nature of EMR is exhibited when a solar cell emits individual electrons when struck with very dim light.
- The wave nature of EMR is demonstrated by the famous double slit experiment that shows cancelling and addition of waves.
- Much of the EMR properties are based on theories since we can only see the effects of EMR and not the actual photon or wave itself.
- Albert Einstein theorized that the speed of light is the fastest that anything can travel. So far he has not been proven wrong.
- EMR can have its wavelength changed if the source is receding or approaching as in the red-shift example of distant galaxies and stars that are moving away from us at very high speeds. The emitted spectral light from these receding bodies appears more red than it would be if the object was not moving away from us.
- We only have full electronic control over frequencies in the microwave range and lower. Higher frequencies must be created by waiting for the energy to be released from elements as photons. We can either pump energy into the elements (ex. heating a rock with visible EMR and letting it release infrared EMR) or let it naturally escape (ex. uranium decay).
- We can only see the visible spectrum. All other bands of the spectrum are depicted as hatched colours.

Système International d'unité prefixes (SI unit prefixes)

Symbol	Name	Exp.	Multiplier
Y	yotta	10^{24}	1,000,000,000,000,000,000,000,000
Z	zetta	10^{21}	1,000,000,000,000,000,000,000
E	exa	10^{18}	1,000,000,000,000,000,000
P	peta	10^{15}	1,000,000,000,000,000
T	tera	10^{12}	1,000,000,000,000
G	giga	10^{9}	1,000,000,000
M	mega	10^{6}	1,000,000
k	kilo	10^{3}	1,000
		10^{0}	1
m	milli	10^{-3}	0.001
µ	micro	10^{-6}	0.000 001
n	nano	10^{-9}	0.000 000 001
p	pico	10^{-12}	0.000 000 000 001
f	femto	10^{-15}	0.000 000 000 000 001
a	atto	10^{-18}	0.000 000 000 000 000 001
z	zepto	10^{-21}	0.000 000 000 000 000 000 001
y	yocto	10^{-24}	0.000 000 000 000 000 000 000 001

Measurements on this chart

Symbol	Name	Value
c	Speed of Light	2.997 924 58 $\times 10^{8}$ m/s
h	Planck's Constant	6.626 1 $\times 10^{-34}$ J·s
$\hbar$	Planck's Constant (freq)	1.054 592 $\times 10^{-34}$ J·s
f	Frequency (cycles / second)	Hz
λ	Wavelength (meters)	m
E	Energy (Joules)	J

Formulas

$E = h \cdot f$
$\lambda = \frac{c}{f}$
$f = \frac{c}{\lambda}$

Conversions

1Å = 0.1nm
1nm = 10Å
1Joule = 6.24 $\times 10^{18}$ eV

Gamma Rays

- Gamma radiation is the highest energy radiation (up to $\approx 10^{20}$ eV) that has been measured. At this energy, the radiation could be from gamma-rays, protons, electrons, or something else.
- Alpha, beta, and delta radiation are not electromagnetic but are actually parts of the atom being released from a radioactive element. In some cases this can cause gamma radiation. These are not to be confused with brain waves of similar names.

Visible Spectrum

- The range of EMR visible to humans is called "Light". The visible spectrum also closely resembles the range of EMR that filters through our atmosphere from the sun.
- Other creatures see different ranges of visible light; for example bumble-bees can see ultraviolet light and dogs have a different response to colours than do humans.
- The sky is blue because our atmosphere scatters light and the shorter wavelength blue gets scattered the most. It appears that the entire sky is illuminated by a blue light but in fact that light is scattered from the sun. The longer wavelengths like red and orange move straight through the atmosphere which makes the sun look like a bright white ball containing all the colours of the visible spectrum.
- Interestingly, the visible spectrum covers approximately one octave.
- Astronomers use filters to capture specific wavelengths and reject unwanted wavelengths. The major astronomical (visual) filter bands are depicted as X

Infrared Radiation

- Infrared radiation (IR) is sensed by humans as heat and is below the range of human vision. Humans (and anything at room temperature) are emitters of IR.
- IR remote control signals are invisible to the human eye but can be detected by most camcorders.
- Night vision scopes/goggles use a special camera that senses IR and converts the image to visible light. Some IR cameras employ an IR lamp to help illuminate the view.
- IR LASERs are used for burning objects.
- A demonstration of IR is to hold a metal bowl in front of your face. The IR emitted by your body will be reflected back using the parabolic shape of the bowl and you will feel the heat.
- Fiber-optic based infrared communication signals are sometimes amplified with Erbium-Doped Fiber Amplifiers EDFA

LASER

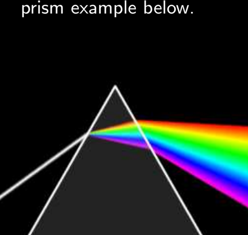
- LASER is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- A LASER is a device that produces monochromatic EMR of high intensity.
- With proper equipment, any EMR can be made to operate like a LASER. For example, microwaves are used to create a MASER.

Polarization

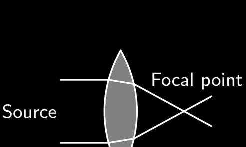
- As a photon (light particle) travels through space, its axis of electrical and magnetic fluctuations does not rotate. Therefore, each photon has a fixed linear polarity of somewhere between 0° to 360°. Light can also be circularly and elliptically polarized.
- Some crystals can cause the photon to rotate its polarization.
- Receivers that expect polarized photons will not accept photons that are in other polarities. (ex. satellite dish receivers have horizontal and vertical polarity positions).
- A polarized filter (like Polaroid™ sunglasses) can be used to demonstrate polarized light. One filter will only let photons that have one polarity through. Two overlapping filters at right angles will almost completely block the light that exits; however, a third filter inserted between the first two at a 45° angle will rotate the polarized light and allow some light to come out the end of all three filters.
- Light that reflects off an electrical insulator becomes polarized. Conductive reflectors do not polarize light.
- Perhaps the most reliably polarized light is a rainbow.
- Moonlight is also slightly polarized. You can test this by viewing the moonlight through a Polaroid™sunglass lens, then rotate that lens, the moonlight will dim and brighten slightly.

Refraction

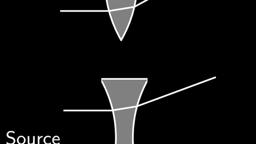
- Refraction of EMR is dependent on wavelength as can be seen by the prism example below.



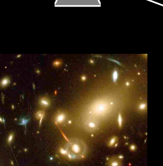
By using a glass prism, white light can be spread by refraction into a spectrum of its composite colours. All wavelengths of EMR can be refracted by using the proper materials. Not all glass prisms behave alike; a right-angle prism will act as a mirror instead of a light refractor. The critical angle of a true light-refracting prism is 42°.



Convex lenses make objects appear closer and are used to correct far-sightedness.



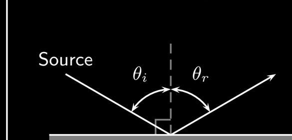
Concave lenses make objects appear farther away and are used to correct near-sightedness.



Heavy objects like dense galaxies and large planets cause light to bend due to gravitational lensing.

Reflection

- Reflection of EMR is dependent on wavelength as demonstrated when visible light and radio waves bounce off objects that X-Rays would pass through. Microwaves, which have a large wavelength compared to visible light, will bounce off metal mesh in a microwave oven whereas visible light will pass through.



EMR of any wavelength can be reflected, however, the reflectivity of a material depends on many factors including the wavelength of the incident beam.

The angle of incidence (θ_i) and angle of reflection (θ_r) are the same.