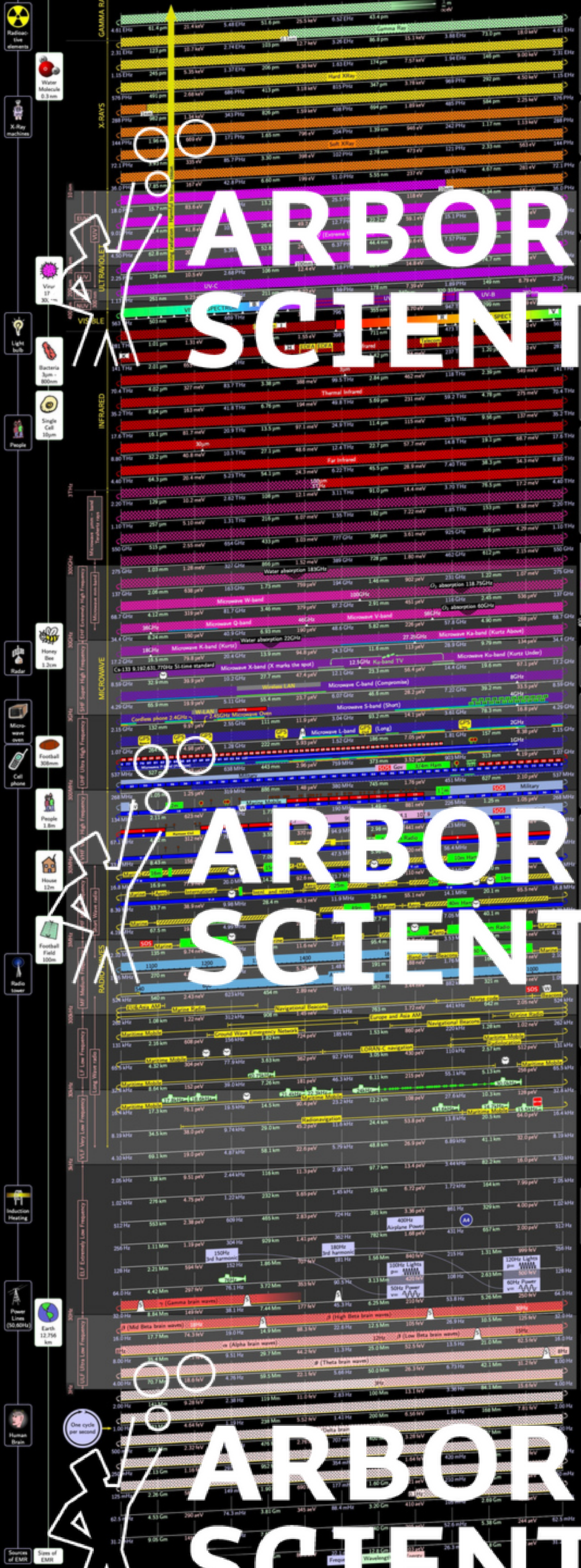
The Electromagnetic Radiation Spectrum



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 in the upward direction, and wrap around from far right to far left.
- 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 labels: Frequency in Hertz, Wavelength in meters, Energy in electronVolts.

Gamma Rays

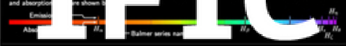
- Gamma radiation is the highest energy radiation (up to ≈ 10^{20} eV) that has been measured. At this energy, the radiation could be from gamma-rays, protons, electrons, or something else.
- Alpha, beta, and delta radiation are not electromagnetic but are actually parts of the atom being released from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

Ultraviolet Light (UV)

- UV light is beyond the range of human vision. A bumblebee can see light in the UVA range which helps them identify certain flowers.
- 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 Sun produces a wide range of wavelengths including all the UV light, however, UVB is partially filtered by the ozone layer and UVC is totally filtered out by the earth's atmosphere.

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. [illegible] discrete [illegible] possible [illegible] energy exist.
- [illegible] this formula [illegible] the photon emission wavelength (λ) [illegible] m is the [illegible] electron energy level integer [illegible] number and [illegible] final electron [illegible] energy level integer number. $\lambda = 364.56\left(\frac{m^2}{m^2-n^2}\right)$
- Much of the [illegible] matter [illegible] simplest atom [illegible]. The [illegible] visible-spectrum emission and absorption [illegible] are shown [illegible]



- 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:

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

Visible Spectrum

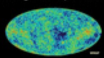
- The range of EMR visible to humans is called "Light". The visible spectrum also closely resembles the range of EMR that filters through our atmosphere from the Sun.
- Other creatures see different ranges of visible light; for example bumble-bees can see ultraviolet light and dogs have a different response to colors 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 colors of the visible spectrum.
- Interestingly, the visible spectrum covers approximately one octave (doubling/halving of frequency).
- Astronomers use filters to capture specific wavelengths and reject unwanted wavelengths. The major astronomical (visual) filter bands are depicted as X

Cosmic Microwave Background Radiation (CMB)

- 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.
- 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

Light Amplification by Stimulated Emission of Radiation (LASER)

- A LASER is a device that produces coherent monochromatic EMR of high intensity .
- With proper equipment, any EMR like visible light, ultraviolet, x-rays, and gamma rays can be made to operate like a LASER. A MASER functions similarly to the LASER and is made with with microwaves and radio waves.

Television (TV)

- Terrestrial broadcast TV uses the VHF and UHF ranges (30MHz - 3GHz) 🟥.
- Satellite television is transmitted in the C-band (4 - 8 GHz) 🟩 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 neighboring satellites.
- TV channels transmitted through cable (CATV) are shown as 🟦. 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, color, and audio frequency carriers grouped together in a channel band as follows:

- The 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 the bands used around the world are shown. Each country has its own rules and regulations for allotting bands in this region. FCC, CRTC, OFCOM, BNA, CII...
- Communication by EMR is done by modulating the carrier waveform:

- RAdio Detecting And Ranging (RADAR) uses microwaves to detect the distance and speed of objects.
- Citizens Band Radio (CB) contains 40 stations between 26.965 - 27.405MHz CB . Schumann resonances are [illegible] between [illegible] ionosphere [illegible] gas emi[illegible] at 21cm [illegible] time [illegible] standards [illegible] other individual [illegible]

Sub[illegible] xxHz | Pager | FRS Gen[illegible] Radio [illegible]
xxm Ham [illegible] International | [illegible] | Sho[illegible]
FRS Family [illegible] Service | Wireless Mic. | Cell[illegible] 3G 4G 5G

International T[illegible]communication [illegible] (ITU) standard morse [illegible]

A ·—	[illegible]	[illegible]	0 [illegible]	& [illegible]
B —···	[illegible]	[illegible]	1 [illegible]	[illegible]
C —·—·	M ——	W ·——	2 ··———	= —···—
D —··	N —·	X —··—	3 ···——	; —·—·—·
E ·	O ———	Y —·——	4 ····—	' ·————·
F ··—·	P ·——·	Z ——··	5 ·····	+ ·—·—·
G ——·	Q ——·—		6 —····	? ··——··
H ····	R ·—·	. ·—·—·—	7 ——···	" ·—··—·
I ··	S ···	@ ·——·—·	8 ———··	/ —··—·
J ·———	T —	: ———···	9 ————·	SOS ···———···

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), and much faster in water at 5328kph (3311mph).
- Humans can only hear sound between ≈20Hz to ≈20kHz. Some bats can hear sound up to 200kHz.
- Infrasound (below 20Hz) can be sensed by internal organs and touch. Frequencies in the 0.2Hz range are often the cause of motion sickness.
- The 88 piano keys of the Equal Temperament scale are accurately located on the frequency chart. The musical note A (A4 or A440 at 440Hz) is depicted on the chart as A4.
- Over the ages people have striven to divide the continuous audio frequency spectrum into individual musical notes that have harmonious relationships besides the octave. Microtonal musicians study various scales. One recent count lists 4700 different musical scales.

Gravitational Waves

- Gravity is the mysterious force which holds large objects together and binds our planets, stars, and galaxies together. No links have been established between gravity and electromagnetic radiation or the other physical forces like; the Weak force, the Electromagnetic force, and the Strong force.
- 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 stars and galaxies.
- "Gravitational waves" appear as ripples in space-time travelling at the speed of light. Long theorized, a gravitational wave was first detected in 2015, and was caused by the merger of two black holes 1.4 billion light years away.

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.

Système International d'Unités prefixes (SI unit prefixes)

Symbol	Prefix	Exp.	Name	Multiplier
Y	yotta	10^{24}	Septillion	1,000,000,000,000,000,000,000,000
Z	zetta	10^{21}	Sextillion	1,000,000,000,000,000,000,000
E	exa	10^{18}	Quintillion	1,000,000,000,000,000,000
P	peta	10^{15}	Quadrillion	1,000,000,000,000,000
T	tera	10^{12}	Trillion	1,000,000,000,000
G	giga	10^{9}	Billion	1,000,000,000
M	mega	10^{6}	Million	1,000,000
k	kilo	10^{3}	Thousand	1,000
		10^{0}		1
m	milli	10^{-3}	Thousandth	0.001
µ	micro	10^{-6}	Millionth	0.000 001
n	nano	10^{-9}	Billionth	0.000 000 001
p	pico	10^{-12}	Trillionth	0.000 000 000 001
f	femto	10^{-15}	Quadrillionth	0.000 000 000 000 001
a	atto	10^{-18}	Quintillionth	0.000 000 000 000 000 001
z	zepto	10^{-21}	Sextillionth	0.000 000 000 000 000 000 001
y	yocto	10^{-24}	Septillionth	0.000 000 000 000 000 000 000 001

Measurements on this chart

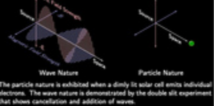
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible] ×10^8 m[illegible]
h	[illegible]ck's Constant	[illegible]1 ×10^{-34}
$\hbar$	[illegible]'s Constant (freq)	[illegible]82 ×$10^{-[illegible]}$
f	Fr[illegible] (cycles / second)	Hz
λ	[illegible]ers)	m
E	[illegible]gy (Joules)	[illegible]4 ×$10^{-1[illegible]}$

Formulas

[illegible] f
[illegible] f
1Å = 0.1nm
1nm = 10Å

Electromagnetic Radiation (EMR)

- EMR is emitted in discrete units called photons but has properties [illegible] waves. EMR can be created by the oscillation or acceleration of electrical charge or magnetic field. EMR travels through space at the speed of light ($c = 2.99792458 \times 10^8\ m{\cdot}s^{-1}$). EMR consists of an oscillating electrical and magnetic field at right angles to each other and spaced at a particular wavelength.



- The particle nature is exhibited when a dimly lit solar cell emits individual electrons. The wave nature is demonstrated by the double slit experiment that shows cancellation and addition of waves.
- The wavelength of EMR is changed when the source is receding or approaching. Red-shift makes high-speed receding stars and galaxies appear more red.

Polar[illegible]n

- [illegible] travel thr[illegible] with no rotation [illegible] elliptically or circularly where its axis of electrical and magnetic fluctuations are rotated. The electrical field is shown here.

- Some crystals 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).
- Polarized filters (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. The Dirac three polarizers experiment shows that a third filter inserted between the first two at 45° allows some light to come out the end of all three filters.

- Reflections from an electrical insulator are polarized. Conductive reflectors do not polarize EMR.
- Light from a rainbow is polarized due to the reflection inside the water droplets.
- Moonlight is slightly polarized. Rotating a polarized sunglass lens causes the moonlight to dim and brighten slightly.

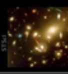
Refract[illegible]

- Refraction [illegible] bending [illegible] EMR, is [illegible]dent on wavelength. All wavelengths of EMR can be refracted by using the proper materials. White light can be spread by refraction into a spectrum of its composite colors with a glass prism.

Glass prism

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

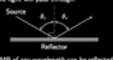
- Heavy objects like dense galaxies, stars, and large planets cause light to bend due to gravitational lensing as seen here in galaxy cluster Abell 2218.



STScI

Reflect[illegible]

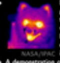
- Reflection of EMR is dependent on wavelength as demonstrated when visible light and radio waves bounce off objects that X-Rays would pass through. Microwaves, which have a large wavelength compared to visible light, will bounce off metal mesh in a microwave oven whereas visible light will pass through.



- 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.

Infrared [illegible] (IR)

- IR is sensed by humans as heat and is [illegible] range of human vision. All creatures emit IR, and snakes can detect it.
- IR remote control signals are invisible to the human eye but can be detected by some electronic cameras.



NASA/IPAC

- 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.

- 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.
- IR LASERs are used for cutting material.
- Fiber-optic based infrared communication signals are sometimes amplified with Erbium-Doped Fiber Amplifiers EDFA.