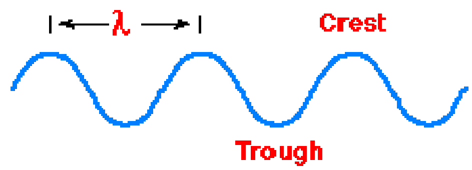
Light

"I'm all in favor of keeping dangerous weapons out of the hands of fools. Let's start with typewriters."

Frank Lloyd Wright

Most of what we know about the Universe comes from information that has been carried to us by the transmission or propagation of light. In modern physics, light or electromagnetic radiation may be viewed in one of two complementary ways: as a wave in an abstract *electromagnetic field* or as a stream of mass-less particles called *photons*. Although either is an acceptable description of light, for our purposes the wave description will be more useful.

Light as a Wave



The quantity that is "waving" is the electromagnetic field, an esoteric but measurable entity: your lights shine and your microwave runs and your radio plays because the electromagnetic field exists. As illustrated in the adjacent image, a wave has a wavelength associated with it. This is related to its frequency.
It is normal to give the wavelength of light the symbol Greek "lambda". Some common units of length employed for wavelengths of electromagnetic radiation are summarized in the following table. (The micrometer is often still called by its old name, the *micron*.)

Units of Wavelength		
Unit	**Symbol**	**Length**
centimeter	cm	10^{-2} meters
Angstrom	Å	10^{-8} centimeters
nanometer	nm	10^{-9} meters
micrometer	nm	10^{-6} meters

Wavelength, Energy, and Frequency

The speed of light in a vacuum is commonly given the symbol *c*. It is a universal constant that has the value

$$c = 3 \times 10^{10} \text{ cm/second}$$

The speed of light in a medium is generally less than this. Normally the term "speed of light", without further qualification, refers to the speed in a vacuum. A wave can be characterized by its wavelength, but we can also characterize it by the *frequency* (how many wavelengths pass a fixed point in a given time; think of sitting on the dock---of the bay---counting the number of water waves passing in one minute) and the *energy* that it carries (think of a water wave knocking you over in heavy surf). For light waves the relationship among the wavelength (usually denoted by Greek "lambda"), the frequency (usually denoted by Greek "nu"), and the energy *E* are

$$E = h\nu = \frac{hc}{\lambda}$$

where *c* is the speed of light and *h* is another universal constant called *Planck's Constant* that has the values

$$h = 4.135 \times 10^{-15} \text{ eV-sec} = 6.625 \times 10^{-27} \text{ erg-sec}$$

in two different useful sets of units (eV stands for "electron volts"; electron volts and ergs are two common units of energy). Thus, these equations allow us to freely interconvert among frequency, wavelength, and energy for electromagnetic waves: specifying one also specifies the others.

Everything and everyone vibrates. These vibrations occur at specific frequencies. It is my belief that there is an inter-relationship between these frequencies, and dimensions, that may explain how paranormal events are possible, scientifically.

The *electromagnetic spectrum* is the distribution of electromagnetic radiation according to energy (or equivalently, by virtue of the relations in the previous section, according to frequency or wavelength). This covers everything, from Radio waves to Gamma Rays, with Sound and Light inclusive.

The visible spectrum (or sometimes optical spectrum) is the portion of the electromagnetic spectrum that is visible to (can be detected by) the human eye. Electromagnetic radiation in this range of wavelengths is called visible light or simply light. There are no exact bounds to the visible spectrum; a typical human eye will respond to wavelengths from 400 to 700 nm, although some people may be able to perceive wavelengths from 380 to 780 nm. In terms of frequency, this corresponds to a band in the vicinity of 500 terahertz. A light-adapted eye typically has its maximum sensitivity at around 555 nm, in the green region of the optical spectrum (see: luminosity function). The spectrum does not, however, contain all the colors that the human eyes and brain can distinguish. Brown, pink, and magenta are absent, for example.

Wavelengths visible to the eye also pass through the "optical window", the region of the electromagnetic spectrum which passes largely unattenuated through the Earth's atmosphere (although blue light is scattered more than red light, which is the reason the sky is blue). The response of the human eye is defined by subjective testing (see CIE), but the atmospheric windows are defined by physical measurement. The "visible window" is so called because it overlaps the human visible response spectrum; the near infrared (NIR) windows lie just out of human response window, and the Medium Wavelength IR (MWIR) and Long Wavelength or Far Infrared (LWIR or FIR) are far beyond the human response region.

The eyes of many species perceive wavelengths different from the spectrum visible to the human eye. For example, many insects, such as bees, can see light in the ultraviolet, which is useful for finding nectar in flowers. For this reason, plant species whose life cycles are linked to insect pollination may owe their reproductive success to their appearance in ultraviolet light, rather than how colorful they appear to our eyes.

Two of the earliest explanations of the optical spectrum came from Isaac Newton, when he wrote his *Opticks*, and from Goethe, in his *Theory of Colours*.

Newton first used the word spectrum (Latin for "appearance" or "apparition") in print in 1671 in describing his experiments in optics. Newton observed that, when a narrow beam of sunlight strikes the face of a glass prism at an angle, some is reflected and some of the beam passes into and through the glass, emerging as different colored bands. Newton hypothesized that light was made up of "corpuscles" (particles) of different colors, and that the different colors of light moved at different speeds in transparent matter, with red light moving more quickly in glass than violet light. The result is that red light was bent (refracted) less sharply than violet light as it passed through the prism, creating a spectrum of colors.

Newton's color circle, showing the colors correlated with musical notes and symbols for the planets. Newton divided the spectrum into seven named colors: red, orange, yellow, green, blue, indigo, and violet; or ROY G. BIV. He chose seven colors out of a belief, derived from the ancient Greek philosophers, that there was a connection between the colors, the musical notes, the known objects in the solar system, and the days of the week. The human eye is relatively insensitive to indigo's frequencies and some otherwise well-sighted people cannot distinguish indigo from blue and violet. For this reason some commentators including Isaac Asimov have suggested that indigo should not be regarded as a color in its own right but merely as a shade of blue or violet.

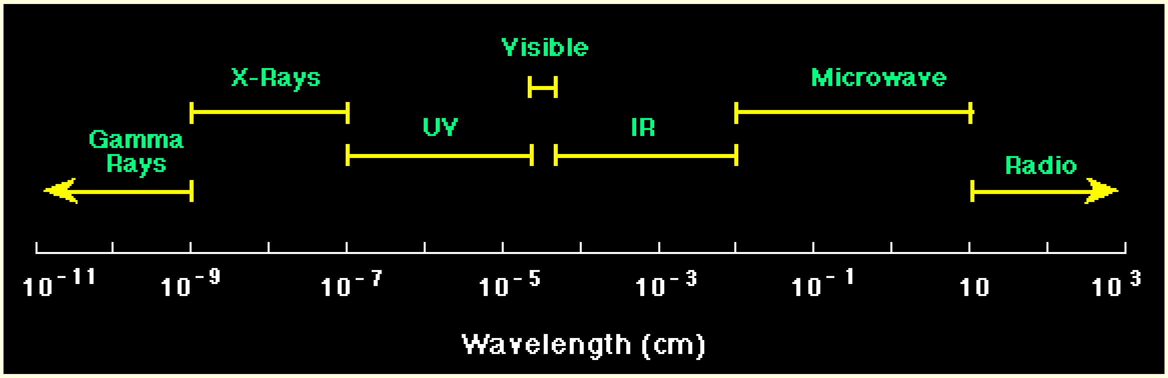
Johann Wolfgang von Goethe contended that the continuous spectrum was a compound phenomenon. Whereas Newton narrowed the beam of light in order to isolate the phenomenon, Goethe observed that with a wider aperture, there was no spectrum - rather there were reddish-yellow edges and blue-cyan edges with white between them, and the spectrum only arose when these edges came close enough to overlap.

Regions of the Electromagnetic Spectrum

The following table gives approximate wavelengths, frequencies, and energies for selected regions of the electromagnetic spectrum.

Region	Wavelength (Angstroms)	Wavelength (centimeters)	Frequency (Hz)	Energy (eV)
Radio	$> 10^9$	> 10	$< 3 \times 10^9$	$< 10^{-5}$
Microwave	$10^9 - 10^6$	$10 - 0.01$	$3 \times 10^9 - 3 \times 10^{12}$	$10^{-5} - 0.01$
Infrared	$10^6 - 7000$	$0.01 - 7 \times 10^{-5}$	$3 \times 10^{12} - 4.3 \times 10^{14}$	$0.01 - 2$
Visible	$7000 - 4000$	$7 \times 10^{-5} - 4 \times 10^{-5}$	$4.3 \times 10^{14} - 7.5 \times 10^{14}$	$2 - 3$
Ultraviolet	$4000 - 10$	$4 \times 10^{-5} - 10^{-7}$	$7.5 \times 10^{14} - 3 \times 10^{17}$	$3 - 10^3$
X-Rays	$10 - 0.1$	$10^{-7} - 10^{-9}$	$3 \times 10^{17} - 3 \times 10^{19}$	$10^3 - 10^5$
Gamma Rays	< 0.1	$< 10^{-9}$	$> 3 \times 10^{19}$	$> 10^5$

The notation "eV" stands for electron-volts, a common unit of energy measure in atomic physics. A graphical representation of the electromagnetic spectrum is shown in the figure below.

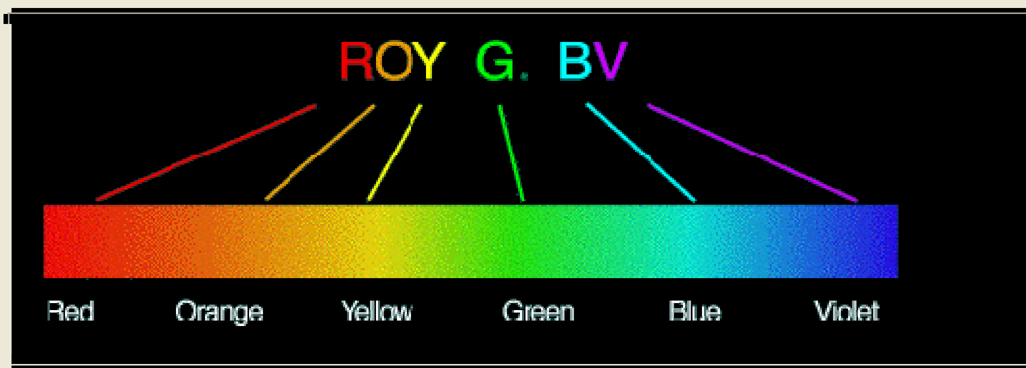


The electromagnetic spectrum

Thus we see that visible light and gamma rays and microwaves are really the same things. They are all electromagnetic radiation; they just differ in their wavelengths.

The Spectrum of Visible Light

The visible part of the spectrum may be further subdivided according to color, with red at the long wavelength end and violet at the short wavelength end, as illustrated (schematically) in the following figure.



The visible spectrum

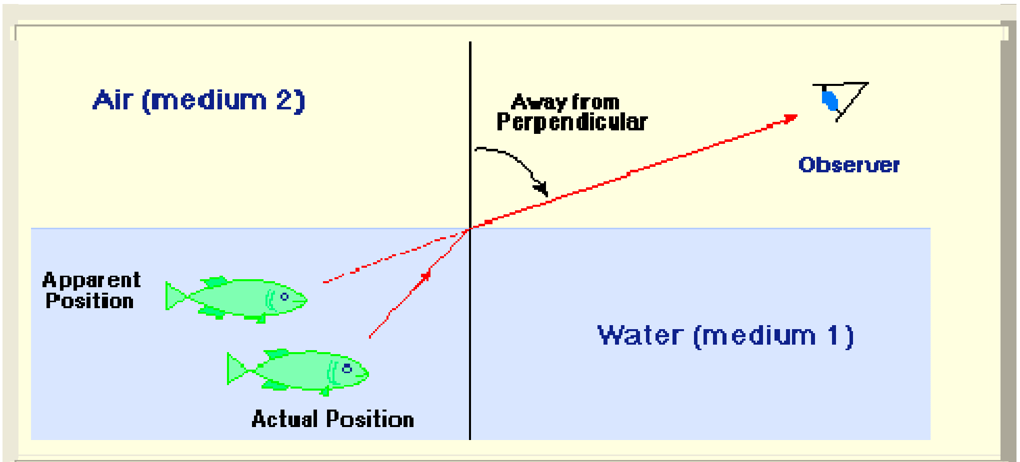
How Roy G. Bv Lost a Vowel

The sequence of colors red, orange, yellow, green, blue, and violet may be remembered by memorizing the name of that fine fellow "ROY G. BV". This was originally "ROY G. BIV", because it used to be common to call the region between blue and violet "indigo". In modern usage, indigo is not usually distinguished as a separate color in the visible spectrum; thus Roy no longer has any vowels in his last name.

The wave nature of light leads to two very important properties: *refraction*, where the direction of light propagation is altered at the boundary between media of different densities, and *diffraction*, which has among its consequences that light can "bend around corners".

Refraction of Light

The direction of light propagation can be changed at the boundary of two media having different densities. This property is called *refraction*, and is illustrated in the following figure for the boundary between air and water.



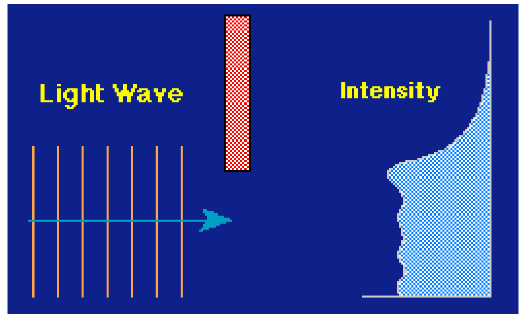
Refraction of light

The apparent and actual positions of the fish differ because the direction of light propagation has been changed as light passes from the more dense water into the less dense air.
If we adopt the convention that the light passes from medium 1 into medium 2, the general rule is that the refraction is

- *Away from the perpendicular* if medium 2 is less dense than medium 1
- *Toward the perpendicular* if medium 2 is more dense than medium 1

Thus, in the above example the refraction is away from the perpendicular because air is less dense than water. Such effects form the basis of the refracting telescope, and of optical devices using lenses in general.

Diffraction of Light



Because light is a wave, it has the capability to "bend around corners". This is called *diffraction*, and is illustrated in the adjacent image. The intensity of light behind the barrier is not zero in the shadow region. Diffractive effects occur generally when a part of a light wave is cut off by an obstruction. Here is a Java applet illustrating diffraction of light by a single slit, and here is an interactive demonstration of refraction and diffraction for ocean waves.
Diffraction has a number of consequences for astronomy. Two of the more important are that this property is the basis for the *diffraction grating* that can be used to separate light into its constituent colors, and that diffractive effects set an absolute limit on the quality of an image observed through an optical instrument such as a telescope. This *diffractive limit* occurs because the lenses of such objects are of finite size and diffract light because they cut off part of the light wave.

In the preceding section we showed that light is refracted at the boundary between two media differing in density. Let us now examine more carefully the factors upon which this refraction depends.

Factors Governing Refraction

The amount of refraction of light at a boundary between two media depends on three things:

1. The nature of the media (embodied in a characteristic quantity called the *index of refraction* for a medium).
2. The angle of incidence for the light ray on the boundary.
3. The wavelength of light.

The dependence of refraction on the wavelength of light is called *dispersion*. This dependence has both positive and negative implications for astronomy. On the positive side, it is the basis for the prism and its ability to separate light according to wavelength; on the negative side, it is the source of *chromatic aberration* in optical devices (the failure of different wavelengths to focus at the same point).

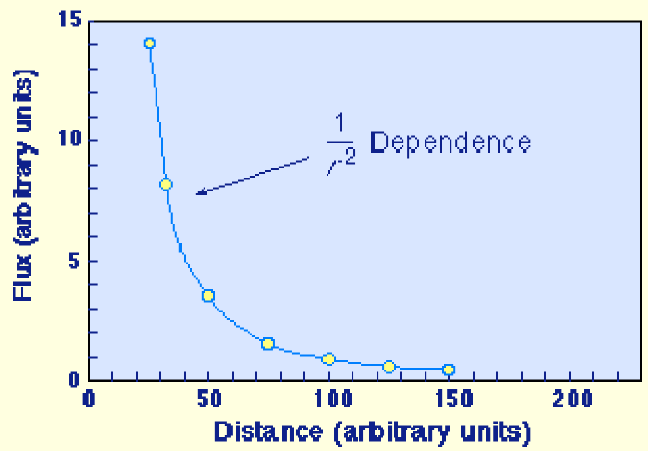
Dispersion and The Prism

Dispersion is the basis for the prism and its ability to spatially separate light according to wavelength, Light separated into its frequency (and therefore energy or wavelength) components is called a *spectrum* of light. Here are Java applets illustrating the dispersion of visible light by a triangular prism and by a rectangular glass slab.

Spectrographs

A *spectrograph* is a refined instrument that produces a spectrum. Although a prism can disperse light according to color, in modern spectrographs it is more common to accomplish the same task by using a diffraction grating. The diffraction grating works on a completely different principle (diffraction rather than refraction) but it also can separate light spatially according to wavelength. We will see in subsequent sections that the spectrograph is a central tool of modern astronomy.

The intensity of light observed from a source of constant intrinsic luminosity falls off as the square of the distance from the object. This is known as the *inverse square law* for light intensity.



The inverse square law for intensity

Thus, if I double the distance to a light source the observed intensity is decreased to $(1/2)^2 = 1/4$ of its original value. Generally, the ratio of intensities at distances d_1 and d_2 are

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}$$

It is now generally accepted that light is composed of photons (which display some of the properties of a wave and some of the properties of a particle; see Wave-particle duality), and that all light travels at the same speed (the speed of light) in a vacuum. The speed of light within a material is lower than the speed of light in a vacuum, and the ratio of speeds is known as the refractive index of the material.

In some materials, known as non-dispersive, the speed of different frequencies (corresponding to the different colors) does not vary, and so the refractive index is a constant. However, in other (dispersive) materials, the refractive index (and thus the speed) depends on frequency in accordance with a dispersion relation: glass is one such material, which enables glass prisms to create an optical spectrum from white light.

Most everyone is familiar with the drop in pitch of a train whistle as a train passes your position and switches from moving toward you to moving away from you. This phenomenon is called the *Doppler Effect* , and is associated with the wave nature of sound: the relative motion of the source causes the wavelength of the sound waves to be decreased ahead of the source and stretched out behind the source (musically, the pitch of a note is correlated with the wavelength of the corresponding sound wave; thus, the longer the wavelength, the lower the pitch). Light also can be described as a wave, and relative motion of the source of light waves leads to a corresponding Doppler effect for light. In this case it is not the pitch but the color (that is, the wavelength) that is shifted by the motion of the source. The wavelength is shifted to larger values if the motion of the source is away from the observer and to smaller values if the motion is toward the observer. The shift to larger wavelengths by motion away from the observer is called a *red shift* by astronomers and a shift to shorter wavelengths caused by motion toward the observer is called a *blue shift*. The terminology is borrowed from the visible part of the spectrum where blue is toward the short wavelength end and red is toward the long wavelength end, but the Doppler Effect occurs for all wavelengths of light, not just the visible spectrum.

The Doppler shift is given by the formula

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_1 - \lambda_2}{\lambda_1} = \frac{v}{c}$$

where λ_1 is the unshifted wavelength, λ_2 is the shifted wavelength, c is the speed of light, and v is the velocity of the object emitting the light relative to the observer.

Example: A spectral line normally at 4000 Angstroms is shifted to 3999 Angstroms by relative motion of the source. What is the velocity of the source along the line of site?

Answer:

$$v = \frac{\lambda_1 - \lambda_2}{\lambda_1} c = \frac{4000 - 3999}{4000} \times 3.0 \times 10^{10} \text{ cm/sec}$$

$$= 7.5 \times 10^{6} \text{ cm/sec}$$

The Doppler shift is positive (to shorter wavelength), so this is a blue shift caused by motion toward the observer.

We have now surveyed some basic properties of electromagnetic radiation. However, light in itself does not carry much information about the Universe. The reason that light is so important for our understanding of the Universe is because light interacts with matter, and that interaction can tell us a great deal about the nature of the matter. Thus, we must understand the interaction of light with matter. We begin with a simple review of some basic properties of matter starting at the atomic level.

The basic building blocks of the "normal" matter that we see in the Universe are atoms, and combinations of atoms that we call molecules. We first consider atoms and then molecules. However, we shall see that although "normal matter" is composed of atoms and molecules, most of the matter in the Universe is not in the form of atoms or molecules, but rather in the form of a *plasma*. We discuss plasmas in the next section.

Constituents of Atoms

Atoms are composed of three classes of constituents, as illustrated in the following table.

Constituent	Symbol	Charge	Mass
Electrons	e^-	-1	9.1×10^{-28} g
Protons	p^+	+1	1836 x electron mass
Neutrons	n	0	Approximately that of p^+

Thus, most of the mass of atoms resides in the neutrons and protons which occupy the dense central region called the *nucleus* (see the Bohr atom below). The number of protons (or the number of electrons) is called the *atomic number* for the atom. The total number of protons plus neutrons is called the *atomic mass number* for the atom. Atoms are electrically neutral because the number of negatively-charged electrons is exactly equal to the number of positively-charged protons. The number of neutrons is approximately equal to the number of protons for stable light nuclei, and is about 1-2 times the number of protons for the heavier stable nuclei.

Isotopes of an Element

Atoms having the same number of protons (and therefore the same number of electrons) but different numbers of neutrons are called *isotopes* of the element in question. Thus, the isotopes of an element have the same atomic number but differ in their atomic mass number. A compact notation for isotopes of an element is illustrated by the following examples.

$$^{235}_{92}U_{143} \quad ^{238}_{92}U_{146} \quad ^{1}_{1}H_{0} \quad ^{2}_{1}H_{1} \quad ^{3}_{1}H_{2}$$

In this notation the element is represented by its chemical symbol, the atomic number is denoted by a lower left subscript, the number of neutrons is denoted by a lower right subscript, and the atomic mass number is denoted by an upper left superscript (some of these superscripts and subscripts may be omitted, depending on the context).
Thus, the above symbols denote, respectively, the mass-235 and mass-238 isotopes of uranium (symbol U), and the mass-1,-2,and -3 isotopes of hydrogen (symbol H). The mass-2 isotope of hydrogen is also called *deuterium* and the mass-3 isotope is also called *tritium*.

Periodic Table of the Elements

The elements have properties that repeat themselves periodically with variation of the number of electrons (atomic number). A chart of the elements arranged to show this periodicity is termed a *periodic table (of the elements)*. Here is a periodic table of the elements which gives the atomic number and symbol for all elements, and the name and basic chemical properties for each of these elements if you click on the element's symbol in the resulting table.

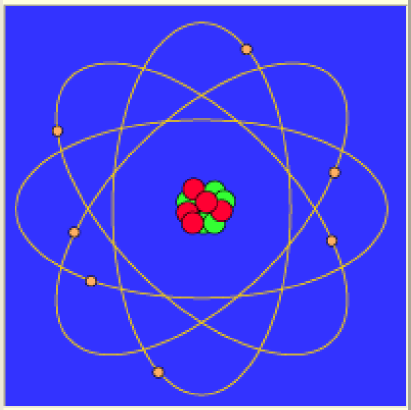
Group**

	1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 -------	9 VIII 8	10 -------	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 vIIIA 8A
1	1 **H** 1.008																	2 **He** 4.003
2	3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
3	11 **Na** 22.99	12 **Mg** 24.31											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
4	19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.59	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
5	37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
6	55 **Cs** 132.9	56 **Ba** 137.3	57 **La** *138.9	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.9	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 190.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.5	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** (210)	85 **At** (210)	86 **Rn** (222)
7	87 **Fr** (223)	88 **Ra** (226)	89 **Ac** ~(227)	104 **Rf** (257)	105 **Db** (260)	106 **Sg** (263)	107 **Bh** (262)	108 **Hs** (265)	109 **Mt** (266)	110 **Ds** (271)	111 **Uuu** (272)	112 **Uub** (277)		114 **Uuq** (296)		116 **Uuh** (298)		118 **Uuo** (?)

Lanthanide Series*	58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** (147)	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.3	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0	71 **Lu** 175.0
Actinide Series~	90 **Th** 232.0	91 **Pa** (231)	92 **U** (238)	93 **Np** (237)	94 **Pu** (242)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (249)	99 **Es** (254)	100 **Fm** (253)	101 **Md** (256)	102 **No** (254)	103 **Lr** (257)

The most important properties of atomic and molecular structure may be exemplified using a simplified picture of an atom that is called the *Bohr Model*. This model was proposed by Niels Bohr in 1915; it is not completely correct, but it has many features that are approximately correct and it is sufficient for much of our discussion. The correct theory of the atom is called *quantum mechanics*; the Bohr Model is an approximation to quantum mechanics that has the virtue of being much simpler.

A Planetary Model of the Atom



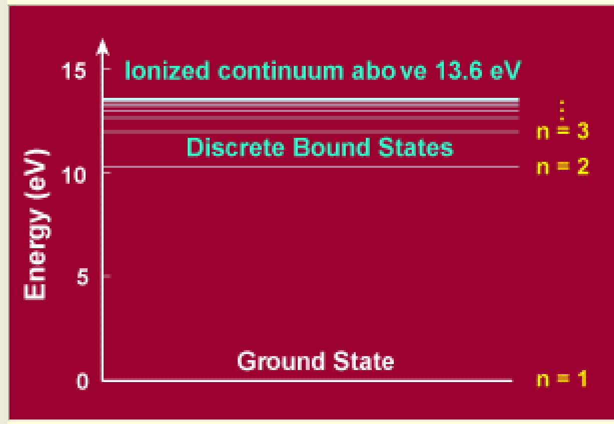
The Bohr atom

The Bohr Model is probably familar as the "planetary model" of the atom illustrated in the adjacent figure that, for example, is used as a symbol for atomic energy (a bit of a misnomer, since the energy in "atomic energy" is actually the energy of the nucleus, rather than the entire atom). In the Bohr Model the neutrons and protons (symbolized by red and blue balls in the adjacent image) occupy a dense central region called the nucleus, and the electrons orbit the nucleus much like planets orbiting the Sun (but the orbits are not confined to a plane as is approximately true in the Solar System). The adjacent image is not to scale since in the realistic case the radius of the nucleus is about 100,000 times smaller than the radius of the entire atom, and as far as we can tell electrons are point particles without a physical extent.

This similarity between a planetary model and the Bohr Model of the atom ultimately arises because the attractive gravitational force in a solar system and the attractive Coulomb (electrical) force between the positively charged nucleus and the negatively charged electrons in an atom are mathematically of the same form. (The *form* is the same, but the intrinsic *strength* of the Coulomb interaction is much larger than that of the gravitational interaction; in addition, there are positive and negative electrical charges so the Coulomb interaction can be either attractive or repulsive, but gravitation is always attractive in our present Universe.)

But the Orbits Are Quantized

The basic feature of quantum mechanics that is incorporated in the Bohr Model and that is completely different from the analogous planetary model is that the energy of the particles in the Bohr atom is restricted to certain discrete values. One says that the energy is *quantized*. This means that only certain orbits with certain radii are allowed; orbits in between simply don't exist.

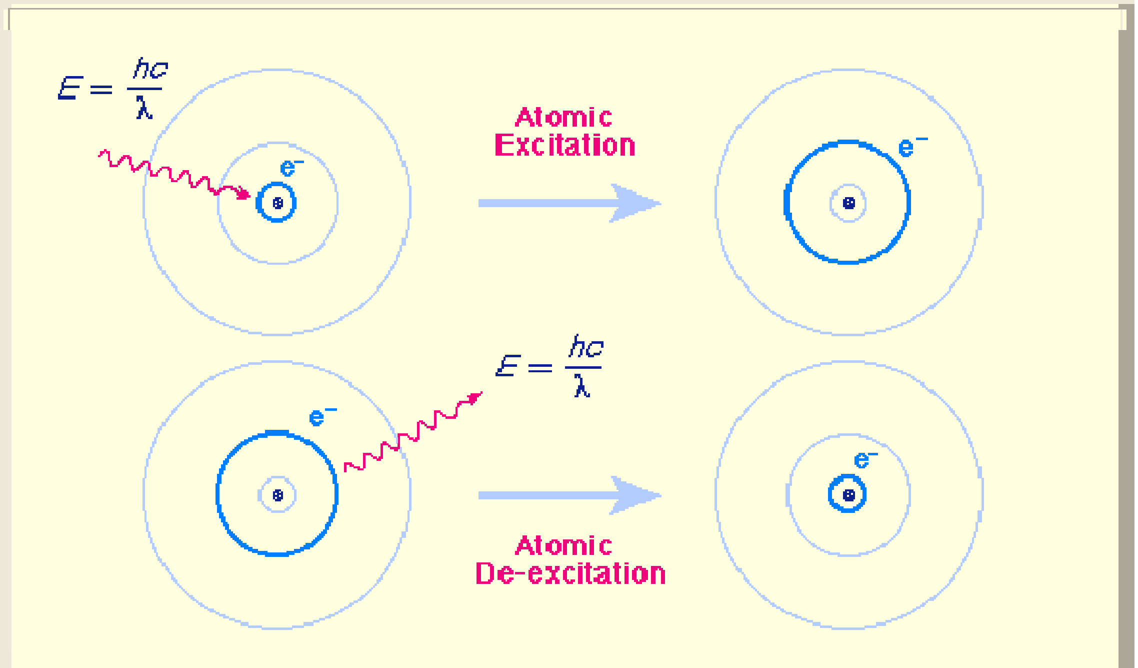


Quantized energy levels in hydrogen

The adjacent figure shows such quantized energy levels for the hydrogen atom. These levels are labeled by an integer *n* that is called a *quantum number*. The lowest energy state is generally termed the *ground state*. The states with successively more energy than the ground state are called the *first excited state*, the *second excited state*, and so on. Beyond an energy called the *ionization potential* the single electron of the hydrogen atom is no longer bound to the atom. Then the energy levels form a continuum. In the case of hydrogen, this continuum starts at 13.6 eV above the ground state ("eV" stands for "electron-Volt", a common unit of energy in atomic physics).
Although this behavior may seem strange to our minds that are trained from birth by watching phenomena in the macroscopic world, this is the way things behave in the strange world of the quantum that holds sway at the atomic level.

Atomic Excitation and De-excitation

Atoms can make transitions between the orbits allowed by quantum mechanics by absorbing or emitting exactly the energy difference between the orbits. The following figure shows an atomic excitation cause by absorption of a photon and an atomic de-excitation caused by emission of a photon.



Excitation by absorption of light and de-excitation by emission of light

In each case the wavelength of the emitted or absorbed light is exactly such that the photon carries the energy difference between the two orbits. This energy may be calculated by dividing the product of the Planck constant and the speed of light *hc* by the wavelength of the light). Thus, an atom can absorb or emit only certain discrete wavelengths (or equivalently, frequencies or energies).

Atoms and molecules are electrically neutral in that the number of negatively charged electrons is exactly equal to the number of positively charged protons. Much of the "normal matter" that we find around us is in this form. However, particularly when there are energy sources available, atoms or molecules can gain or lose electrons and acquire a net electrical charge. This process is called *ionization*.

Ionization of Atoms

Ionization is the gain or loss of electrons. The loss of electrons, which is the more common process in astrophysical environments, converts an atom into a positively charged ion, while the gain of electrons converts an atom into a negatively charged ion. In the subsequent discussion, we will use the terms *ionization* and *ionize* in the sense of losing electrons to form positive ions. There is a standard notation in astrophysics for various levels of ionization of an atom. As illustrated in the following table, this notation uses increasing Roman numerals to indicate higher levels of ionization.

Notation for Degrees of Ionization			
Suffix	**Ionization**	**Examples**	**Chemist's Notation**
I	Not ionized (neutral)	H I, He I	H, He
II	Singly ionized	H II, He II	H^+, He^+
III	Doubly ionized	He III, O III	He^{++}, O^{++}

We also show the standard chemist's notation for such ions, which consists of placing a right superscript on the element symbol indicating the net electrical charge on the ion (in the neutral case the superscript "0" is usually omitted). Thus, for example, we shall speak later of "H II regions", meaning volumes of space in which the radiation from nearby hot stars has completely ionized the hydrogen.

Plasmas

If most of the atoms or molecules in a region are ionized, the resulting state of matter corresponds to a gas that is electrically neutral on a global scale, but composed microscopically of positively charged ions and the negatively charged electrons stripped from the atoms to form the ions. Such a state of matter is called a *plasma*. Most of the matter in stars is in a plasma state. Thus, although what we refer to as "normal matter" consists of atoms and molecules, the evidence is that the most abundant form of matter in the Universe is not atoms and molecules but rather the plasma state.

The average or bulk properties of electromagnetic radiation interacting with matter are systematized in a simple set of rules called *radiation laws*. These laws apply when the radiating body is what physicists call a *blackbody radiator*. Generally, blackbody conditions apply when the radiator has very weak interaction with the surrounding environment and can be considered to be in a state of equilibrium. Although stars do not satisfy perfectly the conditions to be blackbody radiators, they do to a sufficiently good approximation that it is useful to view stars as approximate blackbody radiators.

Planck Radiation Law

The primary law governing blackbody radiation is the *Planck Radiation Law*, which governs the intensity of radiation emitted by unit surface area into a fixed direction (solid angle) from the blackbody as a function of wavelength for a fixed temperature. The Planck Law can be expressed through the following equation.

$$E(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

$h = 6.625 \times 10^{-27}$ erg- sec (Planck Constant)

$k = 1.38 \times 10^{-16}$ erg/ K (Boltzmann Constant)

$c = 3 \times 10^{10}$ cm/sec (Speed of Light)

The behavior is illustrated in the figure shown above. The Planck Law gives a distribution that peaks at a certain wavelength, the peak shifts to shorter wavelengths for higher temperatures, and the area under the curve grows rapidly with increasing temperature.

The Wien and Stefan-Boltzmann Laws

The behavior of blackbody radiation is described by the Planck Law, but we can derive from the Planck Law two other radiation laws that are very useful. The Wien Displacement Law, and the Stefan-Boltzmann Law are illustrated in the following equations.

Steffan - Boltzmann Law: $\boxed{E = \sigma T^4}$

$\sigma = 5.6705 \times 10^{-5}$ erg - cm^2 - K^{-4} - sec^{-1}

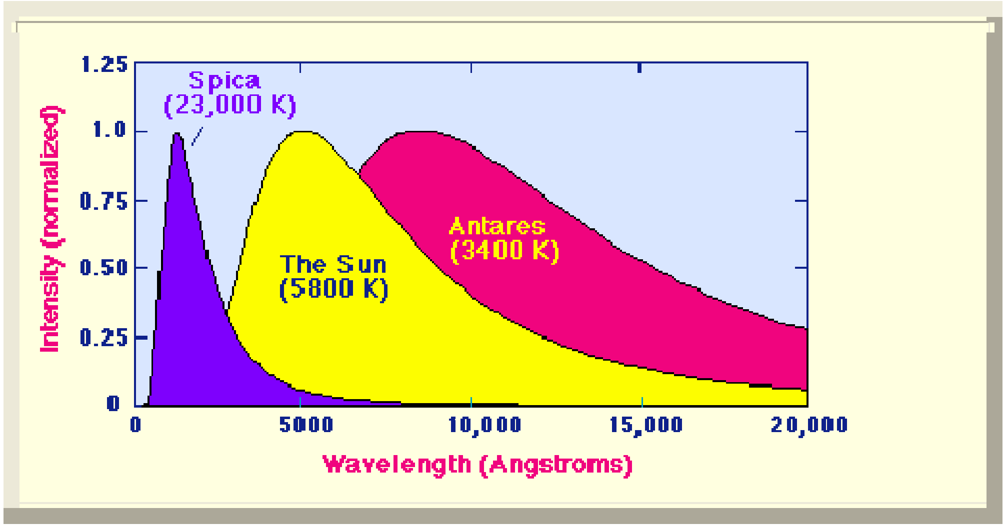
(Steffan - Boltzmann Constant)

Wien Displacement Law: $\boxed{\lambda_{Max} = \frac{3 \times 10^7}{T}}$

(λ in Angstroms, T in Kelvin)

The Wien Law gives the wavelength of the peak of the radiation distribution, while the Stefan-Boltzmann Law gives the total energy being emitted at all wavelengths by the blackbody (which is the area under the Planck Law curve). Thus, the Wien Law explains the shift of the peak to shorter wavelengths as the temperature increases, while the Stefan-Boltzmann Law explains the growth in the height of the curve as the temperature increases. Notice that this growth is very abrupt, since it varies as the fourth power of the temperature.

The following figure illustrates the Wien law in action for three different stars of quite different surface temperature. The strong shift of the spectrum to shorter wavelengths with increasing temperatures is apparent in this illustration.



For convenience in plotting these distributions have been normalized to unity at the respective peaks; by the Stefan-Boltzmann Law, the area under the peak for the hot star Spica is in reality 2094 times the area under the peak for the cool star Antares.

Temperatures and Characteristic Wavelengths

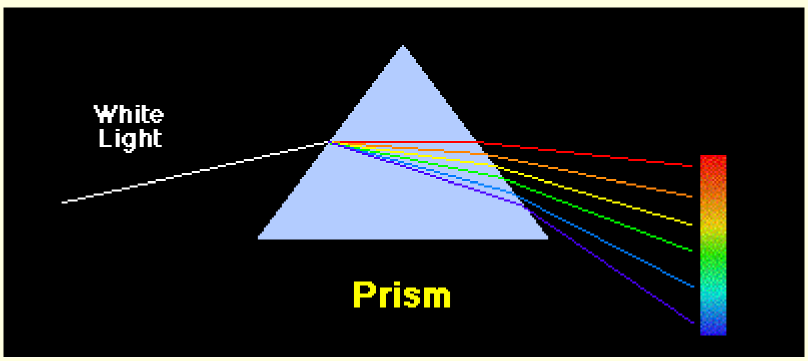
By the Planck Law, all heated objects emit a characteristic spectrum of electromagnetic radiation, and this spectrum is concentrated in higher wavelengths for cooler bodies. The following table summarizes the blackbody temperatures necessary to give a peak for emitted radiation in various regions of the spectrum.

Some Blackbody Temperatures			
Region	**Wavelength (centimeters)**	**Energy (eV)**	**Blackbody Temperature (K)**
Radio	> 10	$< 10^{-5}$	< 0.03
Microwave	10 - 0.01	10^{-5} - 0.01	0.03 - 30
Infrared	0.01 - 7×10^{-5}	0.01 - 2	30 - 4100
Visible	7×10^{-5} - 4×10^{-5}	2 - 3	4100 - 7300
Ultraviolet	4×10^{-5} - 10^{-7}	3 - 10^{3}	7300 - 3×10^{6}

X-Rays	10^{-7} - 10^{-9}	10^{3} - 10^{5}	3 x 10^{6} - 3 x 10^{8}
Gamma Rays	< 10^{-9}	> 10^{5}	> 3 x 10^{8}

Blackbody radiation corresponds to radiation from bodies in thermal equilibrium. We will consider later the emission of non-thermal radiation, which doesn't follow a blackbody law. Such radiation is often produced by violent collisions rather than equilibrium heating. For example, in astrophysical environments radiation at the long and short wavelength ends of the above table is more likely to be produced by non-thermal processes.

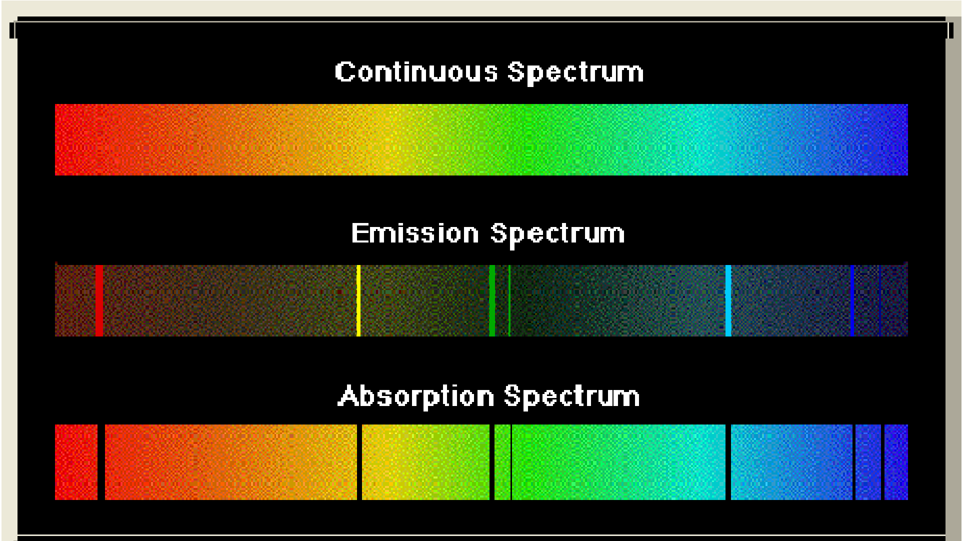
As we have noted in the section on the Bohr atom, isolated atoms can absorb and emit packets of electromagnetic radiation having discrete energies dictated by the detailed atomic structure of the atoms. When the corresponding light is passed through a prism or spectrograph it is separated spatially according to wavelength, as illustrated in the following image.



Separation of light by a prism according to wavelength

Continuum, Emission, and Absorption Spectra

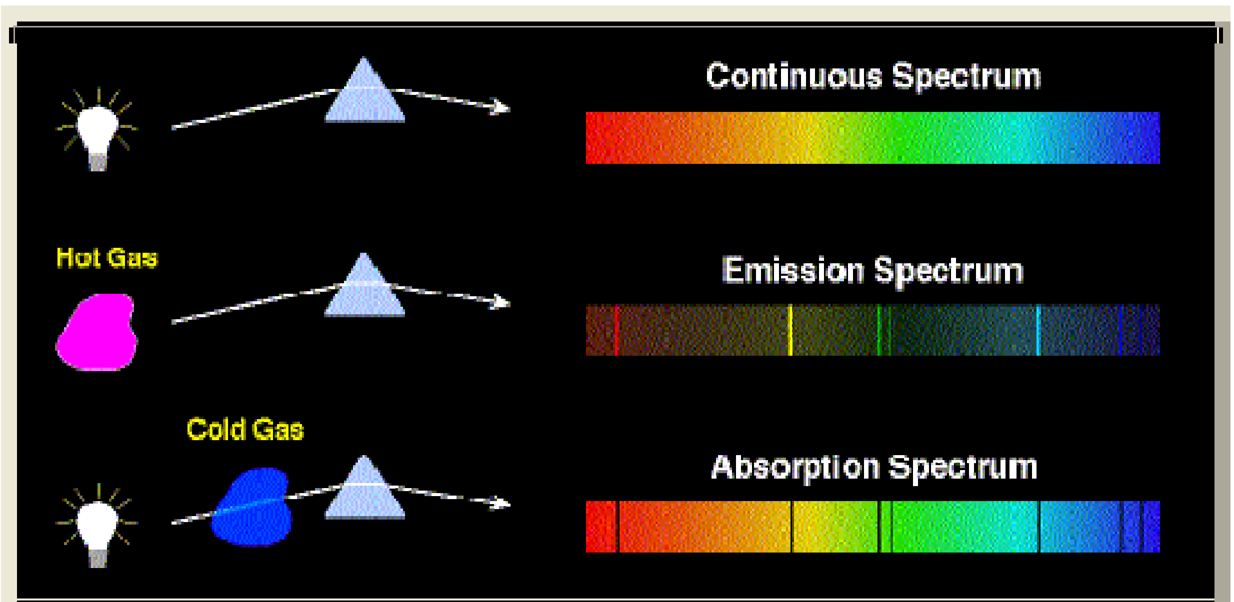
The corresponding spectrum may exhibit a continuum, or may have superposed on the continuum bright lines (an *emission spectrum*) or dark lines (an *absorption spectrum*), as illustrated in the following figure.



Continuous, emission, and absorption spectra

Origin of Continuum, Emission, and Absorption Spectra

The origins of these three types of spectra are illustrated in the following figure.



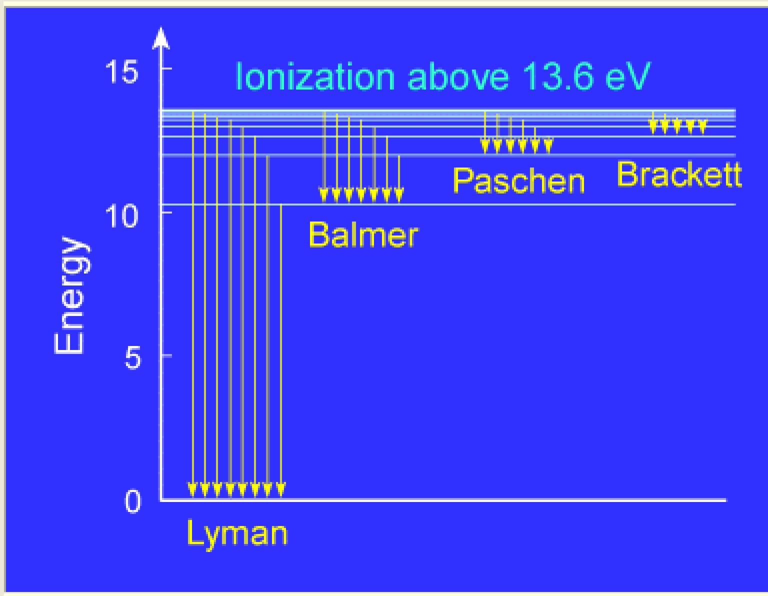
Sources of continuous, emission, and absorption spectra

Thus, *emission spectra* are produced by thin gases in which the atoms do not experience many collisions (because of the low density). The emission lines

correspond to photons of discrete energies that are emitted when excited atomic states in the gas make transitions back to lower-lying levels.
A *continuum spectrum* results when the gas pressures are higher. Generally, solids, liquids, or dense gases emit light at all wavelengths when heated.
An *absorption spectrum* occurs when light passes through a cold, dilute gas and atoms in the gas absorb at characteristic frequencies; since the re-emitted light is unlikely to be emitted in the same direction as the absorbed photon, this gives rise to dark lines (absence of light) in the spectrum.

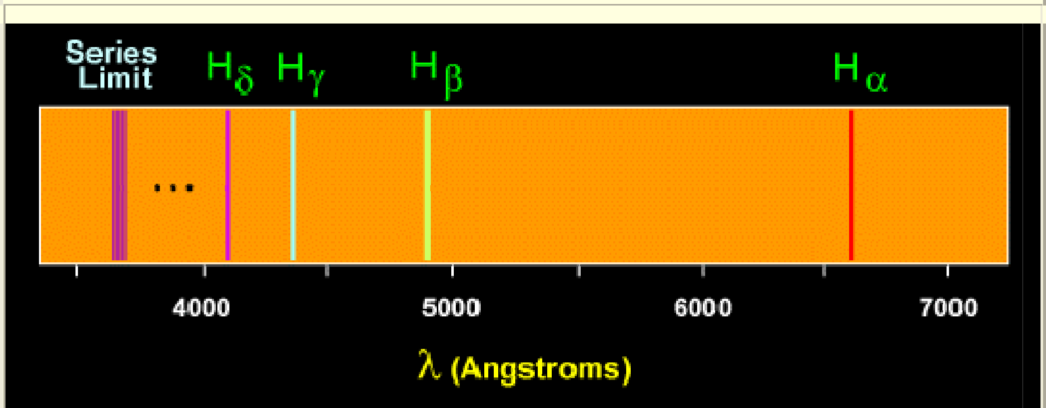
Hydrogen Emission and Absorption Series

The spectrum of hydrogen is particularly important in astronomy because most of the Universe is made of hydrogen. Emission or absorption processes in hydrogen give rise to *series*, which are sequences of lines corresponding to atomic transitions, each ending or beginning with the same atomic state in hydrogen. Thus, for example, the *Balmer Series* involves transitions starting (for absorption) or ending (for emission) with the first excited state of hydrogen, while the *Lyman Series* involves transitions that start or end with the ground state of hydrogen; the adjacent image illustrates the atomic transitions that produce these two series in emission.



Hydrogen emission series

Because of the details of hydrogen's atomic structure, the Balmer Series is in the visible spectrum and the Lyman Series is in the the UV. The following image illustrates some of the transitions in the Balmer series.



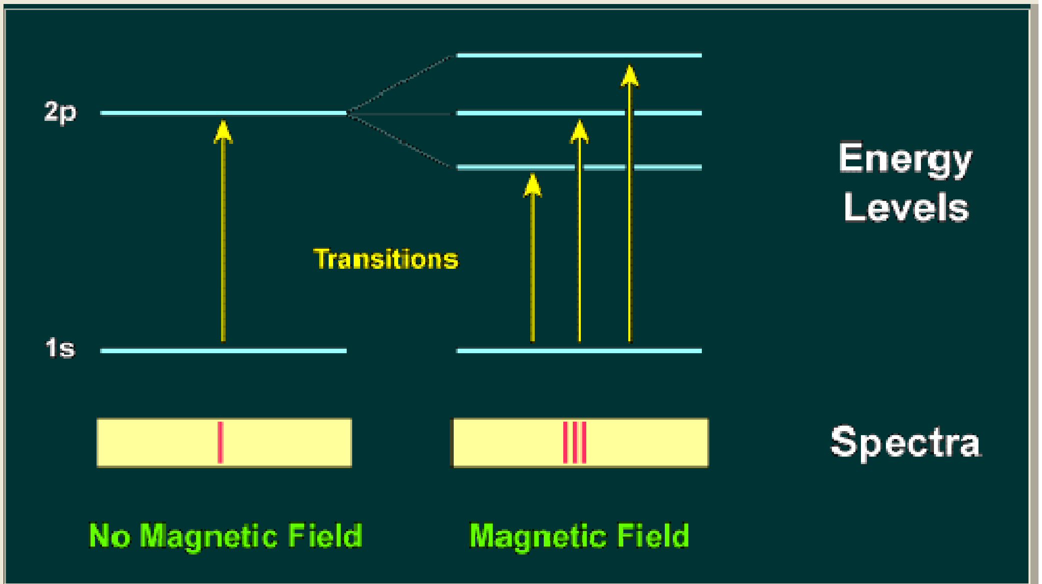
The Balmer spectrum of hydrogen

The Balmer lines are designated by H with a greek subscript in order of decreasing wavelength. Thus the longest wavelength Balmer transition is designated H with a subscript alpha, the second longest H with a subscript beta, and so on.

The atomic energy levels, the transitions between these levels, and the associated spectral lines discussed to this point have implicitly assumed that there are no magnetic fields influencing the atom. If there are magnetic fields present, the atomic energy levels are split into a larger number of levels and the spectral lines are also split. This splitting is called the *Zeeman Effect*.

Zeeman Spectral Splitting

The pattern and amount of splitting are a signature that a magnetic field is present, and of its strength. The splitting is associated with what is called the *orbital angular momentum quantum number* L of the atomic level. This quantum number can take non-negative integer values. The number of split levels in the magnetic field is 2 * L + 1. The following figure illustrates the Zeeman effect.



The Zeeman Effect

Atomic physicists use the abbreviation "s" for a level with L=0, "p" for L=1, and "d" for L=2, and so on (the reasons for these designations are of historical interest only). It is also common to precede this designation with the integer principle quantum number n. Thus, the designation "2p" means a level that has n=2 and L=1.

In the preceding example the lowest level is an "s" level, so it has L=0 and 2L + 1 = 0, so it isn't split in the magnetic field, while the first excited state has L=1 ("p" level), so it is split into 2L + 1 = 3 levels by the magnetic field. Thus, a single transition is split into 3 transitions by the magnetic field in this example.

The Zeeman effect can be interpreted in terms of the precession of the orbital angular momentum vector in the magnetic field, similar to the precession of the axis of a spinning top in a gravitational field.

Polarization of Spectral Lines

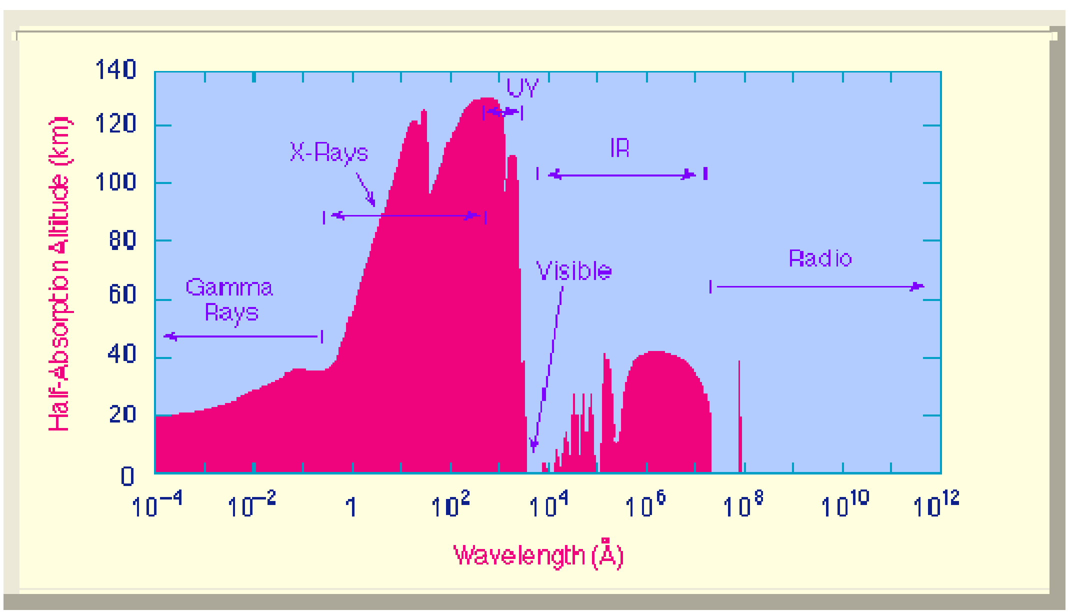
The lines corresponding to Zeeman splitting also exhibit *polarization effects*. Polarization has to do with the direction in which the electromagnetic fields are vibrating. This in turn, can have an effect on whether the spectral light can be observed. For example, polarizing sunglasses are often effective in suppressing ambiant glare because light reflected from surfaces has a particular polarization and polarizing sunglasses are designed to not pass that polarization of light.

One practical example in astronomy of such polarization effects is that in the preceding example the middle transition is polarized such that it cannot be easily be obverved from directly over a surface perpendicular to the magnetic field. As a consequence, when looking directly down on a sunspot (which have strong magnetic fields) typically only two of the three transitions shown above can be seen and the line is observed to split into two rather than three lines (the missing transition could be observed from a different angle where its light would not be suppressed by the polarization effect, but it is very weak when observed from directly overhead).

In addition to spectra associated with atoms and ions, molecules can interact with electromagnetic radiation and give rise to characteristic spectra. Because of basic atomic and molecular structure, the spectra associated with molecules typically involve infrared wavelengths. In addition, because molecules are usually fragile, molecular spectra are important mostly in objects that are relatively cool such as planetary atmospheres, the surfaces of very cool stars, and various interstellar regions.

One important practical consequence of the interaction of electromagnetic radiation with matter and of the detailed composition of our atmosphere is that only light in certain wavelength regions can penetrate the atmosphere well. These regions are called *atmospheric windows*.

The following figure shows the amount of absorption at different wavelengths in the atmosphere. It is presented in terms of the *half-absorption altitude*, which is defined to be the altitude in the atmosphere (measured from the Earth's surface) where 1/2 of the radiation of a given wavelength incident on the upper atmosphere has been absorbed. Windows correspond to those regions where the half-absorption altitude is very small.



The dominant windows in the atmosphere are seen to be in the visible and radio frequency regions, while X-Rays and UV are seen to be very strongly absorbed and Gamma Rays and IR are somewhat less strongly absorbed. We see clearly the argument for getting above the atmosphere with detectors on space-borne platforms in order to observe at wavelengths other than the visible and RF regions.

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