Production of Sunlight and Chemical Spectroscopy

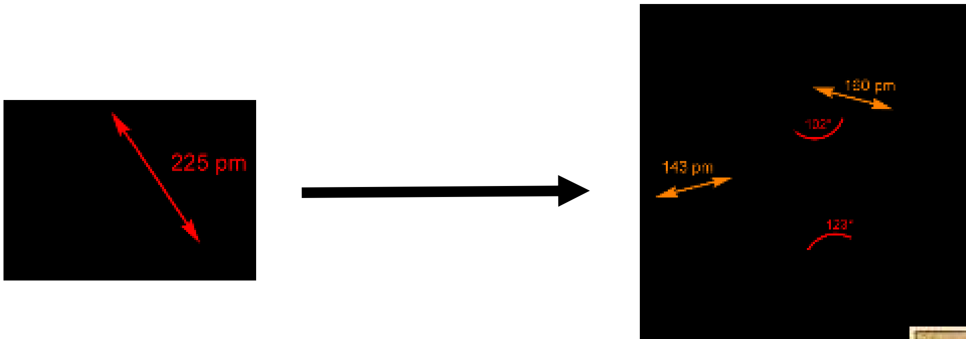
There is a close relationship between chemistry and light. **Phosphorus** is a chemical that can produce light. **Hennig Brand** in 1669 was an **alchemist** who thought that he might find the **Philosopher's Stone** (*lapis philosophorum*) or the secret for converting base or ignoble metals into gold in human urine. Perhaps he was inspired by urine's golden color (produced by urobilin, a breakdown product of heme). In the process of isolating different chemicals in the urine, probably at night, he serendipitously discovered a chemical that was capable of producing light. Consequently, he named the chemical **phosphorus**, meaning **light bearer**, from the Greek *Φωσφόρος*.

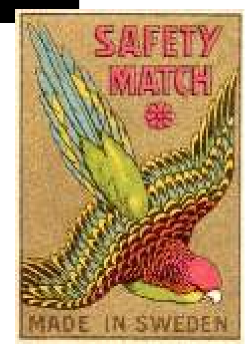
Nothing Gold Can Stay by Robert Frost

Nature's first green is gold,
Her hardest hue to hold.
Her early leaf's a flower;
But only so an hour.
Then leaf subsides to leaf.
So Eden sank to grief,
So dawn goes down to day.
Nothing gold can stay.

We now know that phosphorus in the form of pure white tetrahedral phosphorus (P_4) ignites spontaneously in the presence of oxygen to form phosphorus oxide, transforming chemical energy into radiant energy (light) in the process. The rearrangement of bonds results from the rearrangement of **electrons**.

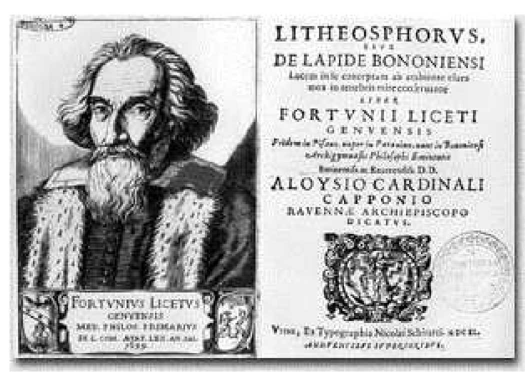
$$P_4 + 5O_2 \rightarrow P_4O_{10}$$





White phosphorus, which can be explosive, can be exposed to sunlight or heated to produce a ***polymerized form*** of phosphorus known as **red phosphorus**, which is more stable. Red phosphorus only gives off light when it is excited by friction (triboluminescence). For this reason, red phosphorus is used to produce **safety matches**.

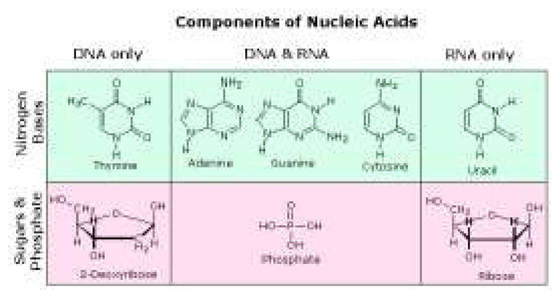
A light-emitting chemical reaction is known as **chemiluminescence**. Phosphorus is not phosphorescent, as it is defined today. **Phosphorescence**, which was named after phosphorus, is defined today as a **delayed re-emission of light that has already been absorbed**. Chemiluminescent substances, such as white phosphorus, do ***not*** require pre-illumination to glow whereas phosphorescent substances, such as the **Bologna Stone**, by contrast, do.



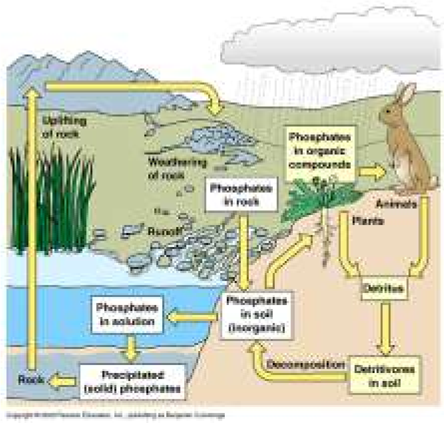
The **Bologna Stone**, or litheosphorus had recently been discovered in Bologna by Vincenzo Casciarolo in his search for the Philosopher's Stone. Casciarolo (1640) wrote in *Litheosphorus*, "*that the stone was most suitable for the production of gold by virtue of its notable weight and content of sulphur. After submitting the stone to much preparation, it was not the Pluto of Aristophanes that resulted; instead, it was the*

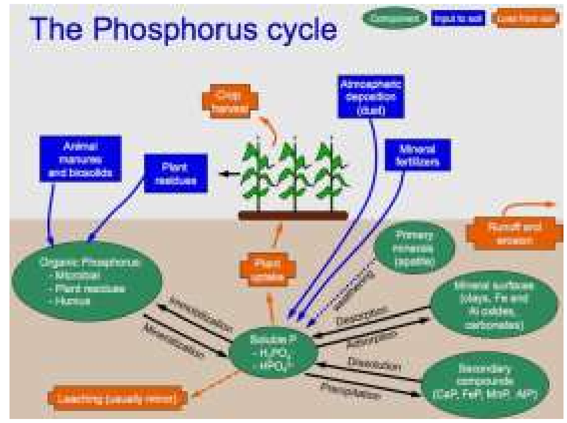
Luciferous Stone, which would not itself produce gold, ***but which would absorb the golden light of the sun, like a new Prometheus stealing a Celestial Treasure****."* The Bologna Stone was later found to be composed of barium sulfate.

The phosphorous first isolated by Hennig Brand was, as we now know, of humble human origin. **Johann Kunckel** (1676) also figured out how to produce phosphorus from urine. It was a difficult process and Kunckel reasoned that anything that comes out of the human body (at a rate of 1.4 g P/day) must also go in. Consequently, he found that many foods of animal and plant origin, when heated in a furnace, produced phosphorous. Kunckel was able to turn phosphorus into gold in that he got rich performing spectacular shows for the nobility with the phosphorus he had created. He also sold phosphorus for medicinal purposes. Indeed, **phosphorus is essential for life** as we know it as it is a constituent of all **nucleic acids**, including DNA, RNA, ATP, and the cGMP involved in vision.

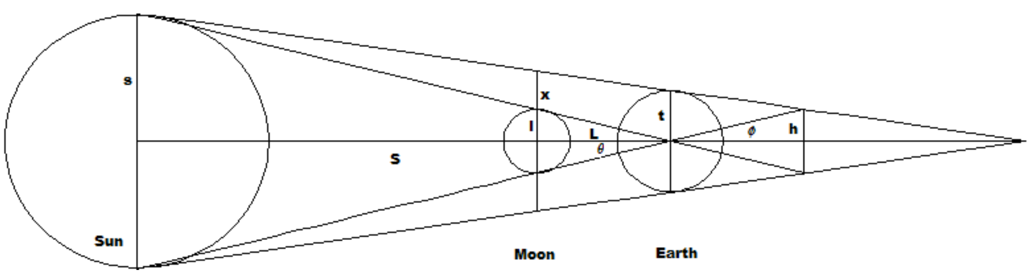


The phosphorus on earth, which was originally **produced in first generation stars**, circulates in the lithosphere (the rocky crust of the earth), the hydrosphere (the water on the surface of the earth), and the biosphere (the living organisms on earth).

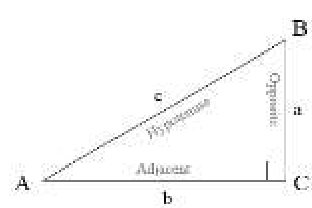




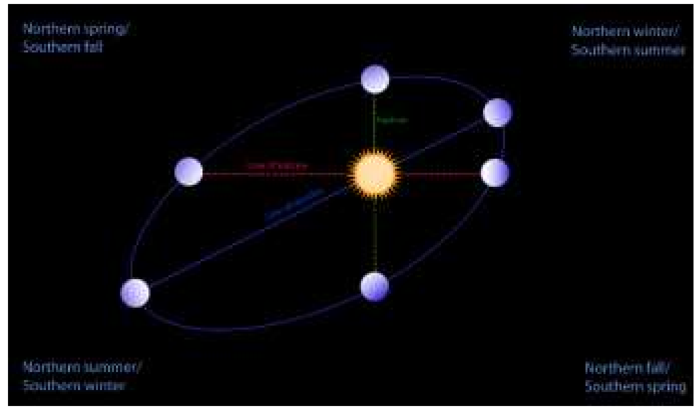
We are now going to discuss the **cause of sunlight**, but before we do, we have to understand a few facts about the sun, such as the **distance** between the sun and the earth and the **diameter** of the sun, so that we can make reasonable inferences about the cause of sunlight. **Hipparchus** (190-120 BC) estimated the mean **distance** from the earth to the sun by making measurements of the angles the edge of sun could be seen from different places on earth during a solar eclipse and used **trigonometry** to analyze the angles and lengths.



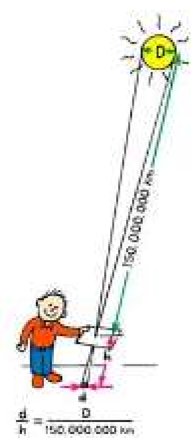
Trigonometry (from the Greek for measuring triangles (τρίγωνο)) was invented by Euclid and Archimedes in the third century BC and Hipparchus used it in the second century BC as a way of simplifying the application of **geometry** (from the Greek for measuring the earth (**γεω**)) to astronomy.



Today the **average** distance between the sun and the earth is defined as approximately **1.5×10^{11} m** (which is a distance of approximately **8.3 light-minutes**, given that the speed of light in the vacuum of space is about 3×10^8 m/s). This means that it takes sunlight approximately eight minutes to reach the earth and that we see the sun where it was eight minutes ago. The distance 1.5×10^{11} m from the earth to the sun is known as 1 **astronomical unit** (au). The astronomical unit is defined as "*the radius of an unperturbed circular Newtonian orbit about the sun of a particle having infinitesimal mass, moving with a mean motion of 0.01720209895 radians per day*."



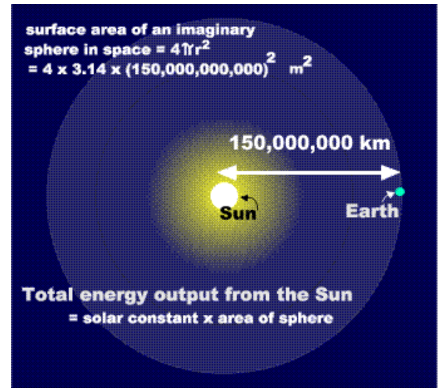
The **diameter of the sun** can be estimated using a **pinhole**. The pinhole will form an image of the sun on a piece of paper. The size of the image will depend on the distance between the image and the pinhole. Use a ruler to measure the diameter of the image (y_i) of the sun and the distance between the pinhole and the image (s_i). Using 1.5×10^{11} m as the distance to the sun (s_o), calculate the diameter of the sun (y_o) using the following formula based on the assumption that vertical angles are equal:



$$\frac{y_o}{y_i} = -\frac{s_o}{s_i}$$

The **diameter** of the sun is about **1.39×10^9 m**; the radius is **0.7×10^9 m**.

We can measure the **luminosity** of the sun, which is the rate at which the sun is radiating energy, by measuring the **intensity** of sunlight at the earth's surface (I_{earth}), which is a distance r from the sun and, by assuming the sun to be a point source of light. We can then use the inverse square law to determine the power of the source (S, as we did in the second lecture) and the luminosity of the sun (L_{sun}, in Watts = Joules/second):

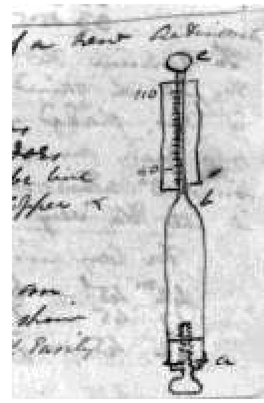


$$I_{earth} = \frac{L_{sun}}{4\pi r^2}$$

The average intensity of sunlight at the earth's surface is known as the **solar constant**, and was first measured by **Claude Pouillet** in 1838 using a **pyrheliometer**, which at the time was a thermometer with a blackened bulb at the end of a tube. He moved the tube with the blackened bulb from the shade to the sun and measured the new temperature. The light intensity was calculated from the difference between the temperature of the thermometer in the sunlight and the thermometer that was kept in the dark. Pouillet determined the solar constant to be 1.228×10^3 W/m^2.

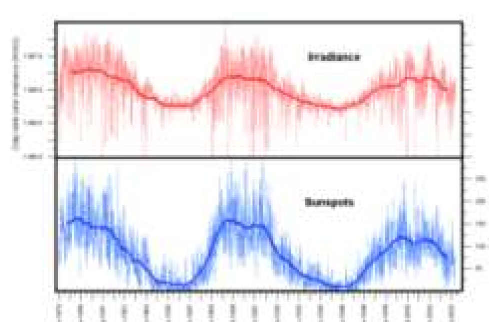
After traveling through the Alpine pass between France and Italy in 1824, **John Herschel**, William Herschel's son, got a sunburn, and unlike most others who get sunburned, he decided to design an instrument to measure the intensity of the sun. He wrote "*...the scorching effect of the Sun's rays upon every exposed part of the skin proved so severe as to excite in my mind a lively desire to subject to some precise means of measurement the cause of so disagreeable an effect.*" He

developed an **actinometer** that was in essence a thermometer placed in water in which black ink was dissolved to measure the light intensity. The light intensity was calculated from the difference between the temperature of the thermometer in the sunlight and in the shade. Herschel determined the solar constant to be 1.004 × 10^3 W/m^2.



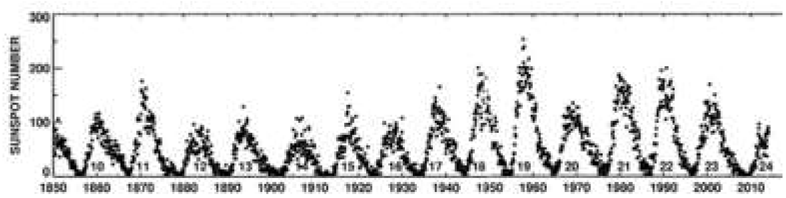
The **solar constant** is currently measured by satellite above the earth's atmosphere to be about **1.36 × 10^3 W/m^2**. The actual solar intensity on earth varies with latitude due to the tilt of the earth. It also varies at a given spot on earth during the day due to the rotation of the earth and during the year due to the ellipticity of the earth's orbit. The solar constant in ***not constant*** but represents an average of these intensities in time and space. Moreover, the actual solar intensity on earth has varied historically since the tilt of the earth, the rotation of the earth and the ellipticity and precession of the earth's orbit change slowly over time. **Milutin Milanković** (1920) took into consideration such changes and proposed that there were long term cycles that affected the value of the solar intensity at a given spot on earth. The solar constant, which characterizes the greatest and most important source of energy available on earth, does not represent a static system, but the changing relationship between sun and the earth.

The solar constant also depends on changes in the physical processes that go on in the sun. The solar constant varies about **0.1%** cyclically with an eleven year period that is correlated with sunspots, which are regions that are cooler than the rest of the sun. Faculae, which are associated with the sunspots are regions that are warmer than the rest of the sun. Since the greater intensity of faculae more than compensates for the lesser intensity

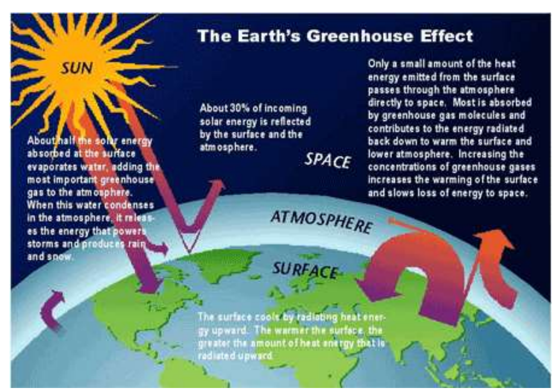


of the sun spots, the magnitude of the solar constant is correlated with the number of sunspots.

The sun is a **plasma** composed of rapidly moving charged particles that generate magnetic fields. The 11 year sunspot cycle is also correlated with an increased flux of charged particles known as the solar wind as well as with an increased magnetic field whose polarity reverses with a 22 year cycle. This magnetic field deflects cosmic rays from striking the earth.



William Herschel (1801) realized that there was variability in the appearance of the sun and wrote "*The influence of this eminent body, on the globe we inhabit, is so great, and so widely diffused, that it becomes almost a duty for us to study the operations which are carried on upon the solar surface.* ***Since light and heat are so essential to our well-being, it must certainly be right for us to look into the source from whence they are derived, in order to see whether some material advantage may not be drawn from a thorough acquaintance with the causes from which they originate…..****We are not only in possession of photometers and thermometers, by which we can measure from time to time the light and heat actually received from the sun, but have more especially telescopes, that may lead us to a discovery of the causes which dispose the sun to emit more or less copiously the rays which occasion either of them. And, if we should even fail in this respect, we may at least succeed in becoming acquainted with certain symptoms or indications, from which some judgment*

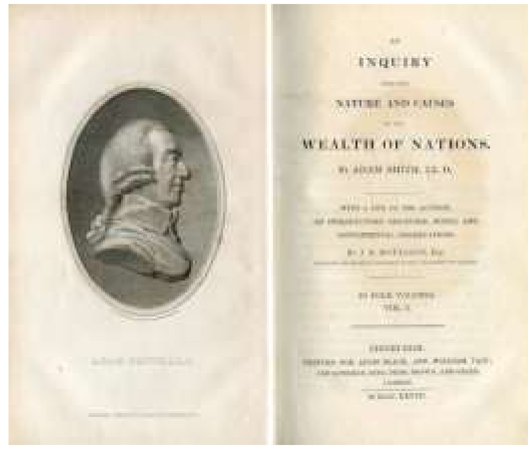


might be formed of the temperature of the seasons we are likely to have." William Herschel made the first attempt to relate the appearance and disappearance of sunspots to the temperature of the earth. He could not measure the intensity of light and heat everywhere and all the factors that control the temperature of the earth, such as the CO_2 concentration in the atmosphere, but his thinking is ingenious and worth knowing.

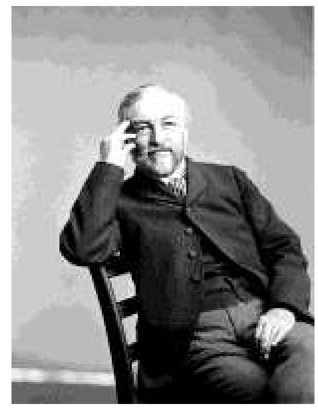
William Herschel (1801) wrote "*With regard to the contemporary severity and mildness of the seasons, it will hardly be necessary to remark, that nothing decisive can be obtained. But, if we are deficient here, an indirect source of information is opened to us, by applying to the influence of sun-beams on the vegetation of wheat in this country. I do not mean to say, that this is a real criterion of the quantity of light and heat emanated from the sun; much less will the price of this article completely represent the scarcity or abundance of the absolute produce of the country. For the price of commodities will certainly be regulated by the demand for them; and this we know is liable to be affected by many fortuitous circumstances. However, although an argument drawn from a well ascertained price of wheat, may not apply directly to our present purpose, yet, admitting the sun to be the ultimate fountain of fertility, this subject may deserve a short investigation, especially as, for want of proper thermometrical observations, no other method is left for our choice."*

"Our historical account of the disappearance of the spots in the sun, contains five very irregular and very unequal periods. The first takes in a series of 21 years, from 1650 to 1670, both included. But it is so imperfectly recorded, that it is hardly safe to draw any conclusions from it; for we have only a few observations of one or two spots that were seen in all that time, and those were only observed for a short continuance. However, on examining the table of prices

of the quarter of nine bushels of the best or highest prices wheat at Windsor, marked in ***Dr. Adam Smith's valuable Inquiry into the nature and causes of the wealth of nations****, we find that wheat, during the time of the 21 years above mentioned, bore a very high price; the average of the quarter being £2, 10s.* $5\frac{19}{21}$ *d. This period is much too long compare it with a*



preceding or following one of equal duration. Besides, no particulars having been given of the time preceding, except that spots in the sun, a good while before, began to grow very scarce. There might be even fewer of them from the year 1650 to 1670. Of the 21 years immediately following, we know that they certainly comprehend two short periods, in which there were no spots on the sun; of these, more will be said hereafter; but, including even them, we have the average price of wheat, from 1671 to 1691, only £2, 4s. $4\frac{2}{3}$ *d. The quarter. The difference, which is a little more than 9 to 8, is therefore still a proof of a temporary scarcity….The result of this review of the foregoing five periods is, that, from the price of wheat, it seems probable that some temporary scarcity or defect of vegetation has generally taken place, when the sun has been without those appearances which we surmise to be symptoms of a copious emission of light and heat. In order, however, to make this an argument in favor of our hypothesis, even if the reality of a defective vegetation of grain were sufficiently established by its enhanced price. It would still be necessary to shew that a deficiency of the solar beams had been the occasion of it. Now, those who are acquainted with agriculture may remark, that wheat is well known to grow in climates much colder than ours; and that a proper distribution of rain and dry weather, with many other circumstances which it will not be necessary to mention, are probably of much greater consequence that the* *absolute quantity of light and heat derived from the sun. To this I shall only suggest, by way of answer, that those very circumstances of proper alternations of rain, dry weather, winds, or whatever else may contribute to favour vegetation in this climate, may possibly depend on a certain quantity of sun-beams, transmitted to us at proper times; but, this being a point which can only be ascertained by future observations, I forbear entering farther into a discussion of it.*"



The **luminosity** or the rate in which the sun radiates energy at the sun's surface (L_{sun}) is given by $I_{earth}4\pi r^2$, where I_{earth} is the measured intensity on earth and r is the distance between the sun and the earth. The luminosity is equal to about **3.8 × 10^26 W**. A Watt equals a Joule/second. The **luminosity** is given in **Watts** while the **intensity**, which is the **rate the sun radiates energy per unit area** is given in Watts per meter squared. The **spectral distribution** of sunlight (intensity vs. **wavelength**) was first measured quantitatively under the Allegheny sky by **Samuel Pierpont Langley** in 1881.

				mm.					
λ = .00035	.0004	.0005	.0006	.0007	.0008	.0009	.0010	.0011	
				div.					
Defl.	12	55	207	246	198	129	80	58	41

Langley became the third **Secretary of the Smithsonian Institution** in 1887 and founder of the Smithsonian Astrophysical Observatory in 1890, which initially did research on solar radiation and the solar constant. Former Cornell University President Skorton is currently the thirteenth Secretary of the Smithsonian Institution.

Modern measurements above the atmosphere give the following somewhat **continuous spectral distribution**:

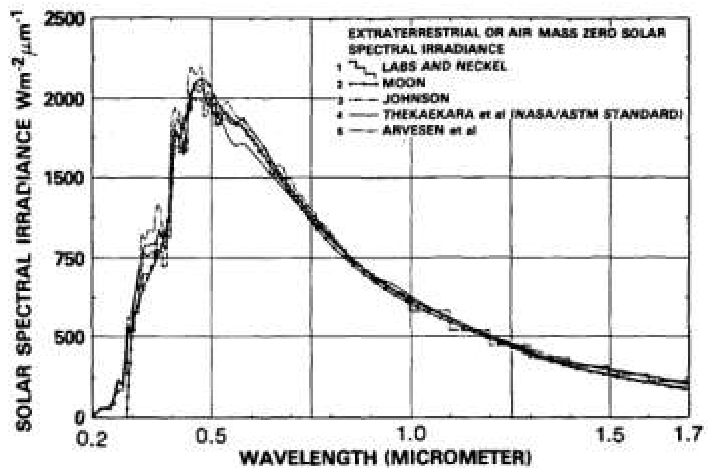


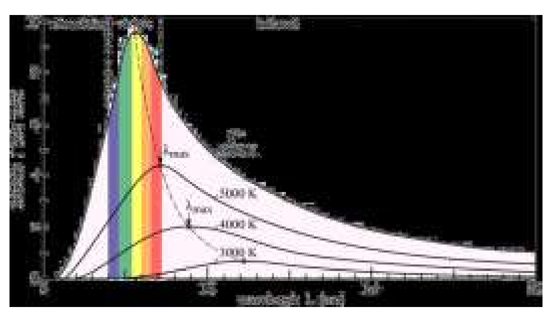
Figure 1. Solar Spectral Irradiance Outside the Atmosphere, 0.2 μm - 1.7 μm reported by: 1. Labs and Neckel, 2. P. Moon, 3. F.S. Johnson, 4. Thekaekara et al (NASA/ASTM Standard), 5. Arvesen et al.

The **temperature (*T*) of the surface of the sun**, which is **5778 K** can be estimated from either the luminosity of the sun ($I_{earth} = \frac{L_{sun}}{4\pi r^2}$) using the **Stefan-Boltzmann law**:

$$L_{sun} = 4\pi r^2 \sigma T^4$$

where σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^4), or from the continuous spectral distribution produced by a "hot" **incandescent body** using **Max Planck's blackbody radiation law**:

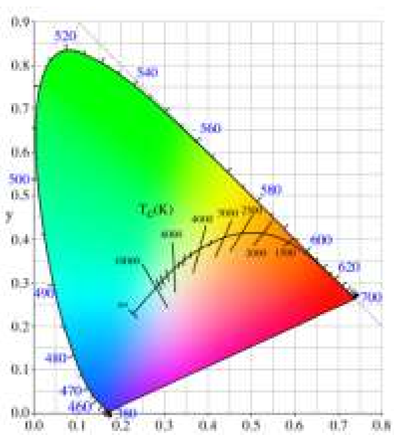
$$I(\lambda) = \frac{2\pi hc^2}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)}$$

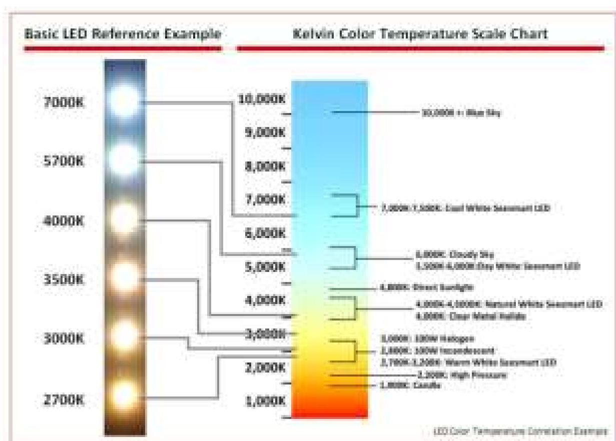


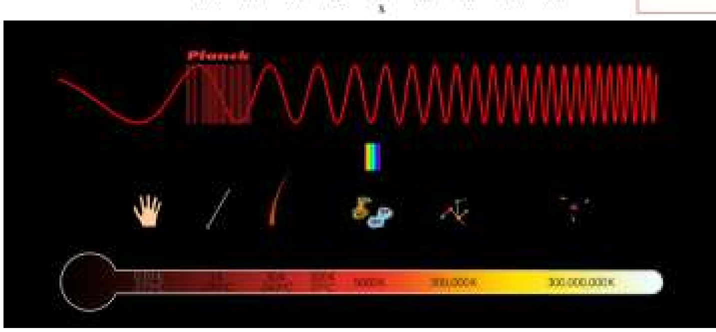
where λ (in m) is the wavelength of light, k is the Boltzmann constant (k = 1.38 × 10^{-23} J/K), c is the speed of light (c = 2.99 x 10^8 m/s) and h is Planck's constant ($h = 6.626 \times 10^{-34}$ J s). The peak for the sun is in the yellow part of the spectrum which is why the sun looks yellow. The Stefan-Boltzmann Planck radiation laws were derived, in part, from measuring the intensity and color of radiated light from bodies of different temperatures (for example, **pottery in the kilns of Josiah and Thomas Wedgwood**). Josiah Wedgwood was an abolitionist and the grandfather of both Charles Darwin and of his wife, Emma.



The commonly-observed relationship between the color (Peak wavelength) and the temperature of a body are presented in various ways in the following figures:







The sun is a **star** and the relationship between the luminosity of a star and its temperature or spectral color class can be shown in a **Hertzsprung-Russell diagram**. $L/L_{\odot}$ is the ratio of the luminosity of a star to the luminosity of the sun. After the stars are assembled using gravitational energy, they spend most of their life on the main sequence (MS). The hot and luminous stars are in the upper left of the main sequence and the cool dim stars are on the bottom right. At the end of a star's life, it develops into a red giant and then into a white dwarf. The cool and brilliant red giants and hot and dim white dwarfs are shown above and below the main sequence, respectively. A star evolves onto a given place in the main sequence depending on the **initial mass** of the clump formed in a given nebula to form a **protostar**.

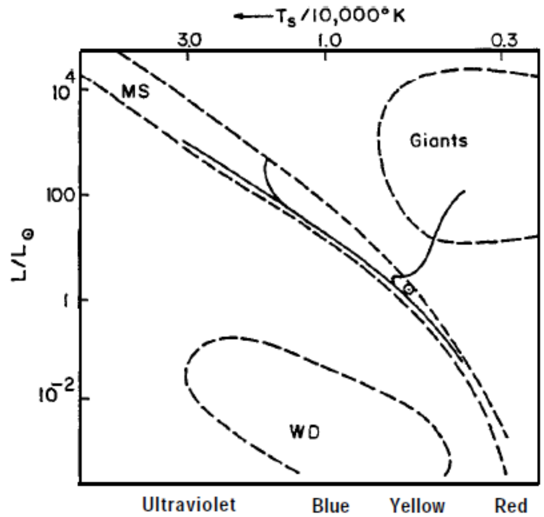


Fig.1. Hertzsprung-Russell diagram. From E.E.Salpeter, in *Apollo and the Universe*, Science Foundation for Physics, University of Sydney, Australia, 1967.

The **luminosity** of a star depends on its **mass**, which is a measure of the gravitational energy of the star and the fuel it has to burn. $M/M_{\odot}$ is the ratio of the mass of a star to the mass of the sun. The solar mass is calculated from the orbits of the planets using **Newton's Law of Universal Gravitation** and the stellar masses can be calculated from the orbits of binary stars.

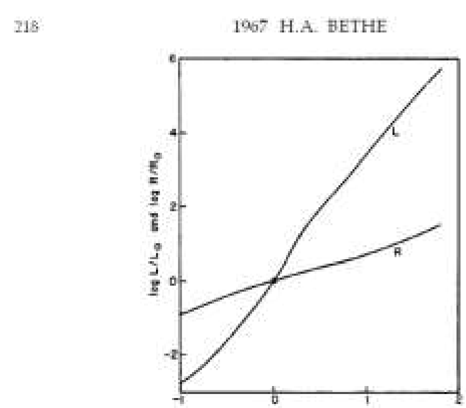
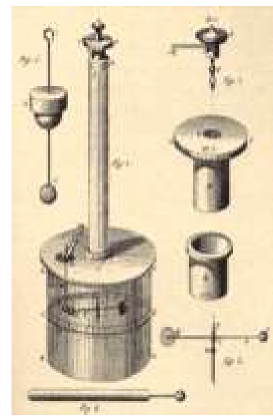


Fig. 2 Luminosity and radius of stars vs. mass. Abscissa is *log* $M/M_{\odot}$. Data from C. W. Allen, *Astrophysical Quantities*, Athlone Press, 1963, p. 203. The curve for log $L/L_{\odot}$ holds for all stars, that for $R/R_{\odot}$ only for the stars in the main sequence. The symbol $\odot$ refers to the sun.

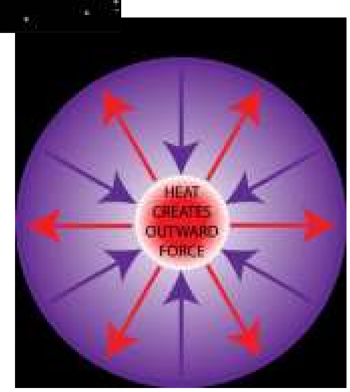
The **most luminous** stars on the main sequence have the **greatest masses** (150 M_{sun}) and the least luminous stars on the main sequence have the smallest masses (0.08 M_{sun}, which is the ***minimal mass*** needed to ignite nuclear reactions).

The mass of the sun (M_{sun}) can be estimated from Newton's Law of Universal Gravitation and Newton's Second Law:

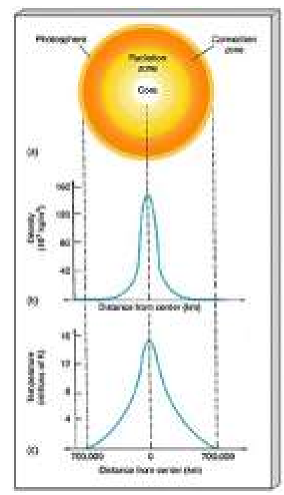
$$mg = G\frac{M_{sun}m}{r^2} = \frac{mv^2}{r} \qquad\qquad M_{sun} = \frac{rv^2}{G}$$



where g (in m s^{-2}) is the acceleration at which a planet with mass m is falling into the sun, G is the gravitational constant measured by Henry Cavendish in 1798 using the torsion balance and is equal to 6.67×10^{-11} $m^3\ kg^{-1}\ s^{-2}$, and r is the distance between a planet and the sun. The velocity (v) of a planet is equal to the ratio of the circumference ($2\pi r$) of the orbit to its period. The acceleration is equal to the velocity squared divided by the radius of the orbit ($g = \frac{v^2}{r}$). From studying the orbits of the planets in the solar system around the sun, the **mass** of the sun has been determined to be **1.99×10^{30} kg**, which is about 300,000 times more massive than the earth.



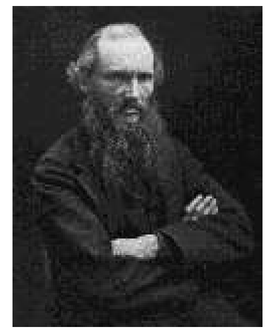
If we plug in the **radius of the sun for *r***, we get the gravitational force per unit mass upon any body at the **surface of the sun**. This gravitational force is so large that it could cause the gravitational collapse of the sun such that the sun would become approximately a point in approximately 30 minutes. The fact that the radius of the sun seems to be **constant** indicates that the gravitational force must be **transformed into an opposing force** when it acts on the sun itself. Indeed it is, the compression of the sun itself results in the production of heat inside the sun. The heat causes the **dissociation of the electrons** from the nuclei of atoms forming a **plasma**. The heat also causes the ionized nuclei and electrons to move very fast and act like an **expanding gas** that exerts a **pressure** that **balances the gravitational force**. As a consequence of the hydrostatic equilibrium, the **radius of the sun remains constant**. **Radiation pressure**, which is pressure due to the force exerted by light itself, also contributes, along with gas pressure, to balance the pressure due to gravitational contractions. The **average density** of the sun is estimated from its **mass** and **volume** ($V = \frac{4}{3}\pi r^3$) to be approximately **1.4 g/cc** and the density in the center which has to balance all of the gravitational force is approximately 150 g/cc. The density of water is approximately 1 g/cc. Although we have never sampled the inside of the sun directly, we just used the laws of nature and a little algebra to give us an idea of the internal conditions of the sun.



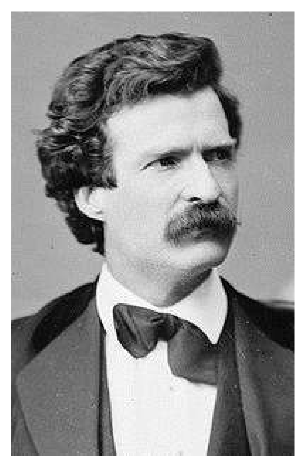
Hermann von Helmholtz (1856) proposed that **gravitational contraction** is the cause of the energy radiated by the sun. The gravitational energy (in Joules) of a spherical sun is related to the gravitational force per radial distance and is given by the following equation.

$$E_{gravitational} = -\frac{3GM_{sun}^2}{5r}$$

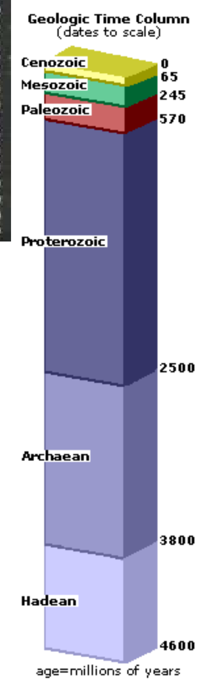
The ratio of the **gravitational energy (2.3×10^{41} J)** to the **luminosity** (**3.8×10^{26} W** = J/s) gives an estimate of the **time** in seconds that it would take to radiate the observed energy if the gravitational contraction served as the only source of energy. The ratio tells us that, if the conversion of gravitational energy into heat was the only source of energy in the sun, then **the age of the sun** would be about **20 million years**, which seemed reasonable in 1856. This would also give an estimate of the age of a habitable earth that depended on the light and heat of the sun. However, in **1859**, when **Charles Darwin** calculated the age of the earth to be greater than 300 million years, from the time it would take for erosion to denude the Weald, 20 million years seemed too short for the age of the sun. An old earth would be consistent with the **gradual origin of species by natural selection**. William Thomson, the **greatest living scientific authority** at the time, who later became **Lord Kelvin**, argued against Darwin. According to Thomson (1862), the sun, which is necessary for life on earth, and which derived its energy from gravity, could not have provided the needed sunlight for 300 million years of evolution by natural selection.



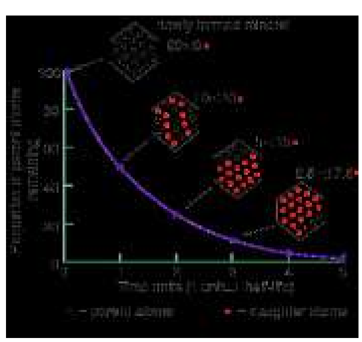
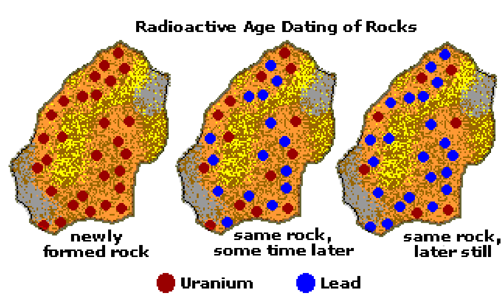
Mark Twain satirized the situation, and wrote, "*Some of the great scientists, carefully ciphering the evidences furnished by geology, have arrived at the conviction that our world is prodigiously old, and they may be right but Lord Kelvin is not of their opinion. He takes the cautious, conservative view, in order to be on the safe side, and feels sure it is not so old as they think. As Lord Kelvin is the* ***highest authority in science*** *now living, I think we must yield to him and accept his views.*"



William Thomson could not have **foreseen** the possibility of thermonuclear transformation of nuclear mass into energy to produce sunlight as the temperature of the sun stayed constant.



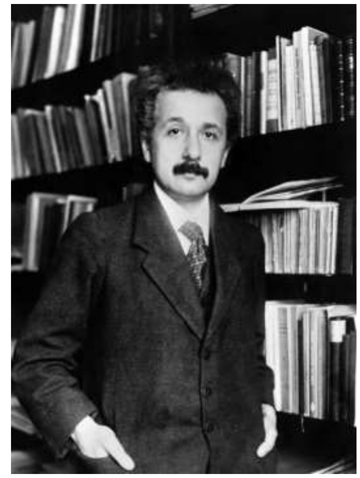
Henri Becquerel (1896), who was interested in the **phosphorescence** of **uranium**, **serendipitously** discovered **radioactivity**, which was due to the emission of electrons, when he noticed that uranium produced an **image** of itself on photographic film it have been resting on in the **dark**. Radioactive elements are transformed into other elements during **radioactive decay** by **fission**, named after bacterial fission. Rutherford called the study of radioactive decay "***the new alchemy***" since radioactive decay resulted in the **transmutation of elements** for example uranium into lead. By measuring the ratio of the radioactive parent element to the stable element it transforms into in various ancient rocks, **Ernest Rutherford** and **Frederick Soddy** estimated the age of the earth. Current radiometric dating estimates the **age of the earth to be approximately 4.54 billion years old**.

Sometimes the greatest living scientific authority is *not* right. Frederick Soddy (1904) described the hullabaloo between **Lord Kelvin**, the physicist and **Charles Darwin**, the biologist concerning the age of the earth like so: "*Throughout the latter part of the last century a **controversy**, as to the possible age of the earth as a planet fitted for habitation, existed between two schools, represented by the physicists on the one side and the biologists on the other. Some of the arguments advanced by the former make strange reading at the present time.*"

In 1898, **Marie Curie**, who coined the term **radioactivity**, and her husband **Pierre Curie** isolated from uranium-rich pitchblende, polonium, named after Marie Curie's native country and **radium**, from the Latin word *radius*, which means ray. In 1903, Pierre Curie noticed that radium released heat but ***unlike*** other thermal processes (e.g. the radiation of heat by an iron rod), the radium did not cool down to the temperature of its surroundings. **Ernest Rutherford** and **Frederick Soddy** as well as **William Wilson**, **John Joly** and **George Darwin**, one of Charles Darwin's sons, all proposed in 1903 that **radioactivity** might be the source of the sun's radiated energy. However, a study of the chemical composition of the sun revealed that the sun was composed primarily of hydrogen and helium and that there were little or no heavy radioactive chemicals in the sun.

In 1905, **Albert Einstein** proposed that mass is related to energy by the famous equation:

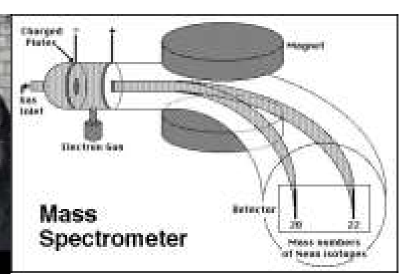


$$E = mc^2$$

In a paper entitled, *Does the inertia of a body depend upon its energy content*?, Einstein realized that because the speed of light c is so large (3×10^8 m/s) his equation meant that a **tiny bit of mass** could be transformed into an **enormous amount of energy**. He also realized that his theory could be tested with radium salts, since the emission of **energy** by radium may be correlated with a decrease in its **mass**.

Could Einstein's equation apply to **thermonuclear fusion** as well as nuclear fission? Could the source of the sun's energy be **thermonuclear fusion** as opposed to nuclear fission? **Thermonuclear fusion** results when protons, the charged nuclei of hydrogen atoms, smash into each other to form a deuteron. Under **ambient temperatures**, protons do not smash into each other because their **electric charge repels** them from other protons. However, by heating the protons to millions of degrees Kelvin, they would have enough **kinetic energy** to overcome the **electrostatic barrier** and could smash into each other.

Using a **mass spectrograph** that separates atoms and molecules according to their mass just as a spectrograph separates light according to its wavelengths, **Francis Aston** (1920) **serendipitously** discovered that one helium nucleus (with an atomic mass of 3.99 Daltons) has less mass than 4 hydrogen



nuclei, each with an atomic mass of 1.008 Daltons. Aston, who was actually interested in looking for isotopes of neon, realized that the difference in mass between four hydrogen atoms and one helium atom is a source of a tremendous amount of energy.

Aston's experimental results gave the following masses for hydrogen and helium:

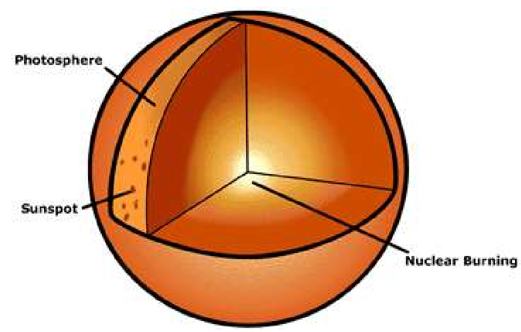
mass of 1 proton (p)	1.67358×10^{-27} kg
mass of 4 protons (4p)	6.6943×10^{-27} kg
mass of helium nucleus (He)	6.6466×10^{-27} kg
difference (4p – He)	0.0477×10^{-27} kg

Arthur Eddington suggested in his presidential address at the 1920 meeting of the British Association for the Advancement of Science that Aston's measurement of the 0.7% mass difference between four hydrogen atoms and one helium atom meant that, if the sun derived its energy from **thermonuclear fusion**, the sun could shine for billions of years by converting hydrogen atoms to helium.

Applying Einstein's equation to the mass deficiency, we see that each fusion of **four hydrogen nuclei** (protons) into a **helium nucleus**, also known as an **alpha particle**, could result in 4.3×10^{-12} J.

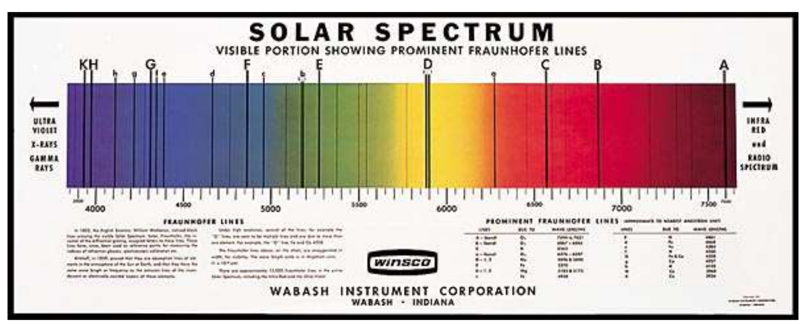
$$E = 0.0477 \times 10^{-27}\ \text{kg}\ (3 \times 10^{8}\ \text{m/s})^2 = 4.3 \times 10^{-12}\ \text{J}$$

In order for fusion to yield the observed **luminosity** of 3.8×10^{26} W, 8.8×10^{37} helium nuclei would have to be formed from four hydrogen nuclei per second. This means that only 5.9×10^{11} kg, which is a trivial proportion of the sun's mass (1.99×10^{30} kg), would have to be burned per second and the sun would burn for billions of years. The enormous amount of energy released from the **nuclear burning** of hydrogen into helium is nearly twenty million times ***greater*** than the amount of energy released by the **electron burning** of the same mass of hydrocarbon into carbon dioxide and water.



The sun, like most stars is composed of hot gas that radiates energy into space. Heat always moves from hotter regions to cooler regions, and, consequently, in the sun, the energy that is radiated from the **cooler surface** must come from a **hotter core** where it is generated. Charged particles as well as energy produced in the core also move to the surface where they are emitted.

Spectroscopic studies carried out during the 19th century showed that the sun was composed primarily of **hydrogen** (71%) and **helium** (27.1%), which was named after the sun (*Helios*) where it was first discovered. Oxygen (0.97%), carbon (0.4%), nitrogen (0.096%), silicon (0.099%), magnesium (0.0765), neon (0.058%), iron (0.14%), sulfur (0.04%) and a small amount of phosphorus make up the rest of the sun's mass.



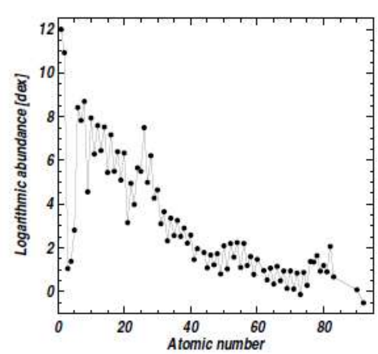
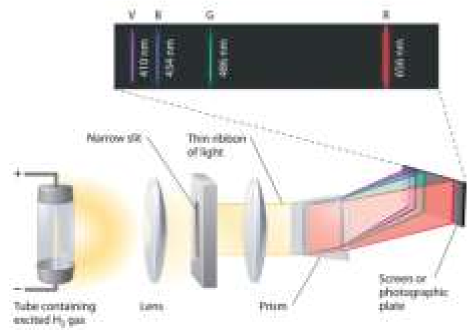


Figure 4: The present-day solar photospheric elemental abundances as a function of atomic number. As throughout this article, the logarithmic abundance of hydrogen is defined to be $\log \epsilon_H = 12.0$.

The elements in the sun's atmosphere are identified by **Fraunhöfer lines**, which are dark lines in the **continuous blackbody spectrum** produced by a hot glowing or **incandescent body**. The dark lines are formed because each element in the sun's atmosphere absorbs certain wavelengths and re-emits them in all directions resulting in less light of those wavelengths coming to the earth. The darker the line, the greater is the abundance of the element that causes the line.

Demonstration: Observe the spectral lines of hydrogen with your spectroscopes.

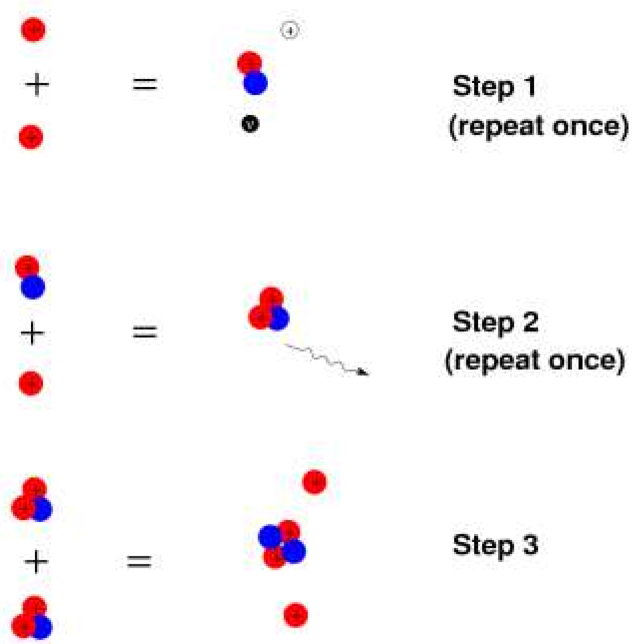
(a)



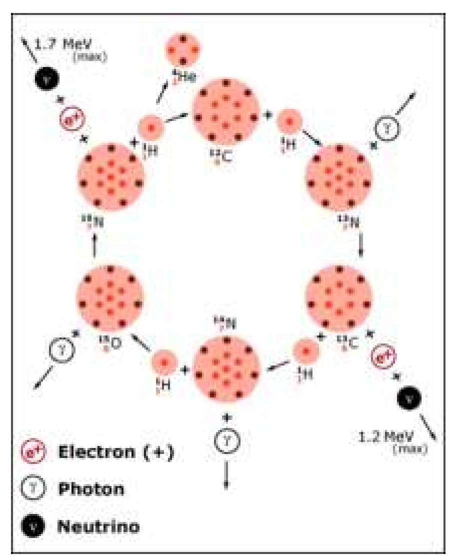
(b)

In 1938, **George Gamow** brought together astrophysicists and physicists at a meeting at George Washington University in Washington DC to exchange expertise in order to understand the sun and other stars. **Bengt Strömgren** asked the physicists there to find an explanation for the temperature, density, and chemical composition of the sun. **Hans Bethe** (Cornell), a nuclear physicist, looked at the various possible ways that nuclear reactions might occur in the sun. Bethe suggested that, if the **core of the sun were 16 million degrees Kelvin, the p—p** (proton-proton) **chain of nuclear reactions** would be the dominant source of energy production. Hans Bethe (1967) won the Nobel Prize for this work.

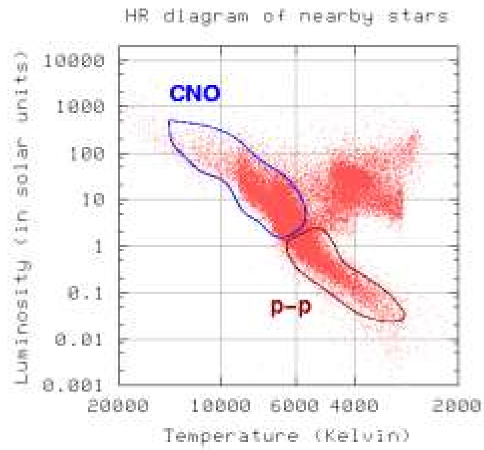
In the typical **p—p** nuclear reaction in the core of the sun (Step 1), two hydrogen nuclei (^1H, protons) are moving fast enough to overcome their electrostatic repulsion and they fuse to produce a heavy hydrogen nucleus (^2H = a deuteron = a proton and a neutron), and a positron and a neutrino are released. In Step 2, deuterons and protons are moving fast enough to overcome their electrostatic repulsion and fuse to produce a light element of helium (^3He) and a **gamma ray is released**. In Step 3, two light helium (^3He) nuclei are moving fast enough to overcome their electrostatic repulsion and fuse to form a normal helium ^4He nucleus and two hydrogen nuclei (^1H, protons), which will continue to participate in nuclear reactions, are released.



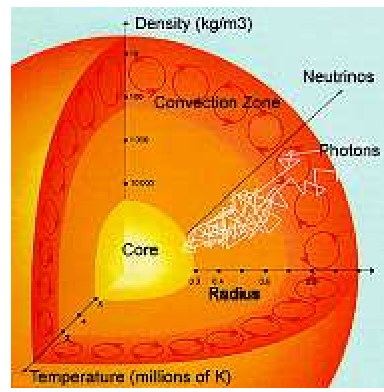
Only as small percentage of nuclei involved in the p—p nuclear reaction move fast enough at the temperature of the core to overcome the electrostatic repulsion and fuse. At the temperature of the core of the sun, the percentage of heavier nuclei, including those of carbon, nitrogen, and oxygen that move fast enough to overcome the electrostatic repulsion is even smaller so only a small amount of fusion involving these elements take place in the sun's core. On the other hand, in stars that are more massive than the sun and closer to the top left corner of the main



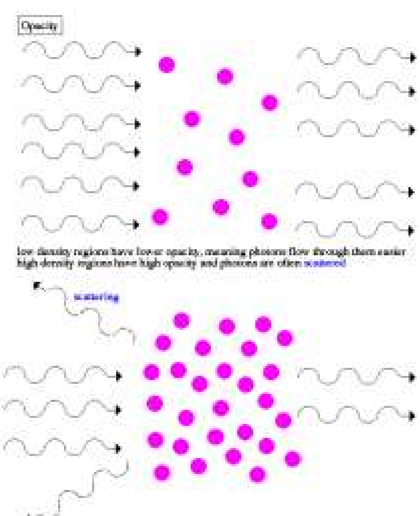
sequence in the **Hertzsprung-Russell diagram**, the temperature is higher and the **carbon-nitrogen-oxygen (CNO) cycle** results in the fusion of four hydrogen nuclei (^1H, protons) into a single helium nucleus (^4He, alpha particle), using carbon as a catalyst, with the emission of energy from the core in the form of gamma rays.



Gamma rays that are released in the nuclear reactions taking place in the **core** travel about 500 micrometers before they strike a free electron and are scattered. The scattering process goes on and on as the gamma rays proceed in a **random walk** to the surface sharing their energy with the electrons. The ionized nuclei and electrons scatter the gamma rays so completely that the sun's interior is almost **opaque** to the gamma rays (just like the plasma, containing positively-charged nuclei and electrons that existed from three minutes after the **big bang** to 300,000 years after the big bang, was opaque to photons).



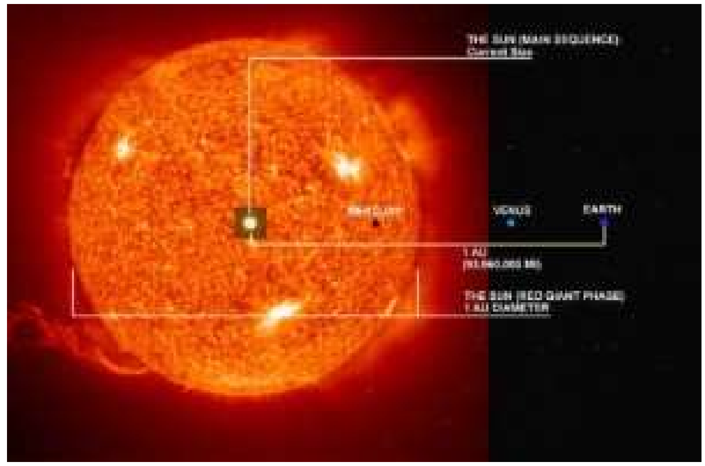
The **opacity** of the interior of the sun is due to the scattering of gamma rays by free electrons that takes place on its way from the core to the surface. With each scattering event, the energy of the gamma ray decreases so that eventually, the energy of radiation is reduced to energies in the **visible range**. As a result of numerous scattering events, it takes approximately **30 thousand years** for the photons formed in the nuclear reactions in the core to reach the



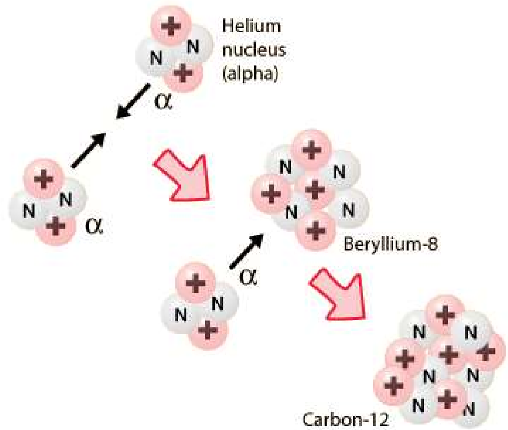
surface. This is much longer than the two seconds it would take a photon at a velocity of 2.99×10^8 m/s to move the same distance through free space. Radiation is not the only way that energy moves from the core to the surface. Near the surface, energy transfer is augmented by **convection**, where warmer plasma rises and cooler plasma falls in response to gravity. Given the radius of the sun, the "speed of light" or perhaps "the slowness of light" through the sun is approximately 2×10^{-7} m/s, far less than the 3×10^8 m/s it travels from the sun to the earth's atmosphere.

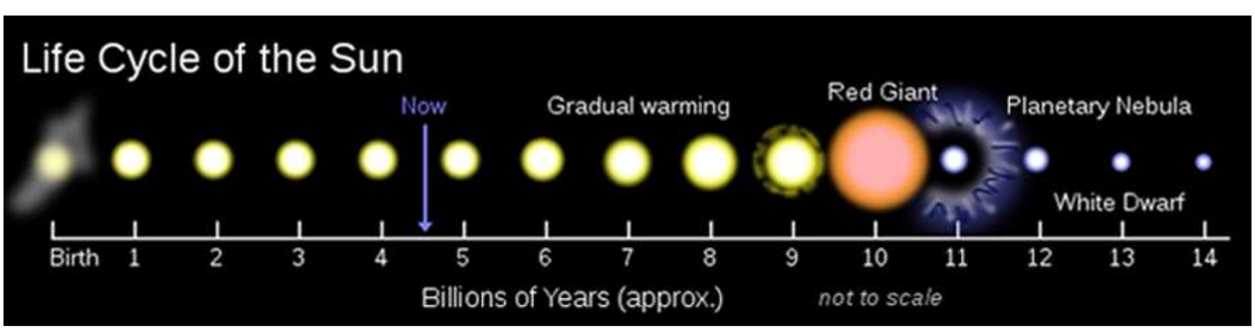
The sun was born approximately 4.6 billion years ago in the Milky Way galaxy when the **gaseous nebula**, which was composed primarily of hydrogen and helium and contained a smattering of dust, attracted itself gravitationally to form a spherical **protostar**. The gaseous **protostar** contracted as a result of the massive amount of **gravitational force** on itself. This compression resulted in the heating of the core and the eventual attainment of **hydrostatic equilibrium** where gravitational energy was balanced by thermal energy. Consequently, the diameter of the sun became stable. Given the temperature of the core, **alchemy** occurred and hydrogen nuclei fused into helium in **thermonuclear reactions**. The alchemical transformation results in helium nuclei that have less mass than the four hydrogen nuclei that compose each one. The lost mass or 0.7% mass defect is radiated away, in part, as radiant energy that diffuses to the surface of the sun, losing energy at each scattering so that the photons are transformed from energetic gamma ray photons to photons of visible light.

When the sun eventually consumes its supply of hydrogen, the core will be primarily composed of **helium**. No more nuclear reactions will take place in the core and it will cool and contract. However, the hydrogen outside the core will continue to burn and will expand. As the core contracts and as the hydrogen burning shell expands, the sun will move off the main sequence and become a **red giant**.



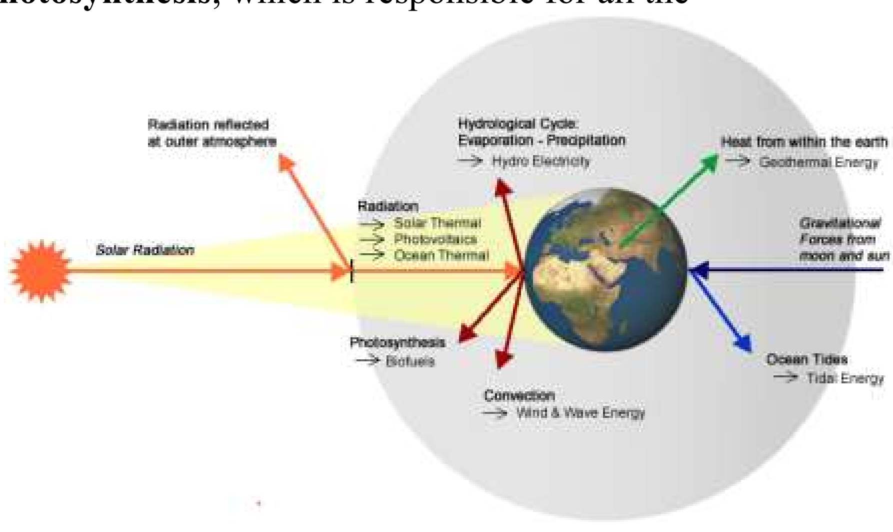
As the central core of the sun continues to contract, the density of helium will increase and the temperature of the core will rise. When the temperature of the core surpasses a threshold (100 million degrees), it becomes possible to burn helium into carbon in the **triple alpha process**. This burning, known as the **helium flash**, is explosive. During the explosion, the short-lived burning hydrogen envelope, known as a **planetary nebula**, is sloughed off and the bright core, now known as a **white dwarf**, is all that is left. The sun is currently about five billion years old; it will become a red giant and then a white dwarf when it is 10 and 11 billion years old, respectively.



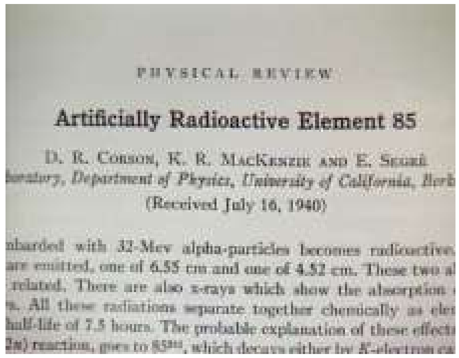


In general, the alchemical process of nuclear fusion results because the **kinetic energy** of the atomic nuclei is great enough to overcome **the electrostatic repulsion** that exists between positively-charged nuclei. As the size of the nucleus increases, it takes more and more energy to give the nuclei sufficient kinetic energy (½ mv^2) to overcome the electrostatic energy ($\frac{q^2}{4\pi\varepsilon_o r}$) barrier. For this reason, the temperature of the star determines how heavy an element can be if it is to be burned. Hydrogen (1 Dalton) burns at 10^7 K, helium (4 Daltons) at 10^8 K, carbon (6 Daltons) at 5 $\times 10^8$ K, oxygen (16 Daltons) at 2 $\times 10^9$ K, and silicon (28 Daltons) at 3 $\times 10^9$ K.

The sun is **massive** in that it has a lot of fuel to burn and **the nuclear reactions** yield far more energy per mass consumed than **chemical combustion reactions**, which involve the **rearrangement of electrons**. The sun, which is in some respects not a renewable resource, will provide the earth with energy for the next five billion years. The sun's radiant energy warms the earth, resulting in **wind** that transports the pollen of grasses. The warmth due to the sun's radiant energy also results in the **evaporation of water** from the sea that leads to **rain on land** that is necessary for the growth of trees, shrubs and herbs. The visible light from the sun provides the **energy for photosynthesis**, which is responsible for all the food we eat. The visible light from the sun provides information for seeing the **colors in the world** around us and for telling the **time of day**, the **season of the year**, and the **direction in space**.



President Emeritus **Dale Corson** designed a sundial so that we can tell the time.



PHYSICAL REVIEW

Artificially Radioactive Element 85

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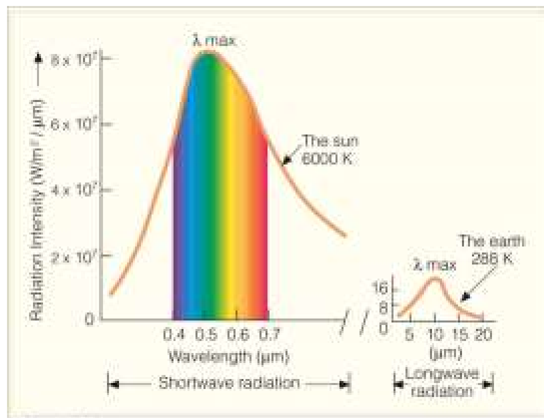
(Received July 16, 1940)

nbarded with 32-Mev alpha-particles becomes radioactive,
are emitted, one of 6.55 cm and one of 4.52 cm. These two al
related. There are also x-rays which show the absorption
s. All these radiations separate together chemically as ele
half-life of 7.5 hours. The probable explanation of these effects



Like the **average temperature** of the sun, the average temperature of the earth is also somewhat constant. As the sun can be considered to be an **incandescent black body** with an average temperature of about 6000 K, the earth can be considered to be a black body with an average temperature of about 288 K. The radiant energy of the sunlight entering the earth's atmosphere is radiated away from the earth as **mid infrared** (5 to (25-40) μm) radiation. That is, since the energy (E in J) of a photon is related to its wavelength (λ in m) by the product (hc = 6.6 × 10^{-34} Js · 3 × 10^{8} m/s) of Planck's constant and the speed of light, the average energy of photons leaving the earth is less than the average energy of photons entering the earth.

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

The **mid-infrared energy** radiated away from the earth, which originates from the **visible light energy** from the sun, will have little contribution to the enormous amount of cosmic **microwave** background radiation that reminds us of the first light.

As you can see, we are able to get to know a fair amount about our sun through observation and theory. **Arthur Eddington** ended his 1920 presidential address by saying, " *In ancient days two aviators procured to themselves wings.* ***Daedalus*** *flew safely through the middle air across the sea, and was duly honoured on his landing. Young* ***Icarus*** *soared upwards towards the Sun till the wax melted which bound his wings, and his flight ended in fiasco. In weighing their achievments perhaps there is something to be said for Icarus. The classic authorities tell us that he was only 'doing a stunt,' but I prefer to think of him as the man who certainly brought to light a constructional defect in the flying-machines of his day. So, too, in Science. Cautious Daedalus will apply his theories where he feels most confident they will safely go; but* ***by his excess of caution their hidden weaknesses cannot be brought to light****. Icarus will strain his theories to the breaking-point till the weak joints gape. For a spectacular stunt? Perhaps partly; he is often very human. But if he is not yet destined to reach the Sun and solve for all time the riddle of its constitution, yet he may hope to learn from his journey some hints to build a better machine.*"

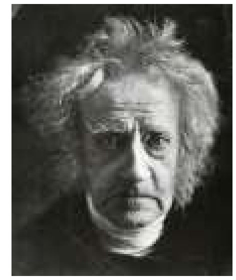
Science, when healthy, sees the values and limitations of both Daedelus and Icarus.

While the sun, like any other **incandescent body** emits a **continuous spectrum** of light with a **spectral distribution** defined only by its **temperature**, upon looking closely, the spectrum is **interrupted** by **dark lines**. These dark spectral lines were used by chemical spectroscopists to identify the chemicals present in the sun. Now I am going to discuss **chemical spectroscopy** itself.

Isaac Newton accomplished with a prism what nature accomplishes with a water droplet in a rainbow. By passing a cylindrical beam of sunlight though a prism, **Isaac Newton** (1671) revealed that the white light from the sun was composed of a continuous spectrum of colors.

By replacing the round hole that admitted the sunlight into the laboratory with a **narrow slit**, **William Hyde Wollaston** (1802) became aware of the fact that the colors of the spectrum were not continuous, but separated by a series of discrete black lines. **Joseph von Fraunhöfer** noticed that the ***black lines*** that were present in the spectra of sunlight were absent in the light from the flame of a lamp. In fact, he noticed that the light from a flaming or electrical lamp had ***bright lines*** in the spectrum that corresponded to the dark lines of the solar spectrum.

Thomas Mellvill (1756) discovered that when he added salts to the flame of a spirit lamp, the color constitution of the light was altered, and he wondered if sunlight might be composed of "*such colours and in such proportions as were seen in the lights of salts and burning spirits*." **John Herschel** (1823) expanded Mellvill's line of investigation by soaking the wick of a spirit lamp in a solution of strontium chloride or copper chloride. Upon lighting the wick, he observed that the salt produced a characteristic color when heated—**strontium** produced a flame with a "*beautiful carmine-red colour*" and **copper** produced a flame with an "*emerald-green colour*." Realizing the importance of this discovery for chemistry, Herschel latter wrote, "*The colours thus communicated by the different bases to flame, afford in many cases a ready and neat way of detecting extremely minute quantities of them.*"

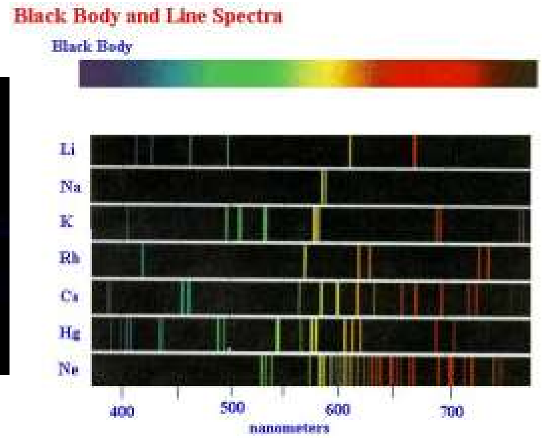


Demonstration: Observe the color of the flame of an alcohol lamp after adding strontium chloride and copper chloride individually using loops made from nichrome wire. Look at the flame with a spectroscope.

William Henry Fox Talbot (1826) came to the same conclusion as John Herschel while he was trying to develop a monochromatic lamp that would be useful for microscopy and for studying the properties of light. Talbot also suggested that "*whenever the prism shows a homogeneous ray of any colour to exist in a flame, this ray indicates the formation or the presence of a definite chemical compound.*"

Every time we see a **fireworks** display, we are reminded of the relationship between the chemical elements and the color emitted.

Gustav Kirchhoff (1863), **Robert Bunsen**, and others using a **Bunsen burner**, firmly established that each **chemical element absorbed** and **emitted** light waves with **characteristic discrete wavelengths**. By meticulously comparing spectra, Kirchhoff in particular showed that the **emission** of light by a given element gave rise to the **bright lines** in the spectrum, and the **absorption** of light by the same element gave rise to the **dark lines** in the spectrum. The light or dark **spectral lines** could be used to **identify chemical elements**.



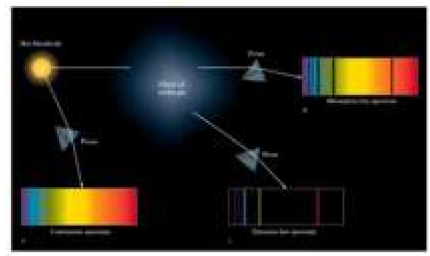
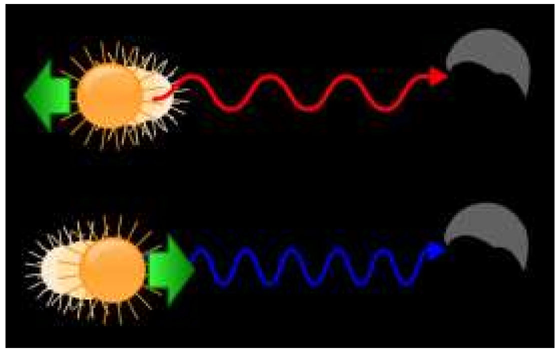


Fig: Emission & Absorption spectrum

The field of **spectrum analysis** made it possible for Kirchhoff, Anders Ångstrom, Norman Lockyer (1887), William Huggins (1899), and others to **identify chemical elements** not only in terrestrial samples, but also in celestial bodies, including the sun.

The **identification of the chemical elements** by their **characteristic spectral lines** should ***not*** depend on the velocity of the observer. However; Ernst Mach (1860) and Hippolyte Fizeau (1870) suggested that as a result of the **Doppler effect**, there may be a **shift** in the position of the spectral bands emanating from the heavenly bodies that depended on their radial motion. If the atom were ***moving relative*** to the observer, the observer would reckon that the atom was absorbing or emitting light with a different wavelength than that which was expected. **Light** emitted by atoms

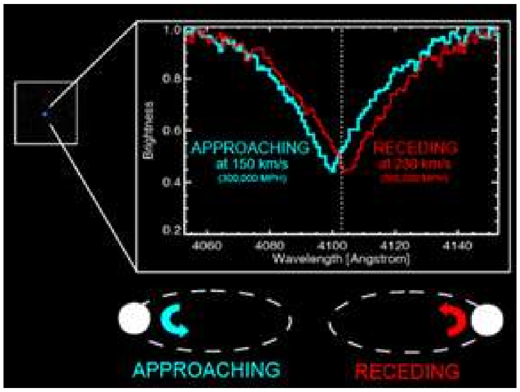
moving away from an observer would be **red shifted** and **light** emitted by atoms **moving towards** an observer would be **blue shifted**.

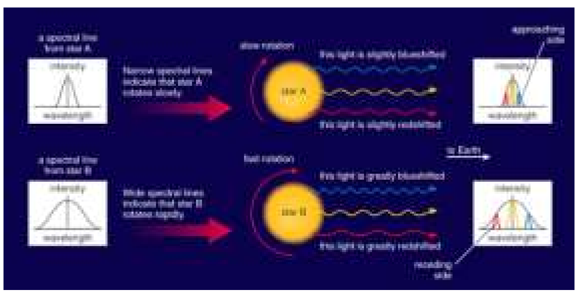


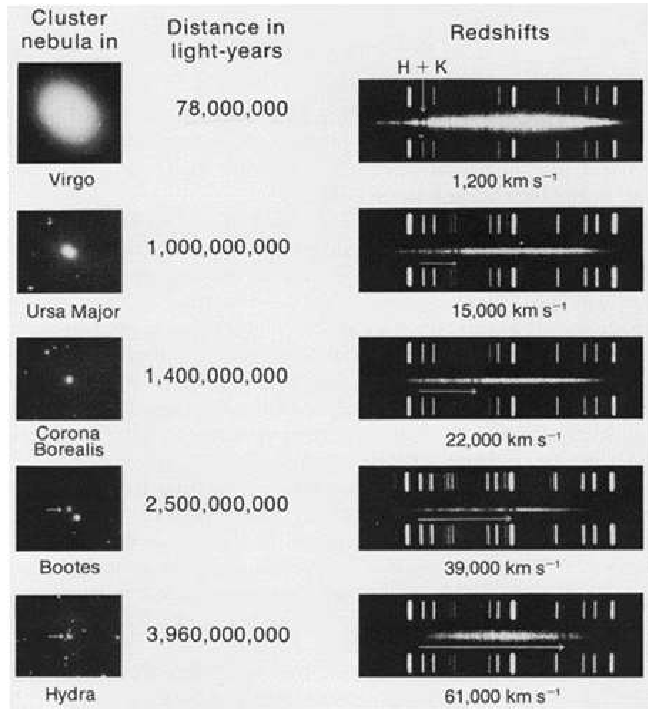
Thus, *prima facie*, it would seem that an observer at rest with respect to the atom and an observer moving relative to the atom would **identify it as an atom of a different element**. In order for the spectral line to be identified as one coming from a given element, **independent of the relative motion**, one would have to use an equation for the spectral lines that would allow any and all observers to agree on the chemical identity of the source of the emitted light. This is the principle of relativity applied to chemical identification. The transformation is:

$$\lambda_{moving} = \lambda_{stationary}\left[\frac{1-\frac{v}{c}\cos\theta}{\sqrt{1-\frac{v^2cos^2\theta}{c^2}}}\right]$$

Chemical elements **moving away** ($\theta = 180°$) from the observer would seem to be red shifted, with the **magnitude of the red shift related to the velocity**; and chemical elements **moving towards** ($\theta = 0°$) the observer would seem to be blue shifted, with the **magnitude of the blue shift related to the velocity**. Assuming that the chemicals in stars are identical with the chemicals on earth, their Doppler-shifted spectral lines have been used to measure radial, rotational, and revolutionary motion.





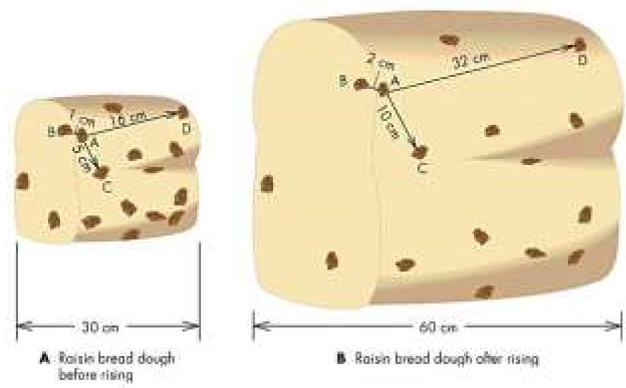


This is the same **red shift** based on the **Doppler effect** that allowed **Vesto Slipher** to measure the **radial velocities of the nearby spiral galaxies**, and given the extraordinary velocities that they were hurling through space, Slipher (1921) surmised, *"If the above swiftly moving nebula* [galaxy] *be assumed to have left the region of the sun at the beginning of the earth, it is easily computed, assuming the geologists' recent estimate for the earth's age, that the nebula* [galaxy] *now must be many millions of light years distant."*

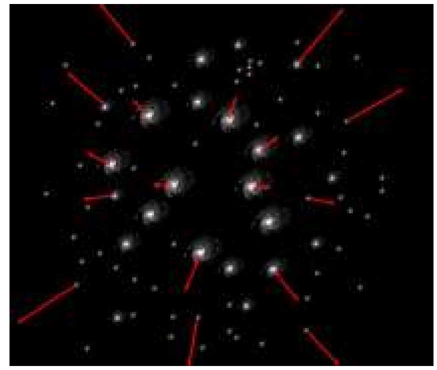
This is the same **red shift** based on the **Doppler effect** that allowed **Edwin Hubble** (1929) to notice "***a linear correlation between distances and velocities***" and that the recession velocities of galaxies were proportional to their distance from the sun. Hubble (1937) pointed out that the "*velocity-shifts, on a microscopic* *scale, are familiar phenomena, and their interpretation is not to be questioned. Now the red-shifts observed in nebular* [galactic] *spectra behave as velocity-shifts behave—the fractional shift dλ/λ is constant throughout a given spectrum—and they are readily expressed as velocities of recession. The scale is so convenient that it is widely used, even by those cautious observers who prefer to speak of 'apparent velocities' rather than actual motion….The law of red-shifts then reads: the nebulae* [galaxies] *are receding from the earth in all directions, with velocities that are proportional to their distances from the earth."*

This is the same **red shift** based on the **Doppler effect** that allowed physicists who had been involved in radar during World War II to turn their instruments towards the heavens to study the cosmos at **radio wavelengths**. Astronomers at Cambridge University surveyed the sky for radio sources that produced electromagnetic radiation with a wavelength of about 1.8 m. These remote radio sources were identified with optical objects and they became known as quasi-stellar radio sources or **quasars**. These remote "radio stars" were among the first stars formed in the universe and exhibit **red shifts** that indicated that they had incredible velocities, such as 110,200 kilometers per second and greater.

The **cosmological principle** states that on a sufficiently large scale, all observers in the universe see the same thing no matter who or where they are. By **assuming** that we are ***not*** in a special place in the universe where the heavenly bodies are all moving away from us and that ***any observer*** in the universe would see similar red shifts, **these red shifts are considered by cosmologists to be a consequence of the expansion of space** using an expanding raisin bread as an analogy. I see things

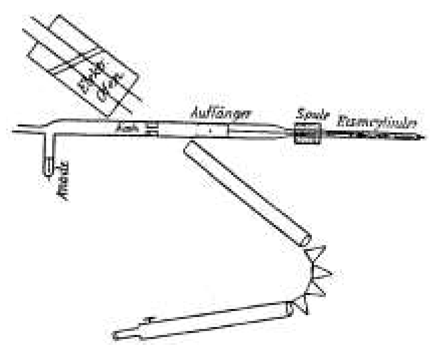


differently (which is not allowed by the cosmological principle)! I do not accept the **cosmological principle** as foundational and I do not accept the assumption that everyone no matter where they are will see red shifts, just like I believe that two observers can look at the southern sky and the northern sky and see different constellations.

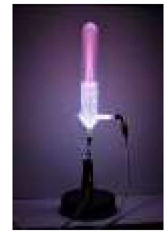


Therefore I consider the red shifts to be a consequence of their **velocity *in* space** as opposed to the **velocity *of* the expansion of space**. This would make us near the center of the universe. You are free to make your own decisions.

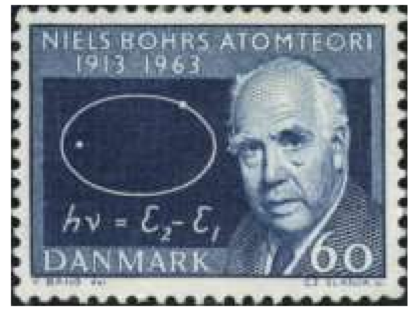
Johannes Stark (1902) realized that the **Doppler effect** would also apply to terrestrial light sources and consequently, a given chemical atom would have different characteristic spectra depending on its relative velocity. Using the positively-charged atoms that make up canal rays, Stark observed that, consistent with the Doppler effect, the positions of the spectral lines emitted from the atomic ions moving **towards** him were shifted towards the **blue end** of the spectrum and the positions of the spectral lines emitted from the atomic ions **moving away from** him were shifted towards the **red end** of the spectrum. Stark used the Doppler shift to determine the velocity of the positively-charged atoms that made up the canal rays.

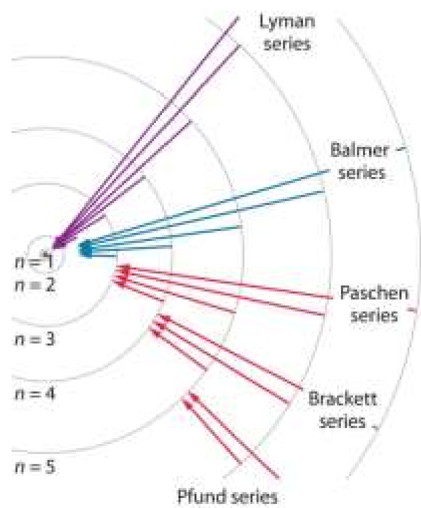


Demonstration: Observe the cathode rays (electrons) and anode or canal rays (protons).



In 1913, **Niels Bohr** proposed a **model** of a stationary hydrogen atom based on the **discrete spectral lines** it **absorbs** or **emits**. Bohr proposed that the reason atoms emit discrete spectral lines is because the **electrons move around the nucleus in circular orbits that can have only certain allowed radii** characterized by an integer **(n = 1, 2, 3…)**. When a negatively-charged electron jumps from an orbit to one closer to the positively-charged nucleus, it **emits** light of a given spectral line, consistent with the **electrostatic energy lost** by an atom when opposite charges move closer together. When an electron **absorbs** light corresponding to a given spectral line, the electron overcomes the electrical attraction and moves from an orbit near the positively-charged nucleus to one farther away, consistent with the electrostatic energy gained by an atom when opposite charges move away from each other.





According to Bohr, the energy (E) of each orbit (n) is given by the following formula, where R represents a constant known as the Rydberg constant, which is equal to 1.097×10^7 m^{-1}.

$$E = \frac{Rhc}{n^2}$$

The energy (E) absorbed (+Rhc) or emitted (-Rhc) by an electron following from the initial orbit (n_i) to the final orbit (n_f) is given by:

$$E = \pm Rhc\left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right]$$

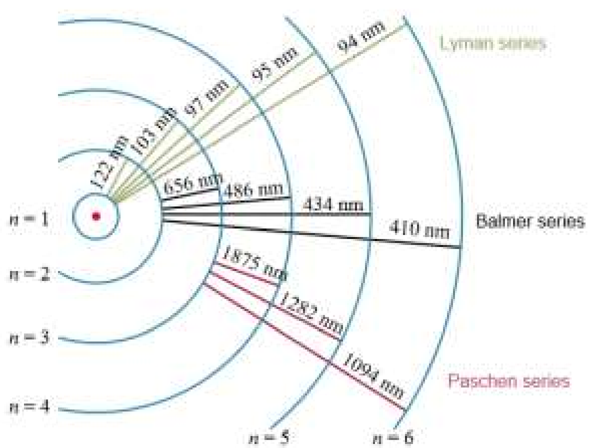
Since $E = \frac{hc}{\lambda}$, the wavelength of light that is emitted or absorbed by the transition from one orbit to another is given by:

$$E = \pm Rhc\left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right] = \frac{hc}{\lambda}$$

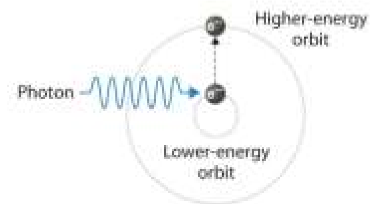
$$\frac{1}{\lambda} = \pm R\left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right]$$

What is the wavelength emitted by an electron jumping from orbit 2 to orbit 1, closer to the positively-charged nucleus? 121.54 nm.

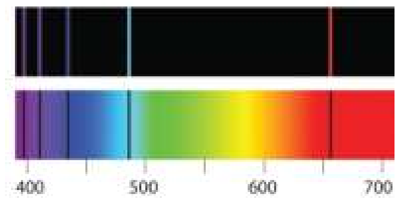
What is the wavelength emitted by an electron jumping from orbit 3 to orbit 2, closer to the positively-charged nucleus? 655.74 nm.



According to the Bohr model, the **absorption** of light by an atom and the dark band it produces can be pictured like so:

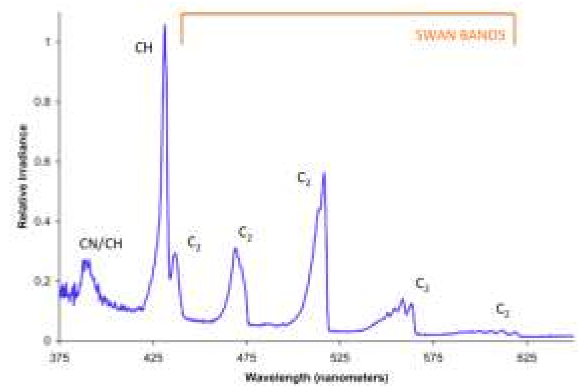


(a) Electronic absorption transition



(b) H_2 emission spectrum (top), H_2 absorption spectrum (bottom)

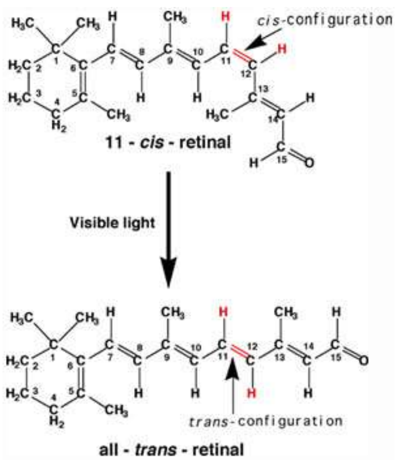
When atoms are bonded together into molecules, the molecules absorb and emit light in a manner that depends on their atomic composition and the type of bonds. When a **carbon** atom bonded to a **hydrogen** atom as **CH** cools, it emits light, when it is cooled, it absorbs light. When **two carbon** atoms, bonded together as **C_2** cool, it also emits light, but light of different wavelengths than CH. When the C_2 is cool, it absorbs light. These are the molecules that give rise to the **blue region of a flame**. By analyzing the emission or absorption of light from a carbon-containing molecule, one can deduce its structure. Conversely, if one knows its structure, one can estimate its absorption or emission spectrum.

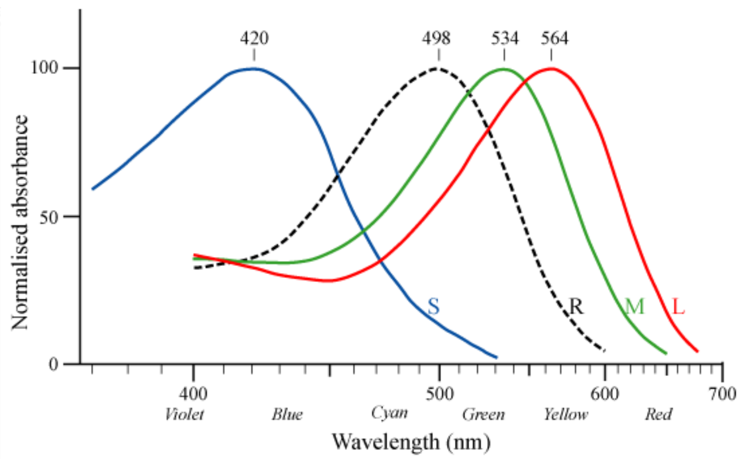


Below are the structures of various **pigments** that function in the absorption of sunlight that makes life possible and enjoyable. We will discuss these pigments and the processes they mediate over the semester.

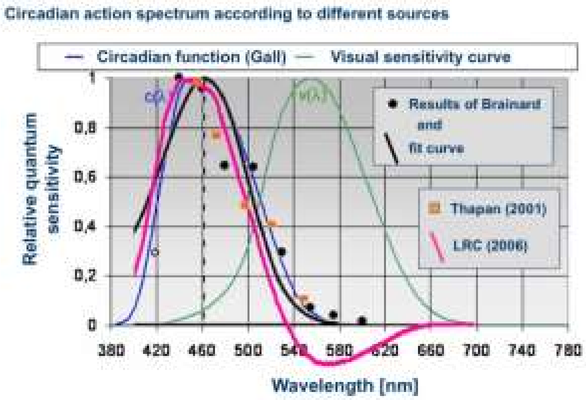
The **pigments** have much in common. Notice that they each have many **conjugated double bonds** (-C=C-C=C-). That is, **single bonds and double bonds alternate, resulting in delocalized electrons** that are not bound to a single positively-charged nucleus. Also notice that the **delocalized electrons** result in absorption spectra that are **more continuous** (less discrete) than those of **gaseous atoms** and **less continuous** (more discrete) that that of an **incandescent object**.

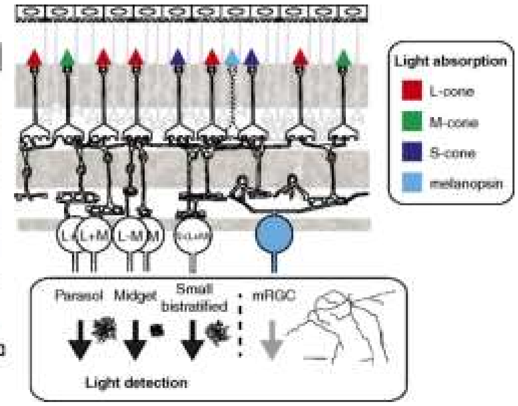
Rhodopsin and **photopsins** are **pigments** composed of **retinal** attached to different **opsin proteins** that make scotopic and photopic **vision** possible. Differences in the opsin proteins result in the differences in the peak spectral sensitivities.



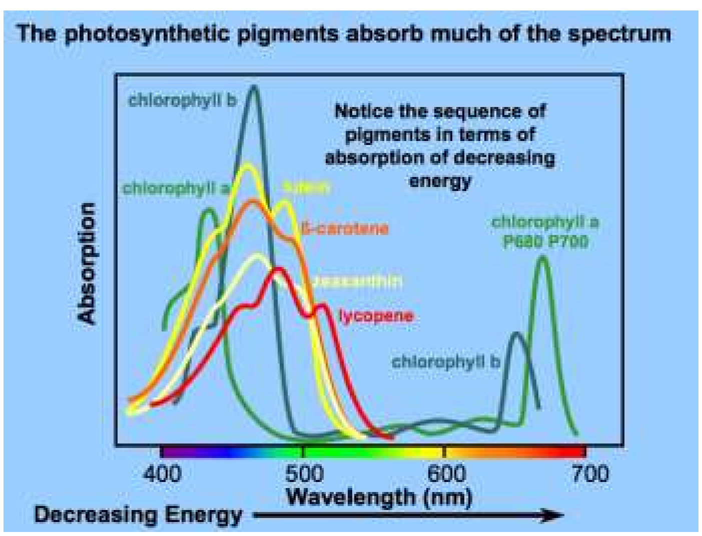


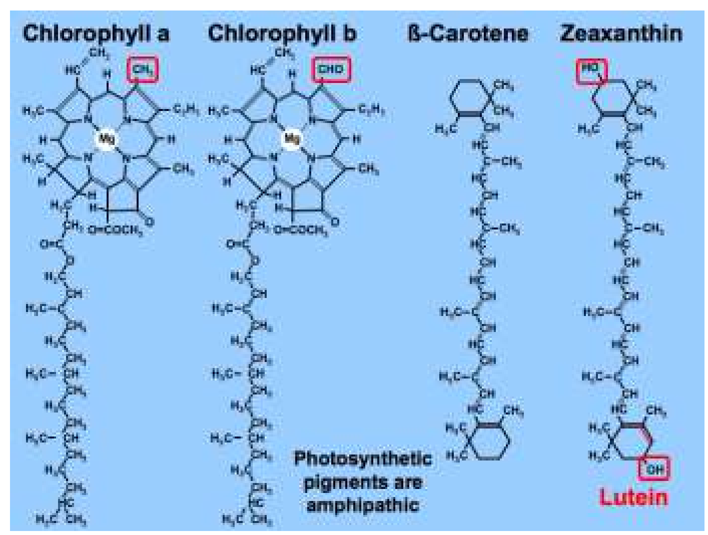
Melanopsin is another pigment found in 1-2% of the **ganglion cells** in the retina of the vertebrate eye. Melanopsin is also composed of **retinal** attached to an opsin protein. The opsin protein in human melanopsin is more similar to invertebrate opsins involved in vision than to the vertebrate opsins involved in vision. Melanopsin functions in the **pupillary light reflex response** and to **tell time** necessary to maintain **circadian rhythms** and synchronize our **sleep-wake cycle** with the natural **light-dark cycle**.



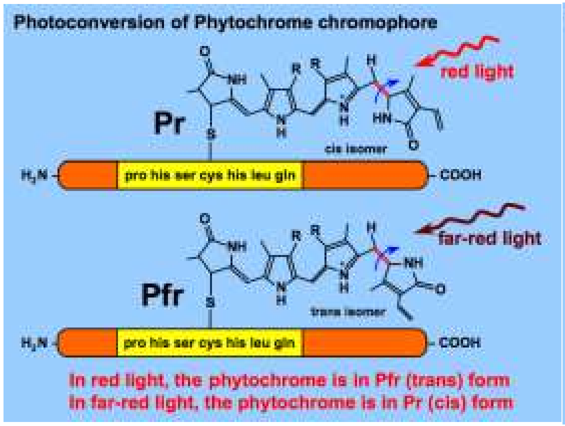


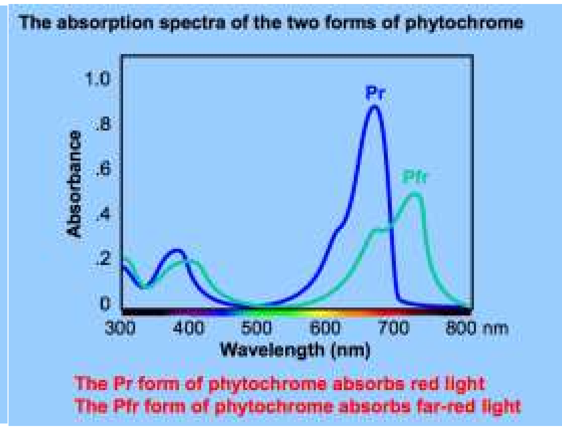
Chlorophylls, **carotenoids** and **zeaxanthin** are the **pigments** involved in **photosynthesis** in green plants.



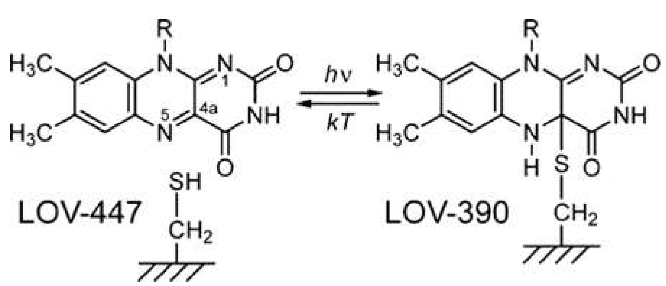


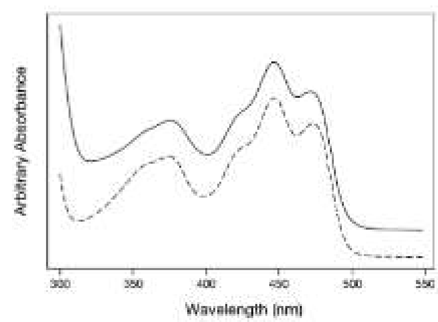
Phytochrome, **phototropin**, and **cryptochrome** are three **pigments** important for plants to respond to the environment. **Phytochrome** is a biliprotein that is involved in flowering, shade avoidance and seed germination.



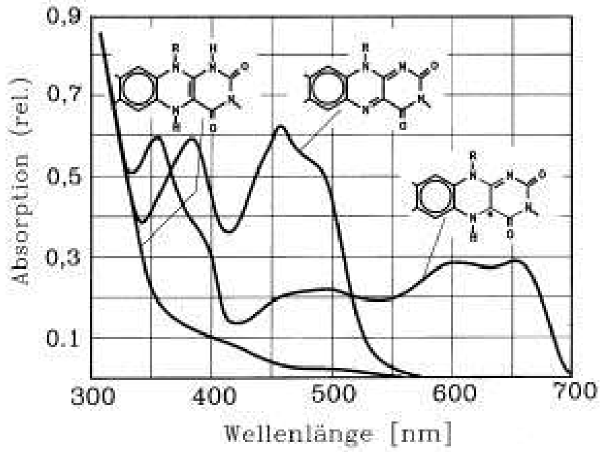


Phototropin is a flavoprotein involved in phototropism, which is the bending response towards light.



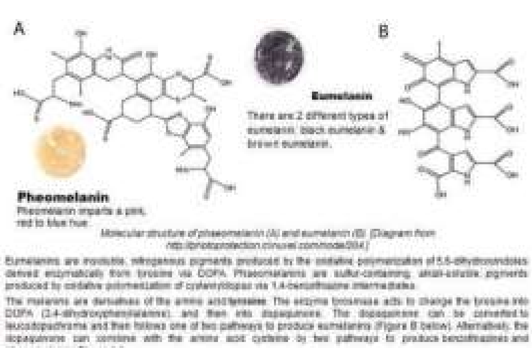


Cryptochrome, like phototropin, is another flavoprotein. It seems to be part of a light-regulated molecular clock involved in biological circadian rhythms in both plants and invertebrates.



Anthocyanins are **pigments** that make the **attractive colors** of many **flowers** and **fruits**. The color depends on the acidity of the cell.

Eumelanin and **Pheomelanin** are melanin pigments that color our eyes, skin and hair.



The **absorption of the various wavelengths** that compose sunlight and the **transmission** of others by inorganic pigments in or on glass can be appreciated when looking at the **image** of **Isaac Newton** in the chemically stained glass window of the Wren Library (Isaac Newton being presented to George III with Francis Bacon looking on, designed by Giovanni Battista Cipriani, 1771); the chemically stained glass window of the Olney Parish Church that depicts the **image** of **John Newton**; the chemically stained glass window at the Fountain Street Church in Grand Rapids, Michigan that depicts the **image** of **Charles Darwin**; and the chemically stained glass window at the Grace Cathedral in San Francisco that depicts the **image** of **Albert Einstein** and his equation $\boldsymbol{E = mc^2}$**.**

Stephen Spender (1955) poem read by Silvan S. Schweber at a celebration of Hans Bethe's Life:

I Think Continually of Those Who Were Truly Great

*I think continually of those who were truly great.
Who, from the womb, remembered the soul's history
Through corridors of light, where the hours are suns,
Endless and singing. Whose lovely ambition
Was that their lips, still touched with fire,
Should tell of the Spirit, clothed from head to foot in song.
And who hoarded from the Spring branches
The desires falling across their bodies like blossoms.*

*What is precious, is never to forget
The essential delight of the blood drawn from ageless springs
Breaking through rocks in worlds before our earth.
Never to deny its pleasure in the morning simple light
Nor its grave evening demand for love.
Never to allow gradually the traffic to smother
With noise and fog, the flowering of the spirit.*

*Near the snow, near the sun, in the highest fields,
See how these names are fêted by the waving grass
And by the streamers of white cloud
And whispers of wind in the listening sky.
The names of those who in their lives fought for life,
Who wore at their hearts the fire's centre.
Born of the sun, they travelled a short while toward the sun
And left the vivid air signed with their honour.*