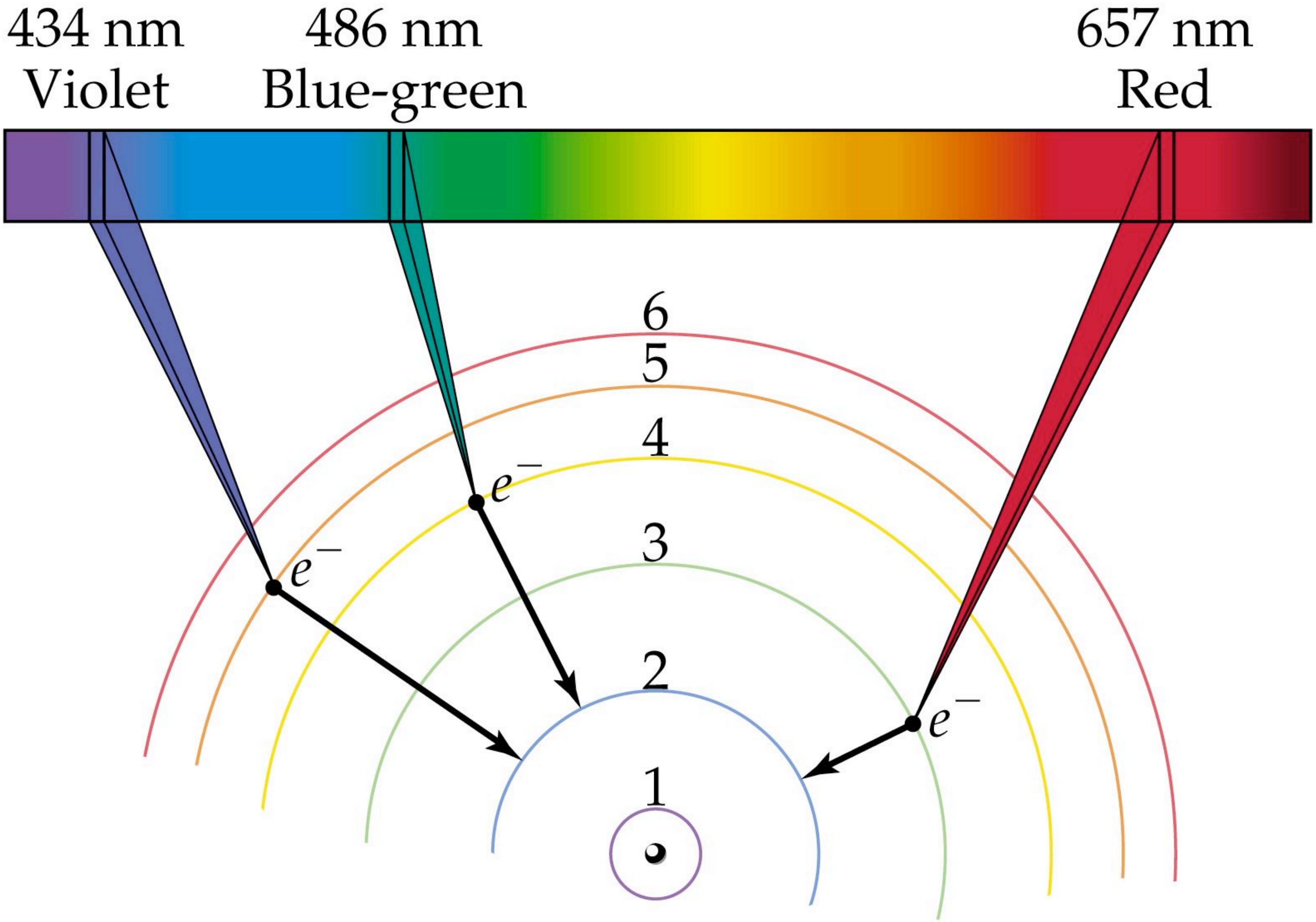
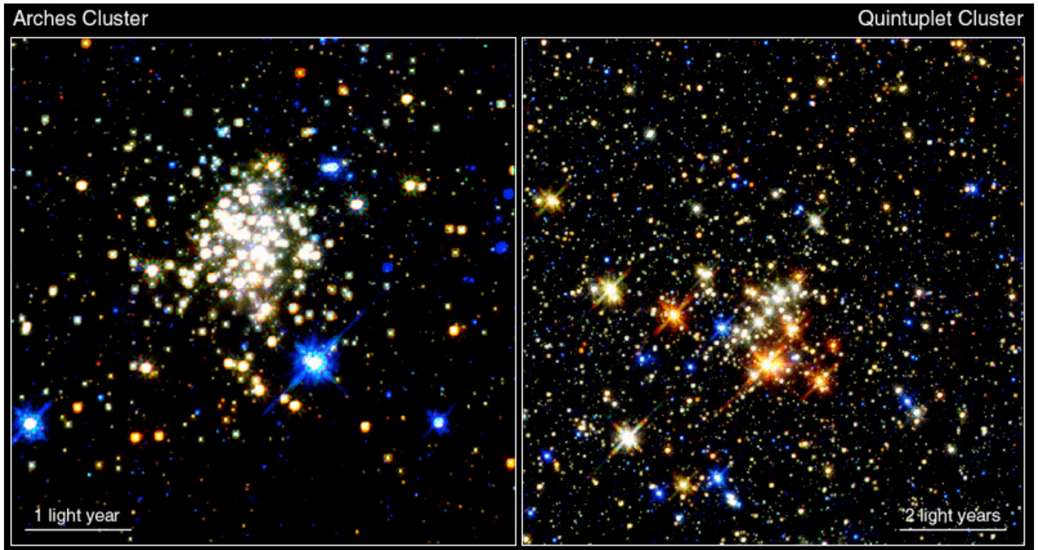
Atoms and Starlight

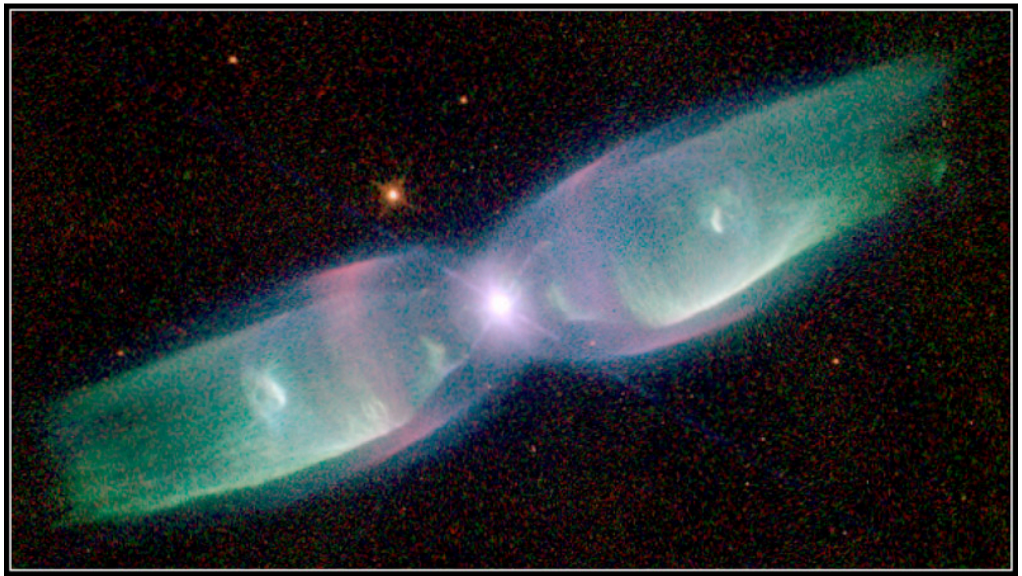


Where do the all the colours come from in astronomical images? Why are some stars blue and others red? Why does the gas around and inbetween stars glow different colours? In this lecture we will try to understand the connection between light and matter so that we can interpret these images.



Star Clusteres Near the Center of the Galaxy **HST • NICMOS**

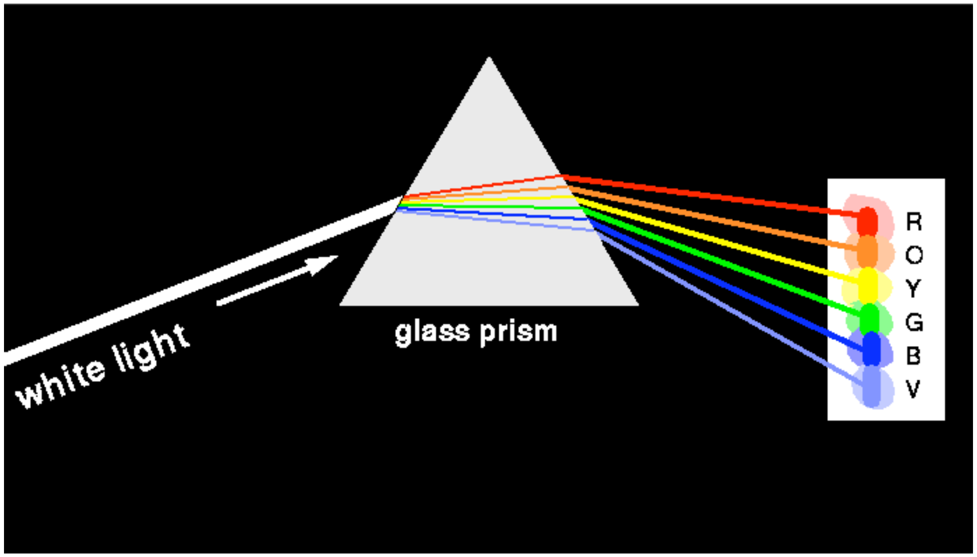
PRC99-30 • STScI OPO • D. Figer (STScI) and NASA



Planetary Nebula M2-9 HST • WFPC2

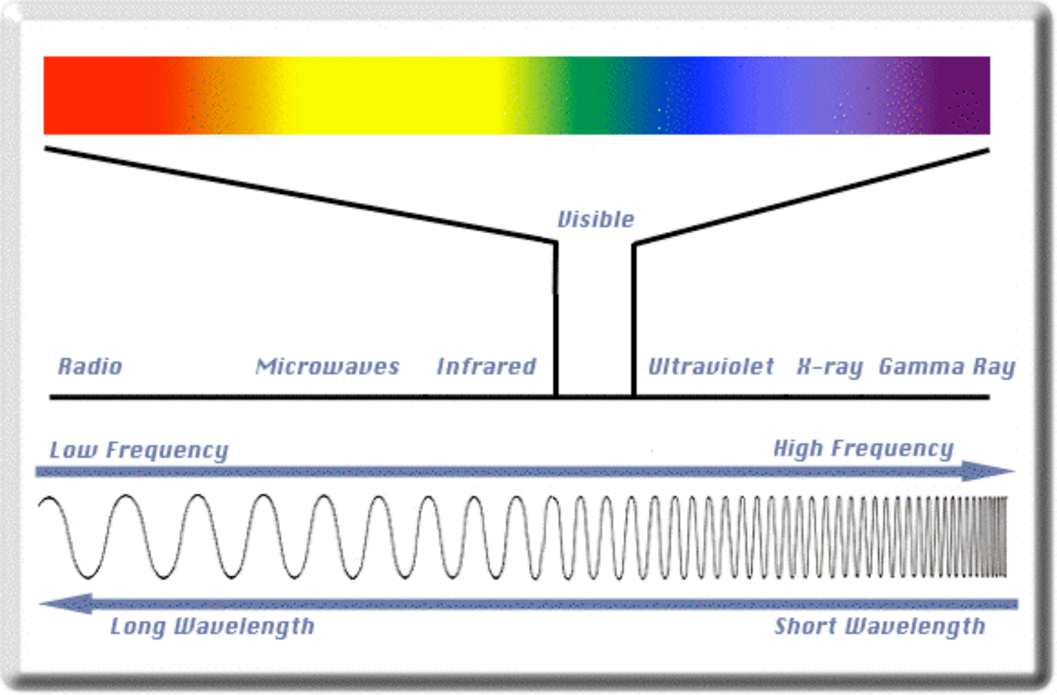
PRC97-38a • ST Scl OPO • December 17, 1997

B. Balick (University of Washington) and NASA



Dispersion of White Light by Glass Prism

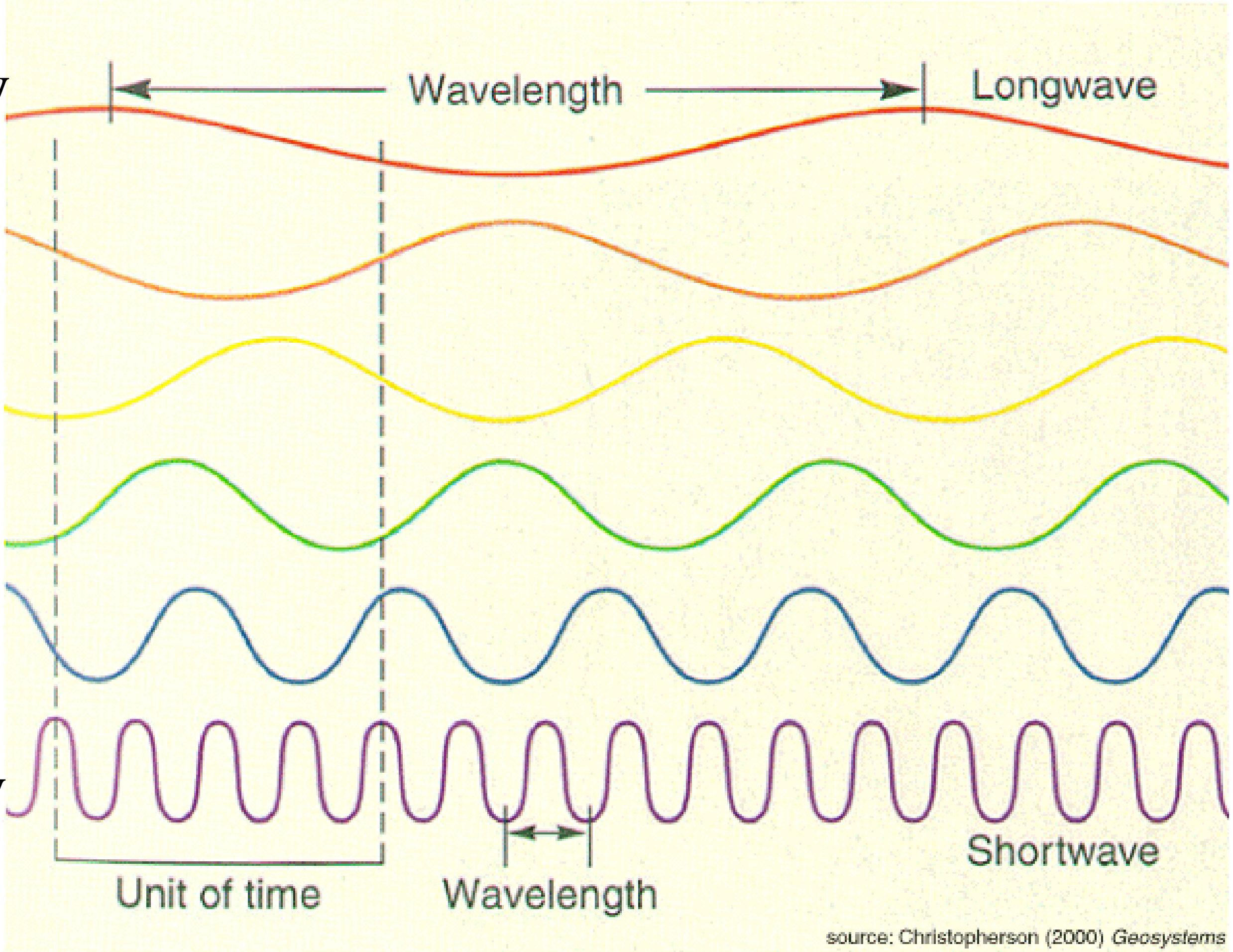
Newton was one of the first scientists to understand the wave nature of light. He found that a prism would break up white light into its constituent colours. This occurs because blue light gets more severely refracted as it passes through the glass, so it gets bent more.



White light, or visible light is just one example of electromagnetic radiation. Electromagnetic radiation can be described as a wave-like disturbance caused by oscillating electric and magnetic fields, and can travel even in a vacuum (unlike sound which needs vibrating atoms to travel). Visible light constitutes a tiny part of the electromagnetic spectrum, which is made up waves of different energies. All electromagnetic radiation travels at the speed of light (often written ‘c’) in a vacuum.

Lowest frequency

Highest frequency



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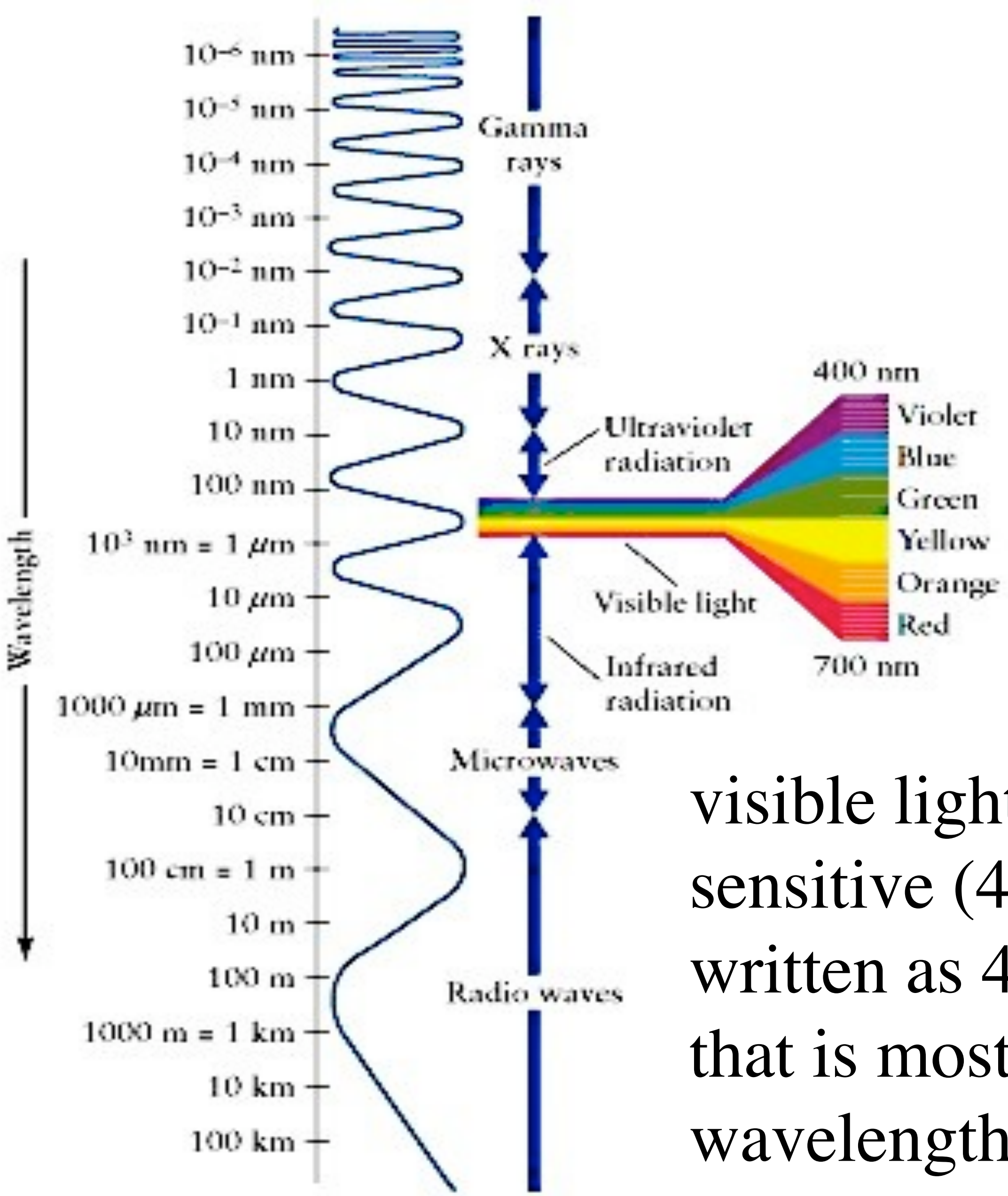
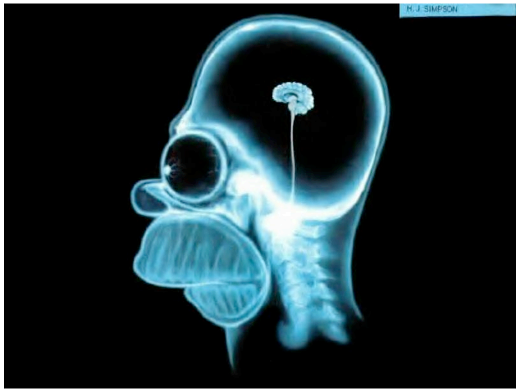
We characterise light by its wavelength, I.e. the distance between successive peaks. Wavelength has a unit of length (e.g. nm). We can also define frequency, where a high frequency corresponds to a short wavelength and vice versa.



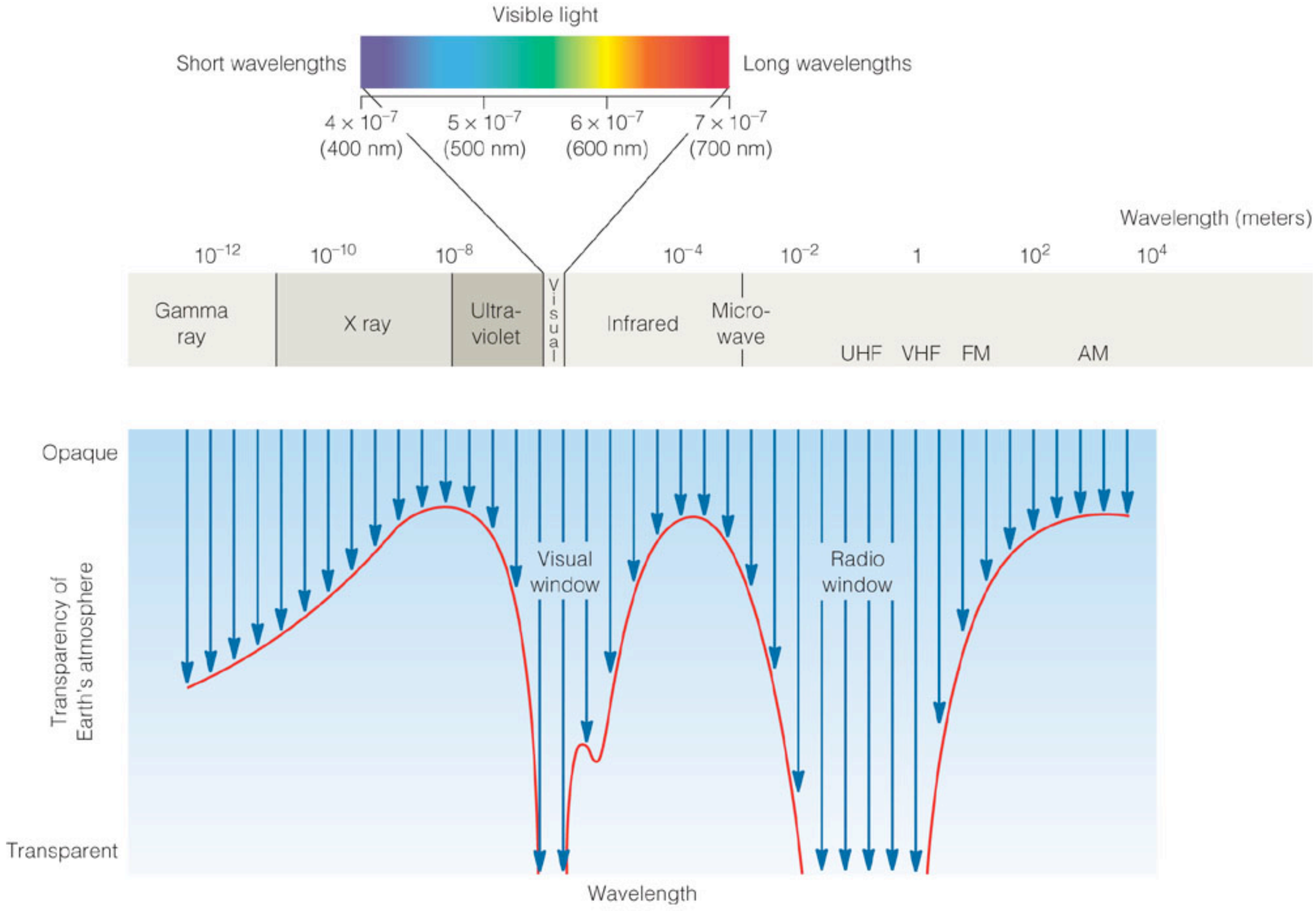
Sometimes, astronomers use Angstroms instead of nanometres. An Angstrom (Å) is ten times smaller than a nanometre I.e. 1 Å = 10^{-10} m. Therefore, the blue extreme of visible light to which our eyes is sensitive (400 nm) can also be written as 4000 Å. We chose a unit that is most convenient for the wavelength in hand, avoiding too many zeros and decimal points.

So far, we have treated light as a wave. However, quantum mechanics tells us that every particle has wave-like properties and vice versa. However, only very small particles ever exhibit wave-like properties. Sometimes it is more convenient to consider light as a particle, which we call a photon.

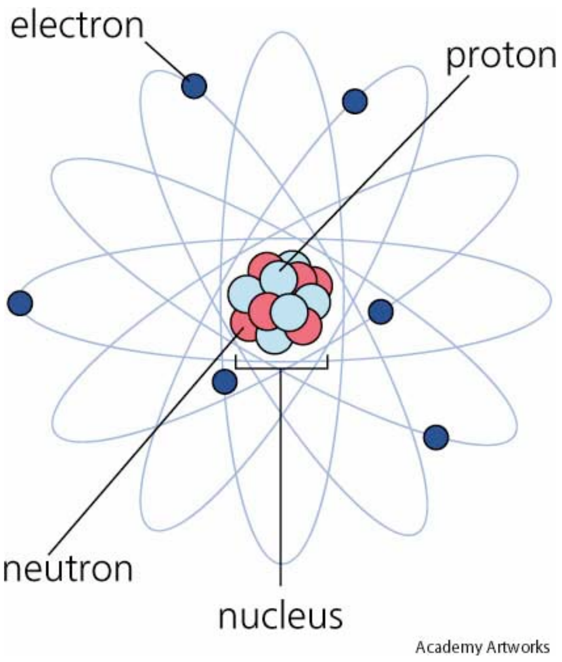


Photons carry energy, the amount of energy carried by a given photon depends on its wavelength. A photon with short wavelength (high frequency) carries more energy than a long wavelength (low frequency) photon. So an X-ray photon carries more energy than a radio wave.

Radiation from all over the electromagnetic spectrum can be found in space. Fortunately, our atmosphere protects us from much of this radiation. The main atmospheric windows are in the radio and the optical.

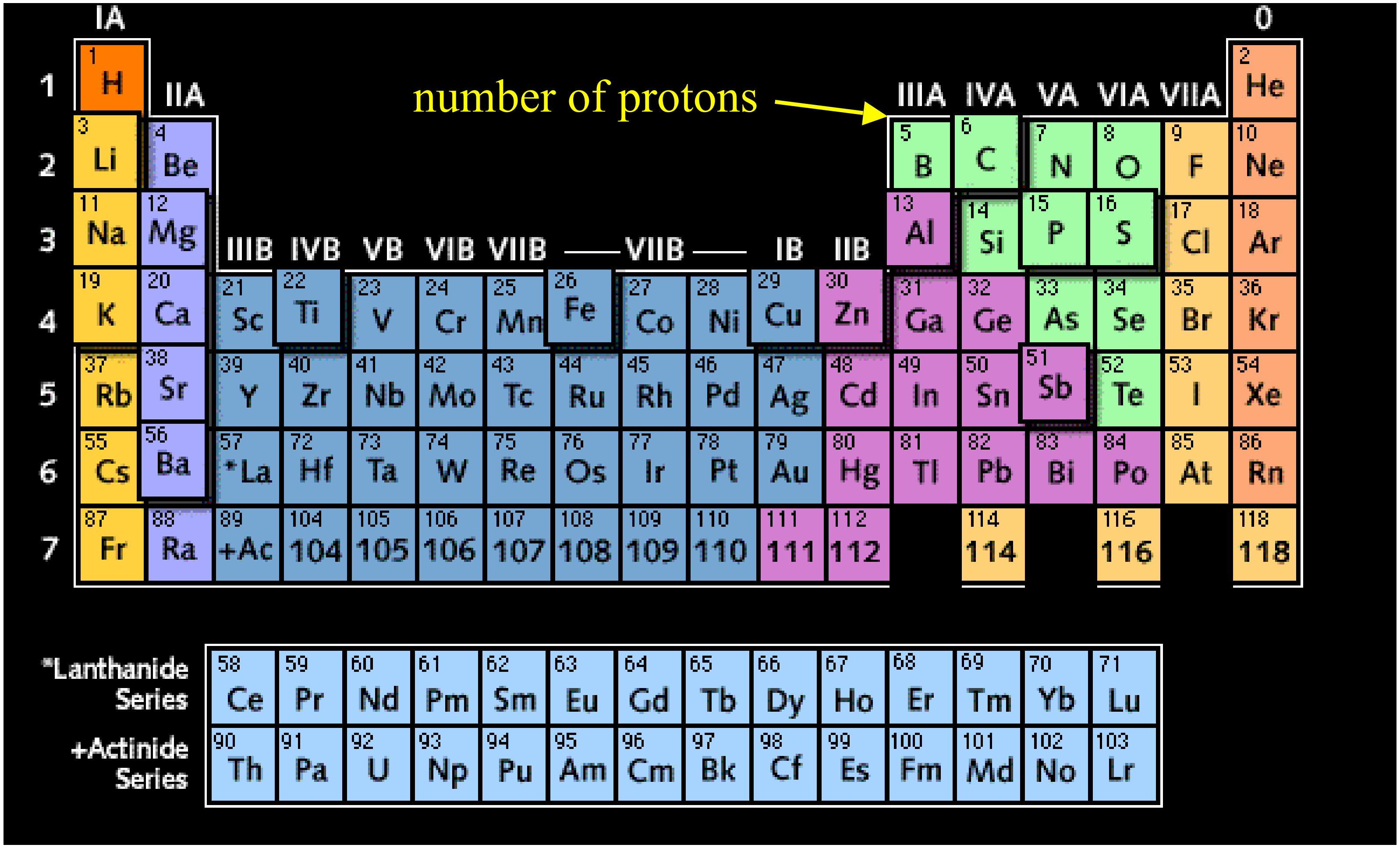


So now we know a bit about light. Next, let us review what we know about atoms.



The nucleus is the dense centre of the atom which contains most of the mass. Both the positively charged protons and neutrally charged neutrons reside here. The light, negatively charged electrons ‘orbit’ the nucleus. When the number of electrons equals the the number of protons we have a neutral atom. If the charges are not balance, we have an ion, positively charged if the atom has lost electrons or negative if it has gained excess electrons.

An given chemical element (e.g. hydrogen, helium, carbon) is defined by how many protons it has. I.e. if a nucleus has 6 protons, it is by definition, carbon, regardless of how many neutrons and electrons it has.

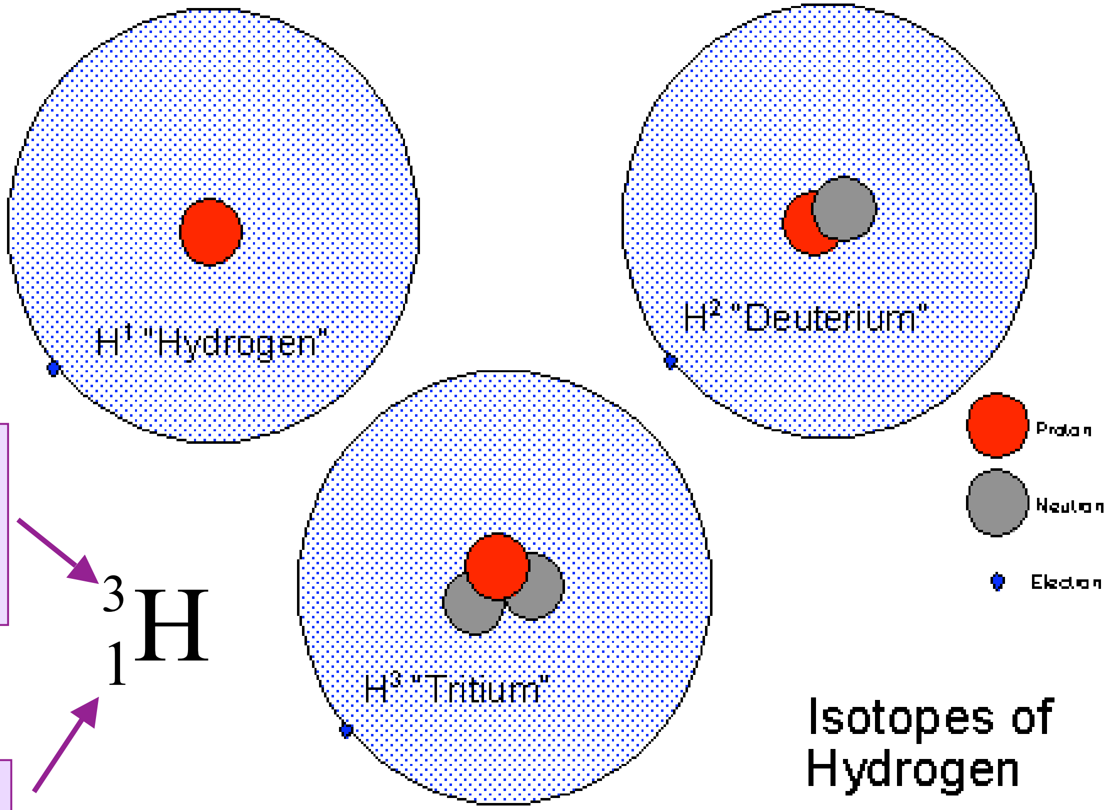


number of protons

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	—— VIIB ——			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 104	105 105	106 106	107 107	108 108	109 109	110 110	111 111	112 112		114 114		116 116		118 118

*Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

$^{1}_{1}\mathrm{H}$



$^{2}_{1}\mathrm{H}$

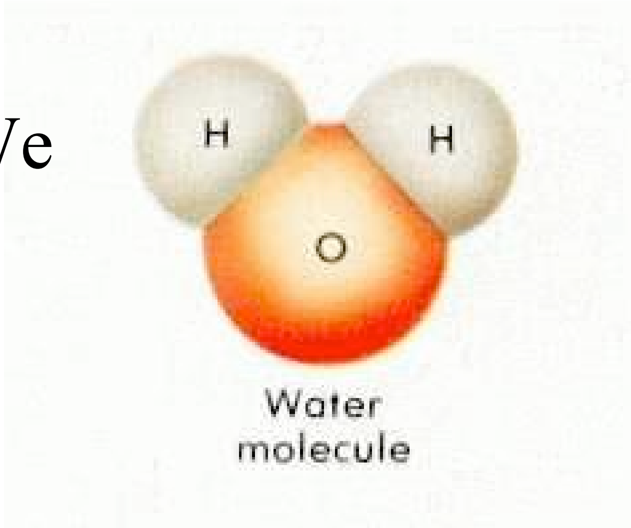
atom mass (no. p+n)

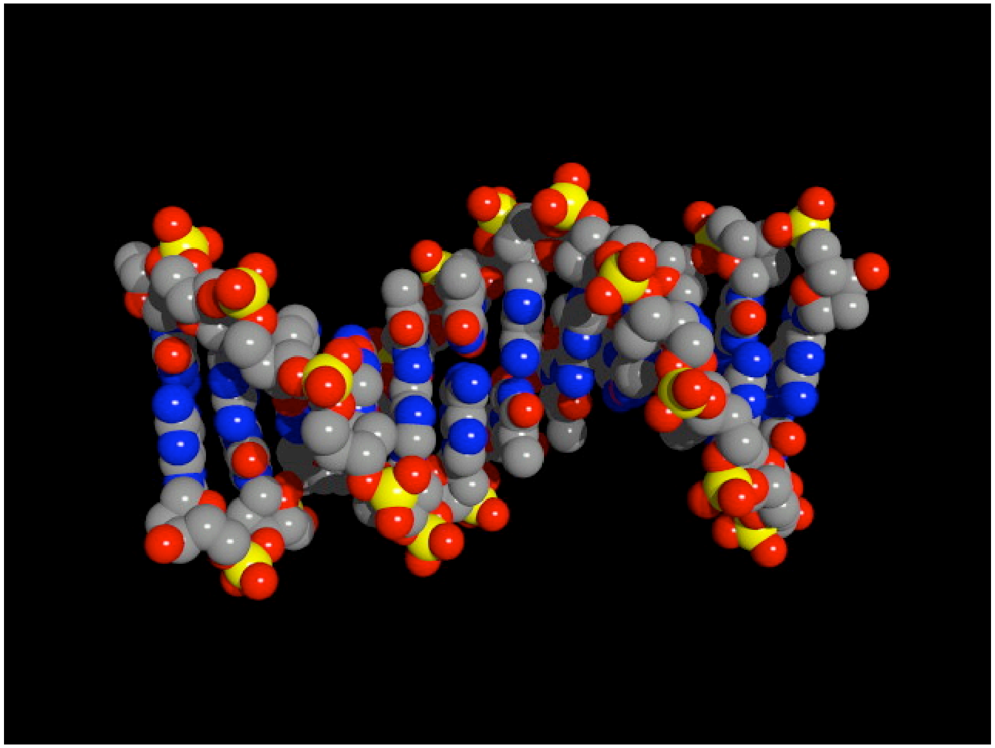
$^{3}_{1}\mathrm{H}$

no. protons

We have already seen that adding electrons creates ions. Adding neutrons creates isotopes. For example, carbon has 2 stable isotopes ^{12}C which has 6 protons and 6 neutrons and ^{13}C which has 7 neutrons.

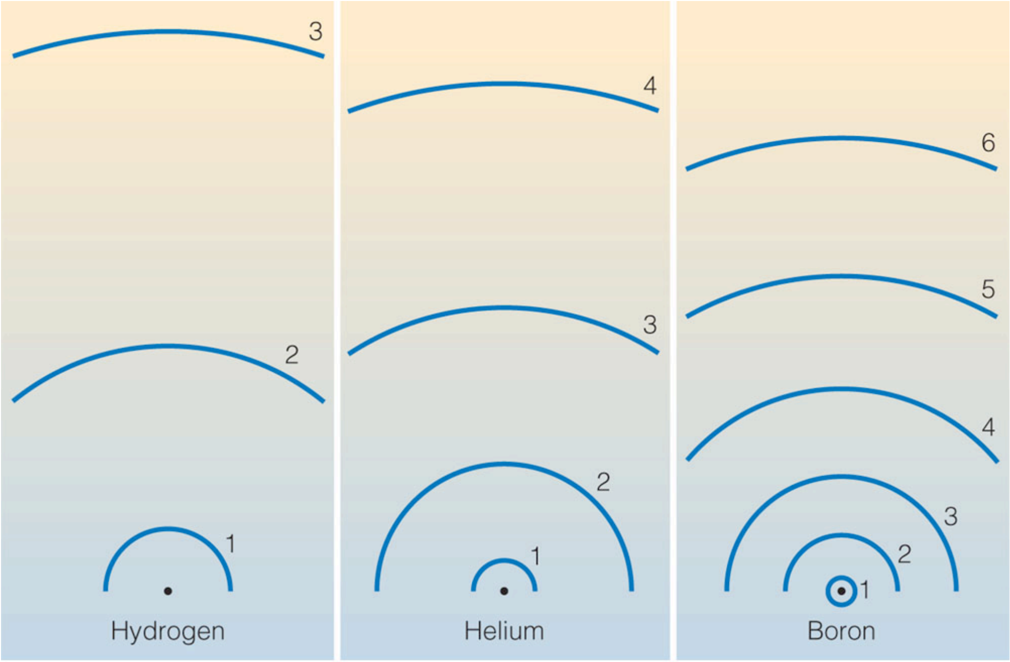
When two or more atoms 'team up' to share electrons, we have a molecule. We write down the number of atoms that went into making the molecule like this H_2O - two hydrogen and one oxygen.





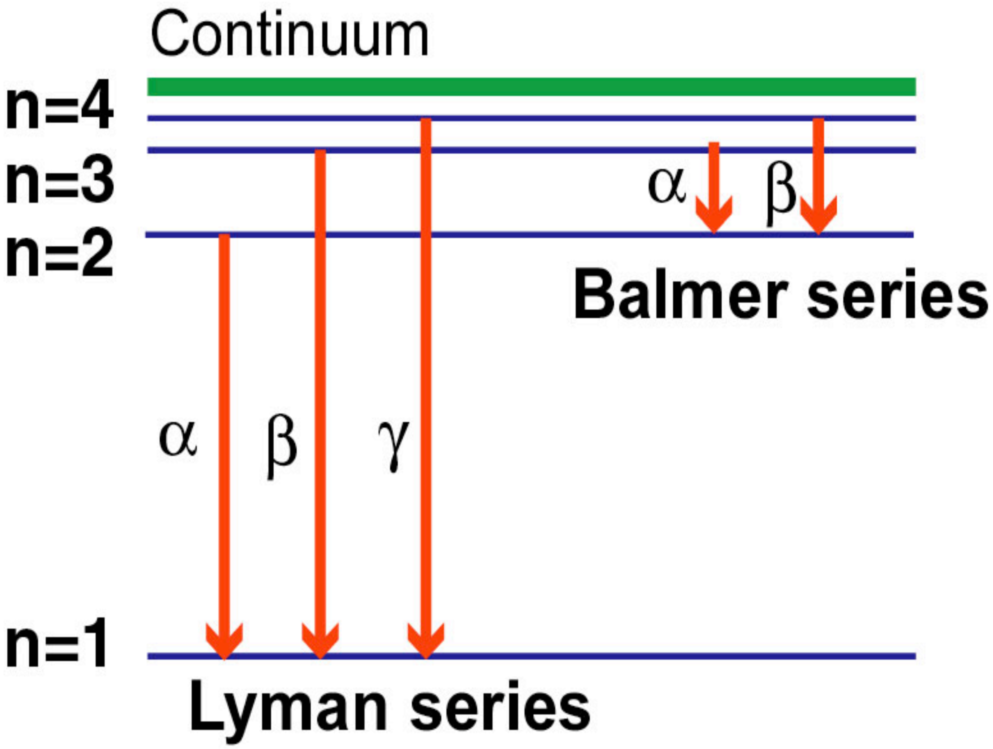
Molecules can be very complicated, like those that make up our DNA.

We often picture electrons ‘orbiting’ the nucleus. This description correctly conveys the fact that electrons have only certain permitted positions in an atom. Because different nuclei have different masses and charges, electrons of different elements have different orbit structures.

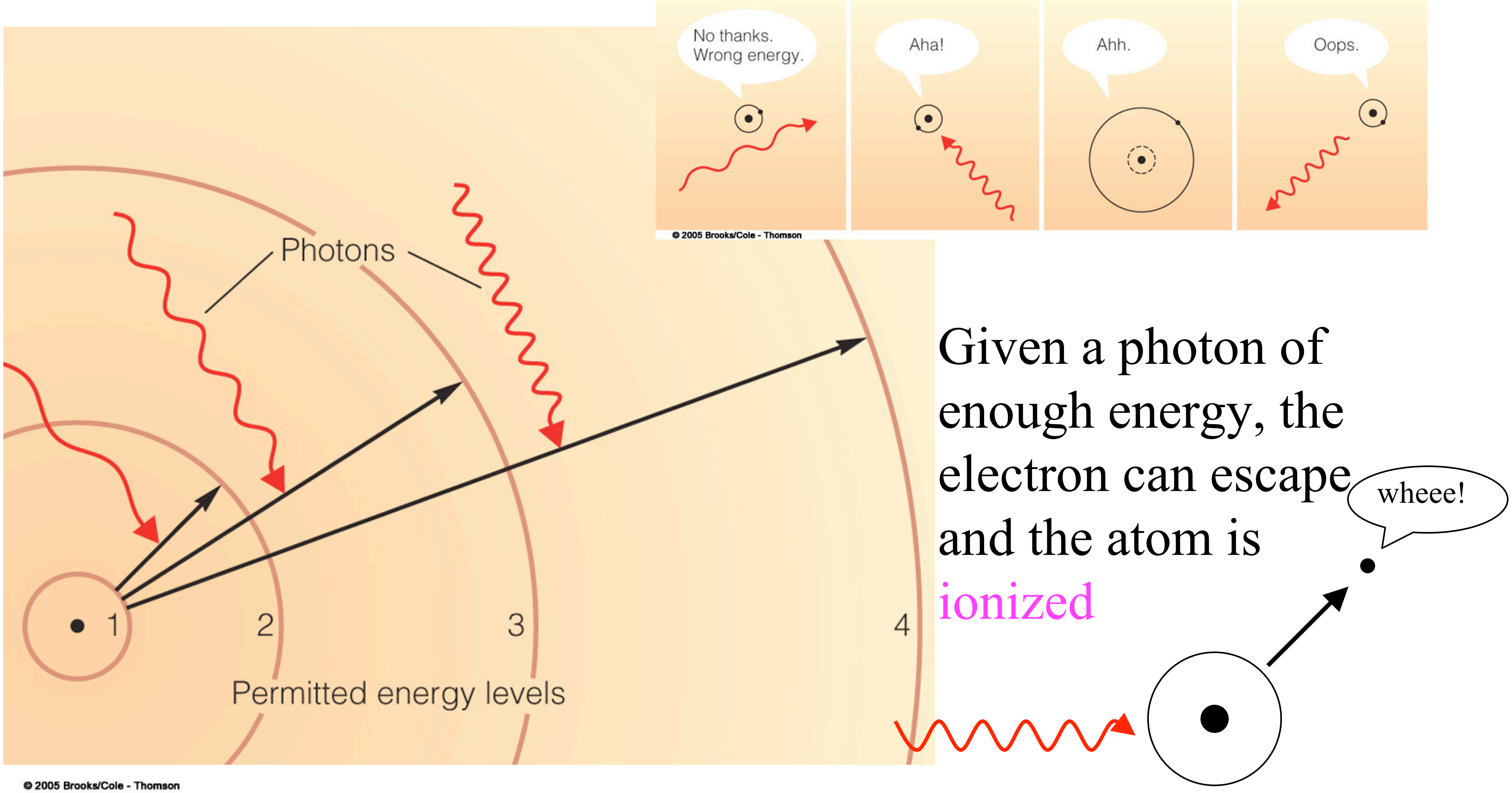


To allow easy reference to different electron levels and transitions we label each level n=1,2,3 etc. starting at n=1 for the ground state (lowest energy level).

In addition, we refer to transitions in a hydrogen atom according to how many levels the electron moves. The Lyman series involves transitions from the n=1 level and Balmer from n=2. We also give a Greek letter to show how many levels the electron has moved: α for one jump, β for 2 levels, γ for 3 levels etc. Used together, the Lyman α line refers to an electron moving between the n=1 and n=2 levels.

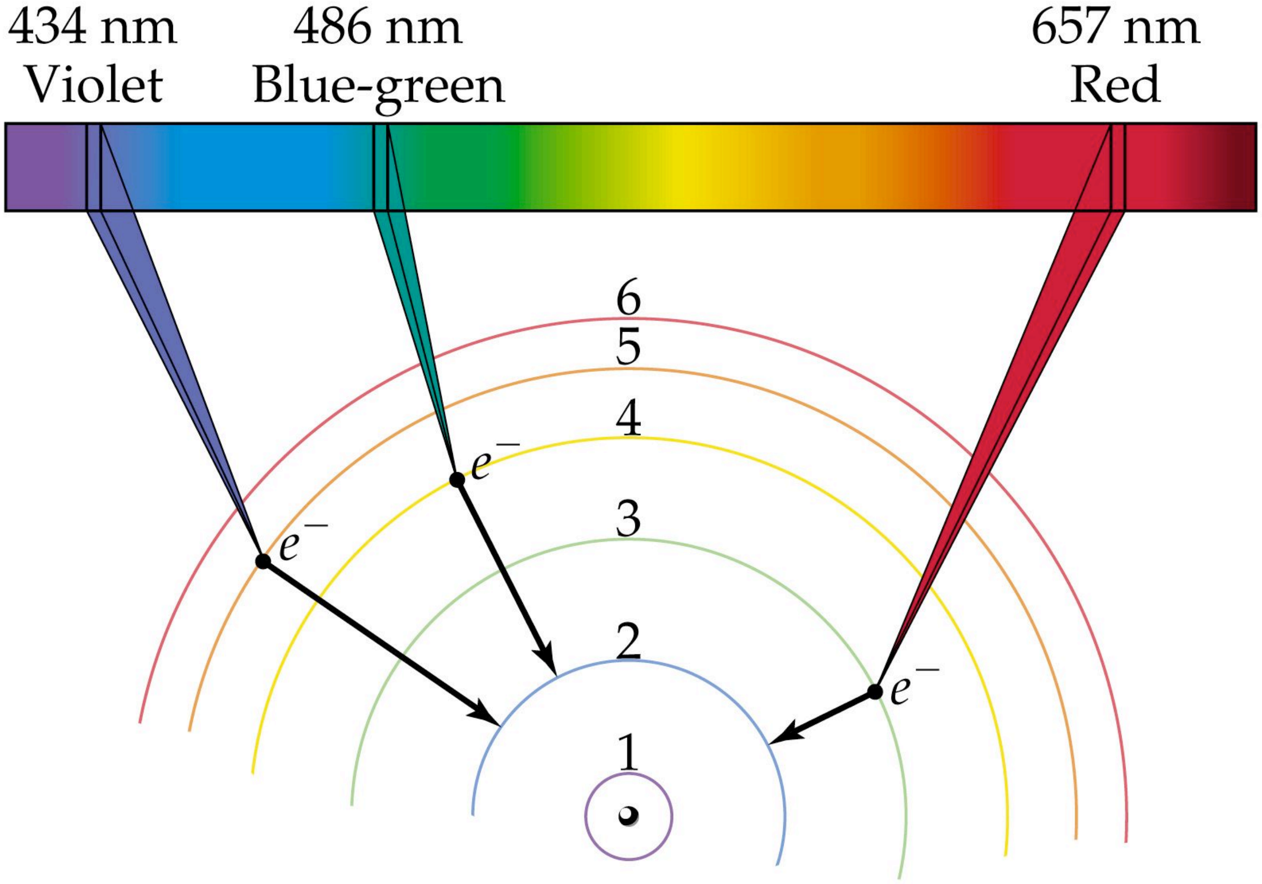


Electrons can move between orbits if they are given enough energy, e.g. by a passing photon. But only a photon with the exact amount of energy will do! Eventually, the electron will decay back to a lower level.



Given a photon of enough energy, the electron can escape and the atom is ionized

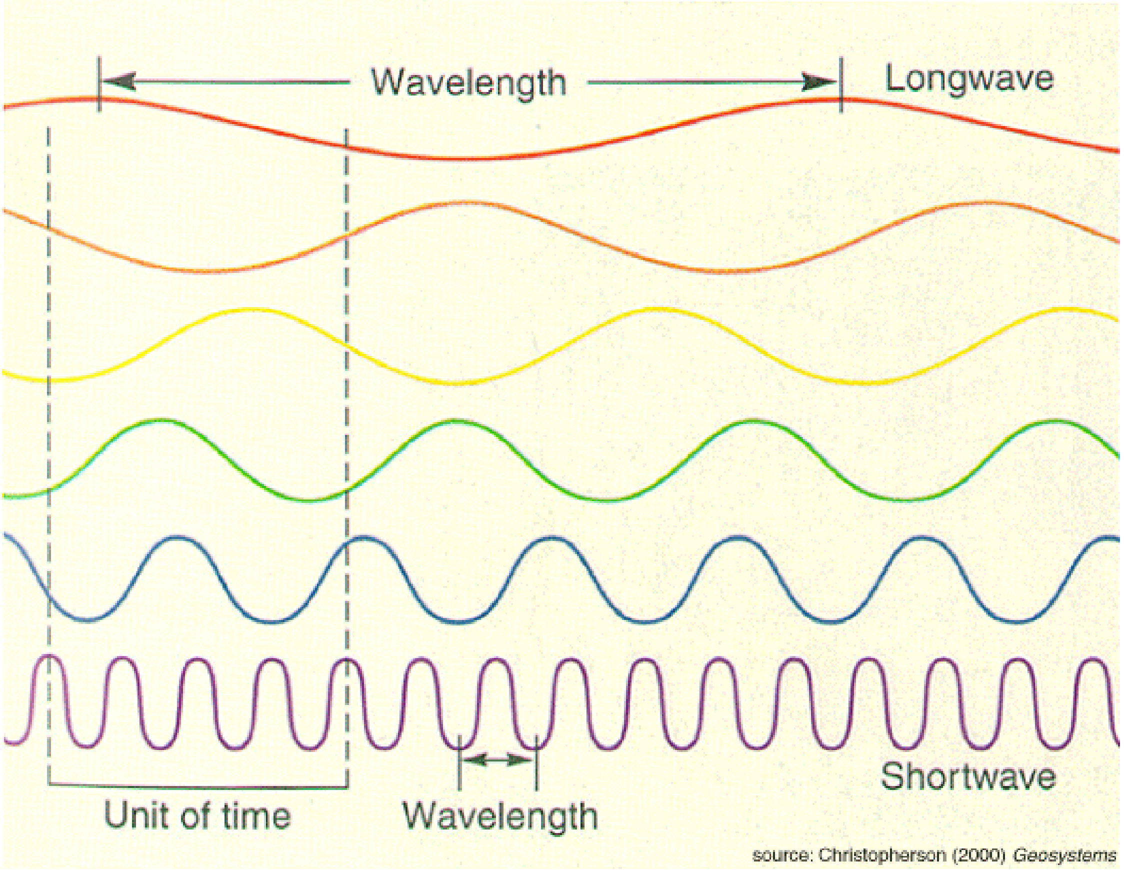
A more energetic (blue) photon is needed in order to excite an electron to higher orbits from the ground state (lowest energy level). Less energetic (red) photons are required for smaller jumps.



Similarly, each time an electron drops from a higher energy level to a lower energy, a photon is emitted with an energy (wavelength) corresponding to the gap between the two levels. A small jump gives a red photon and a big jump (larger change in energy) gives a blue photon.

Low energy

High energy



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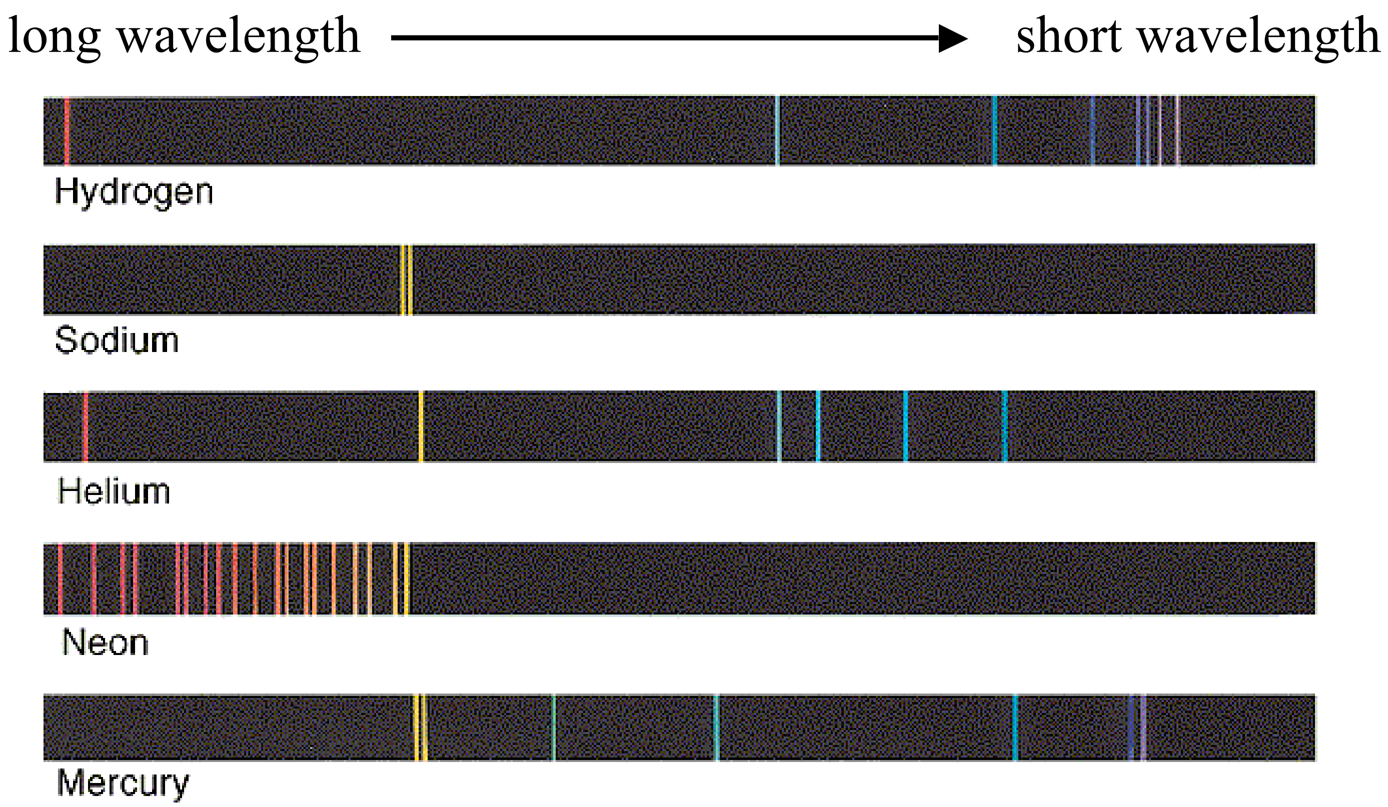
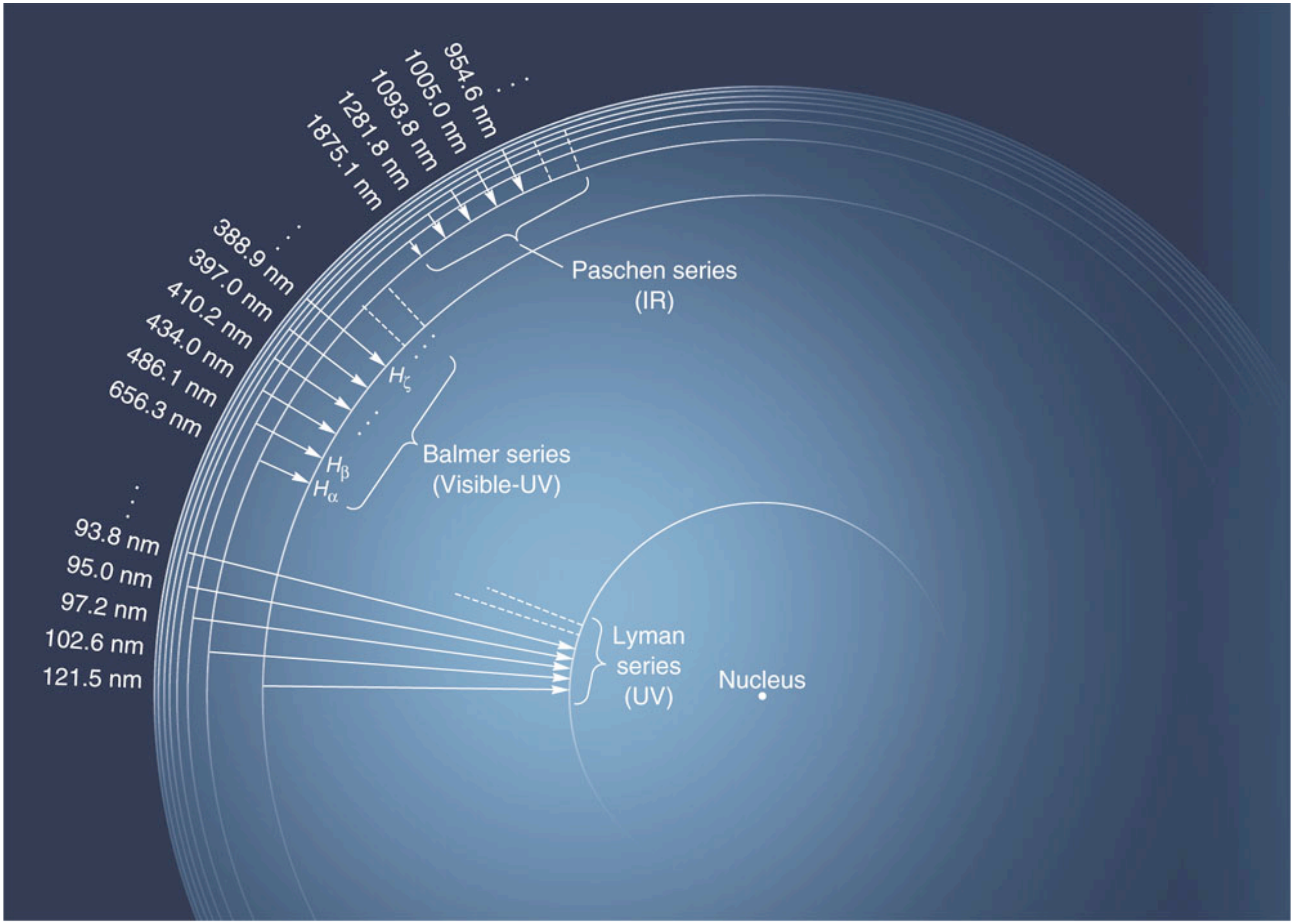
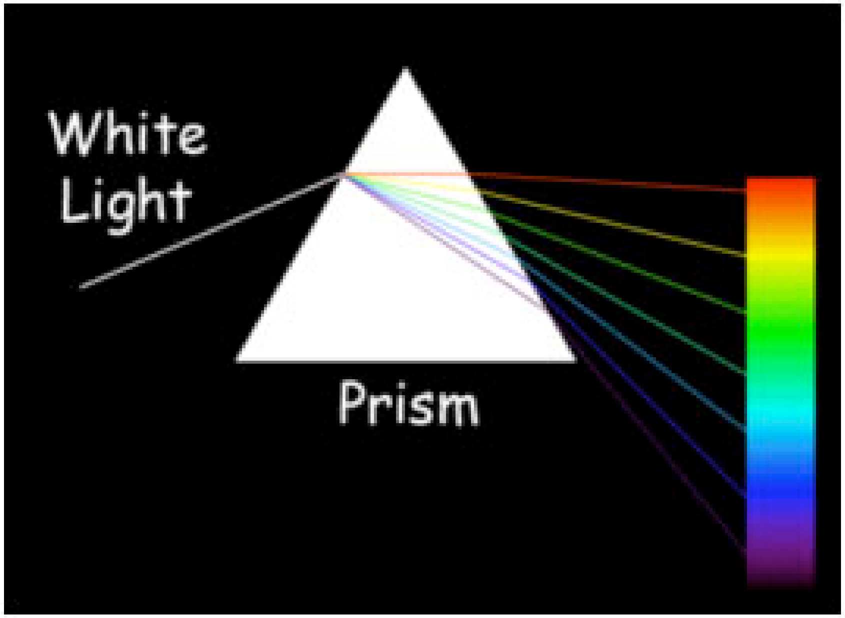


In this way, a hot gas (I.e. one that is excited by incoming photons) produces an emission spectrum, consisting of sharp emission lines at fixed wavelengths, each corresponding to a different electron transition. because each element has a unique configuration of electron orbits, its emission spectrum is unique, like a fingerprint.

Not all of these lines occur in the visible, the higher energy ones occur in the ultra-violet (UV) and lower energy ones are seen in the infra-red (IR).



However, this emission spectrum is very different from the continuous spectrum we see when sunlight is refracted through a prism. So there must be another way of making light in stars.



This starlight originates in the outer part of the star called the photosphere. This light comes from moving electric charges, such as electrons. A moving charged particle creates electromagnetic energy - light! These moving charges create a continuous spectrum, I.e. light at all wavelengths.

A hot object glows because the moving electrons create electromagnetic energy that is emitted as photons. This kind of emission (that produces a continuous spectrum) is called blackbody radiation and has a very distinctive shape.

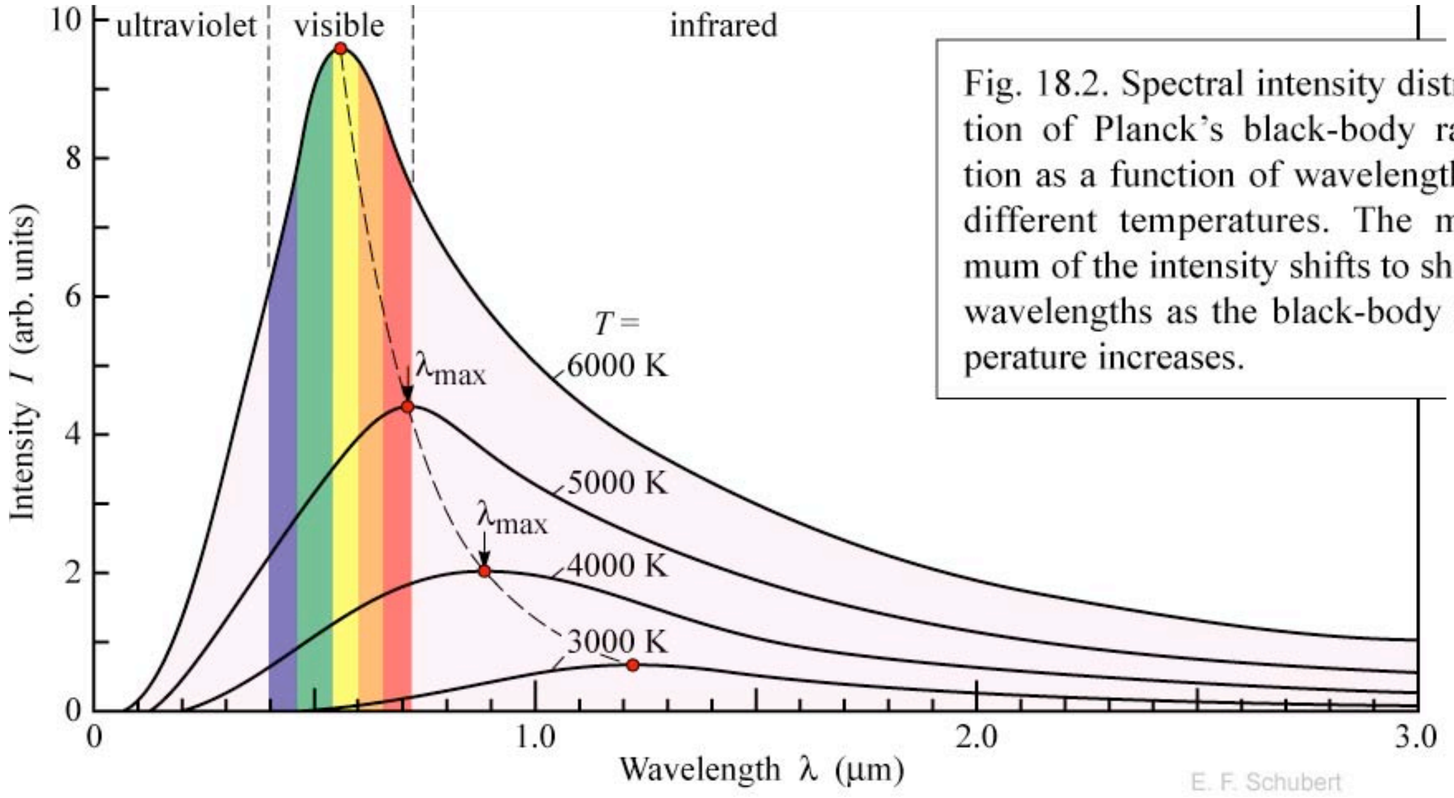
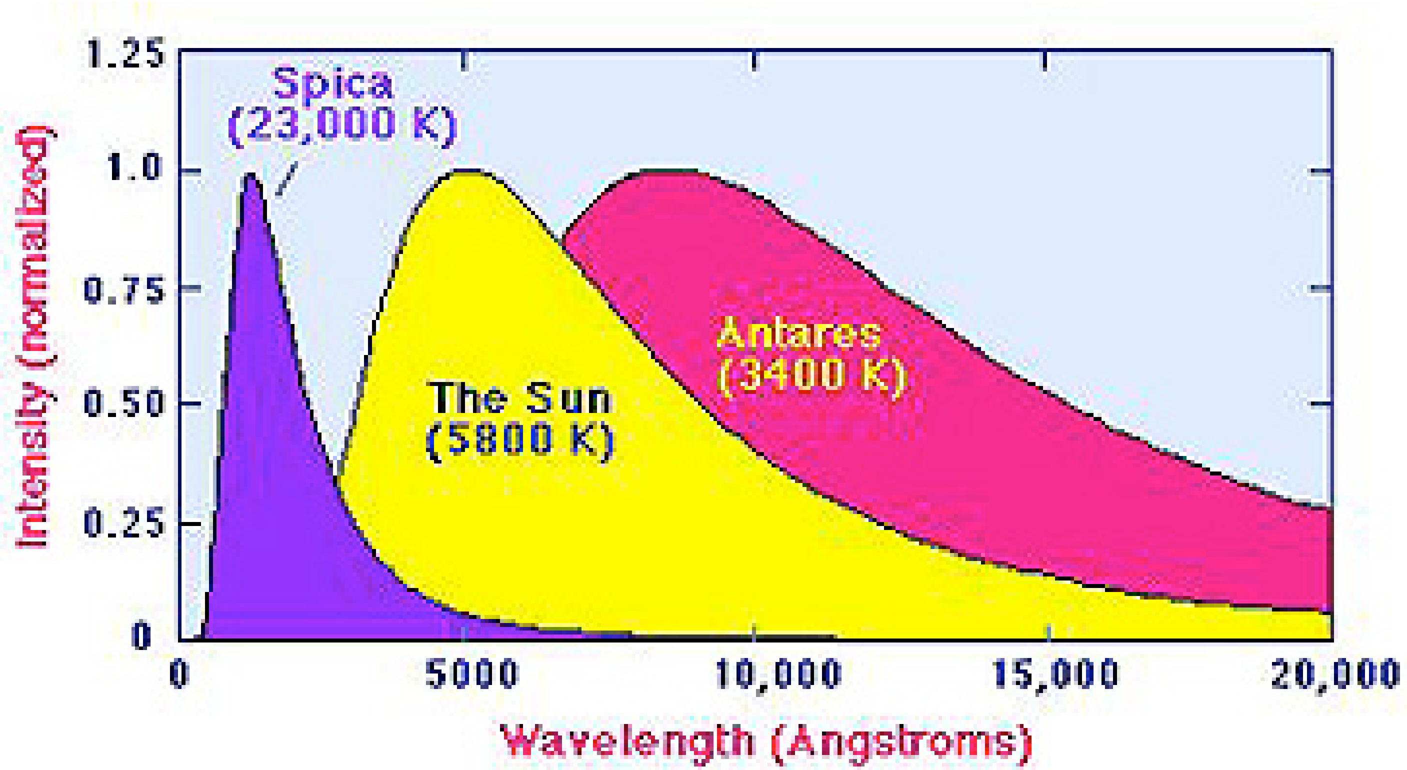


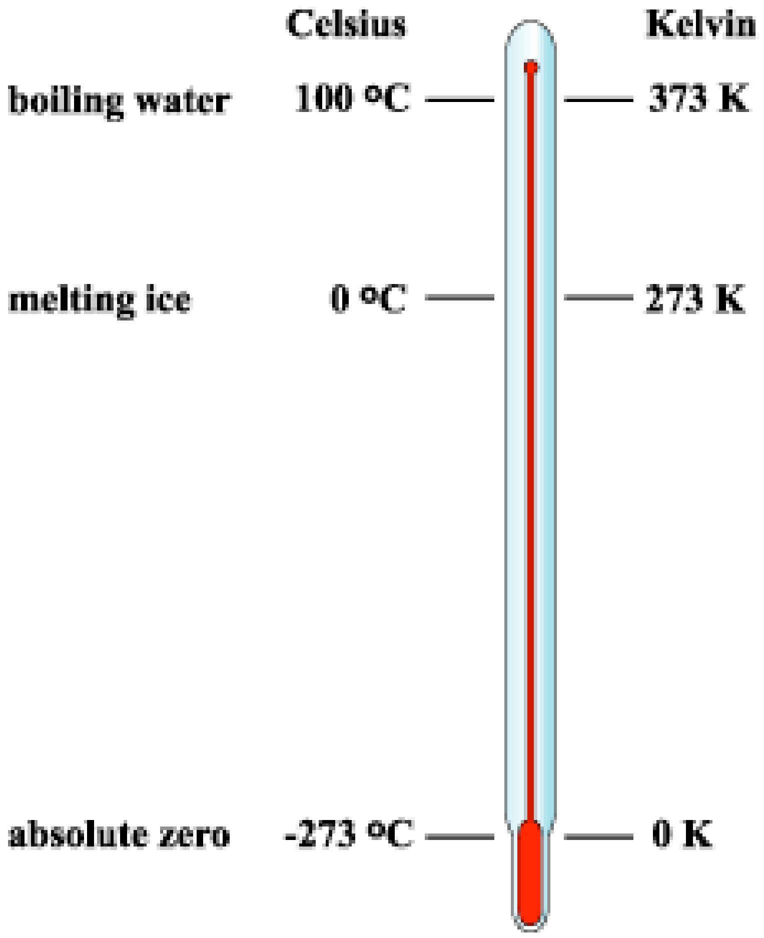
Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

E. F. Schubert

The wavelength at which a blackbody emits most of its radiation (λ_{max}) depends on its temperature. A hotter body contains more energetic particles so has λ_{max} at a shorter wavelength, but the overall shape of the radiation stays the same. This is the reason that hotter objects look bluer than cooler objects (which have a redder colour).



Temperature is a measure of energy. If a system is hot it has more energy than a cold system because the atoms are moving around much faster. In astronomy, we measure temperatures on the Kelvin scale. A change of 1K is the same as 1 centigrade (celsius). The only difference is that there is a 273 degree offset between centigrade and Kelvin. 0 K is also know as absolute zero, this is the coldest possible temperature.



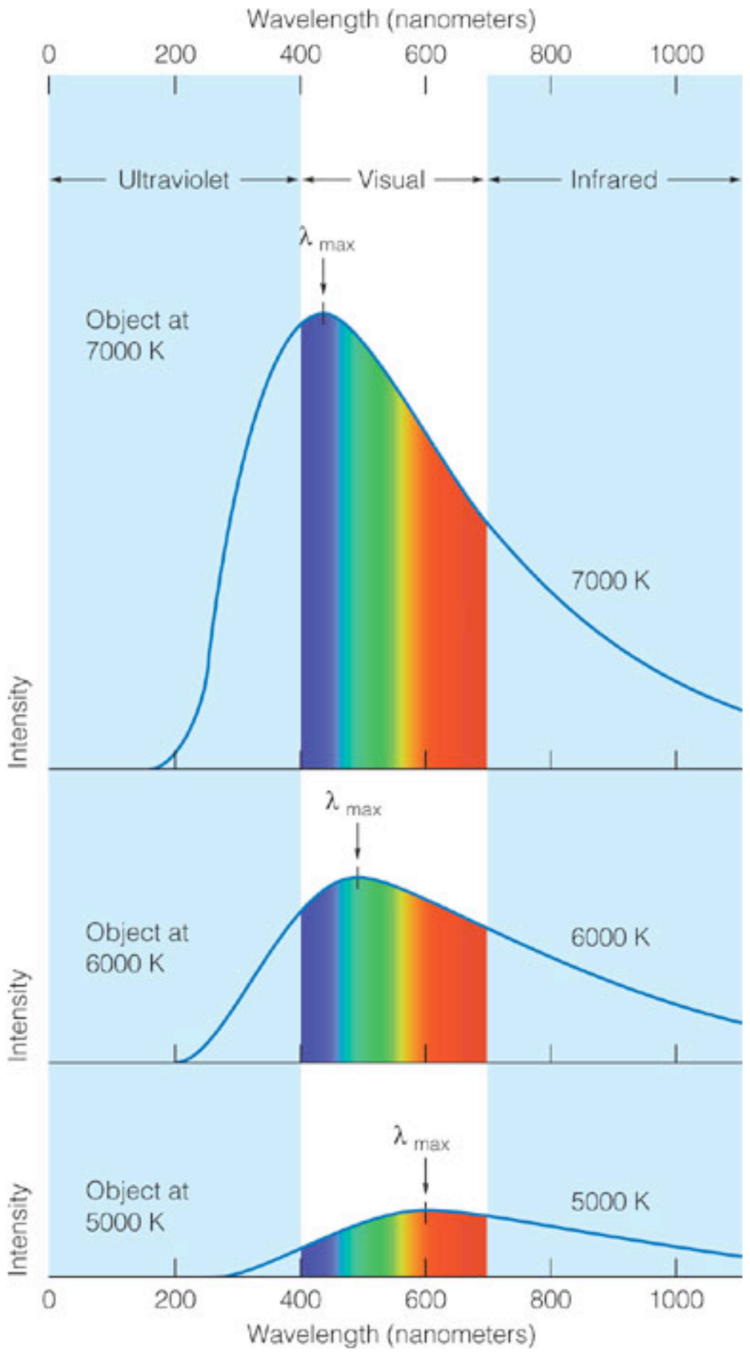
At absolute zero, atoms are no longer moving, ie a minimum energy has been reached.

temperature (K) = temperature (C) + 273

The value of λ_{max} and temperature are connected by Wien's law:

$$\lambda_{max}\,(\text{nm}) = \frac{3 \times 10^6}{\text{Temperature (K)}}$$

The temperature of the sun's surface is about 6000 K, so it emits most of its light in the middle of the optical window. If the sun were much hotter/cooler, its light would fall in the UV/IR and get blocked by our atmosphere!



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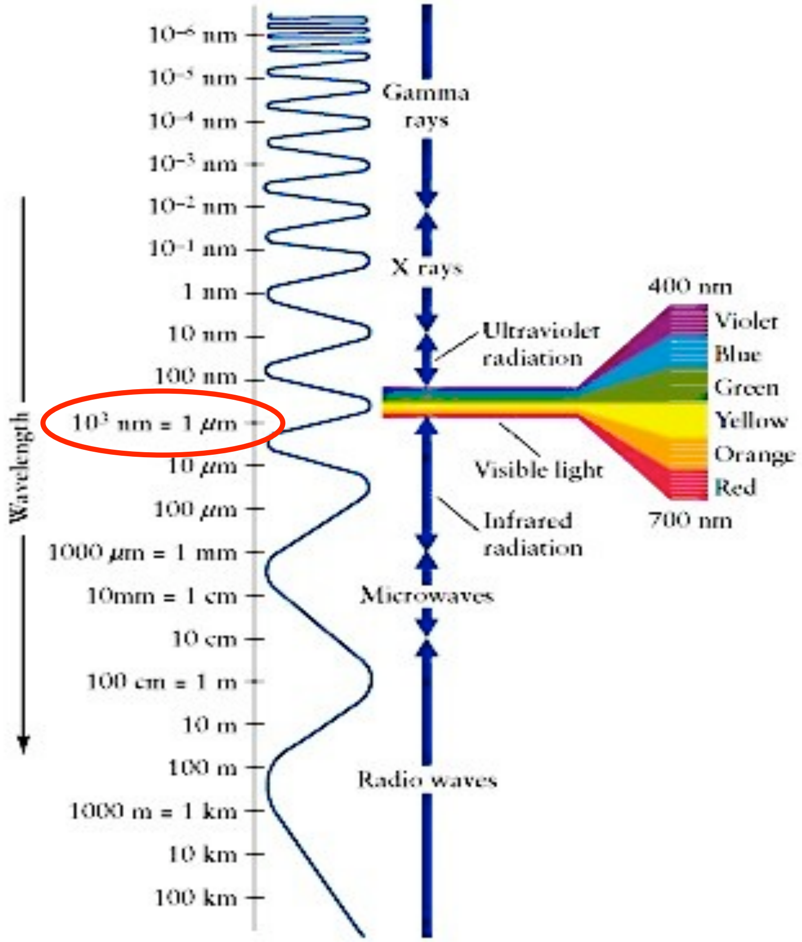
Example: Your body temperature is about 37 degrees centigrade, what is this in kelvin? At what wavelength do you emit most of your radiation? What part of the electromagnetic spectrum is this?

$$T_{kelvin} = T_{centigrade} + 273 = 37 + 273 = 310\text{ K}$$

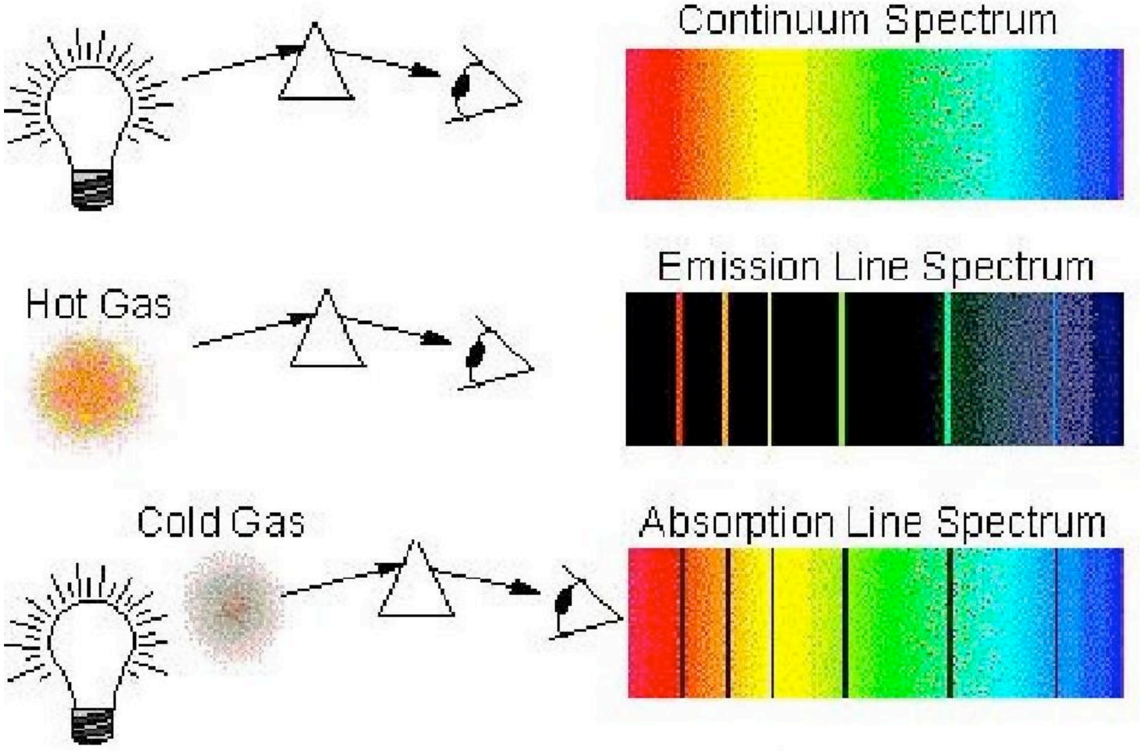
$$\lambda_{max}\,(\text{nm}) = \frac{3 \times 10^6}{\text{Temperature (K)}}$$

$$= \frac{3 \times 10^6}{310} = 9677\text{ nm}$$

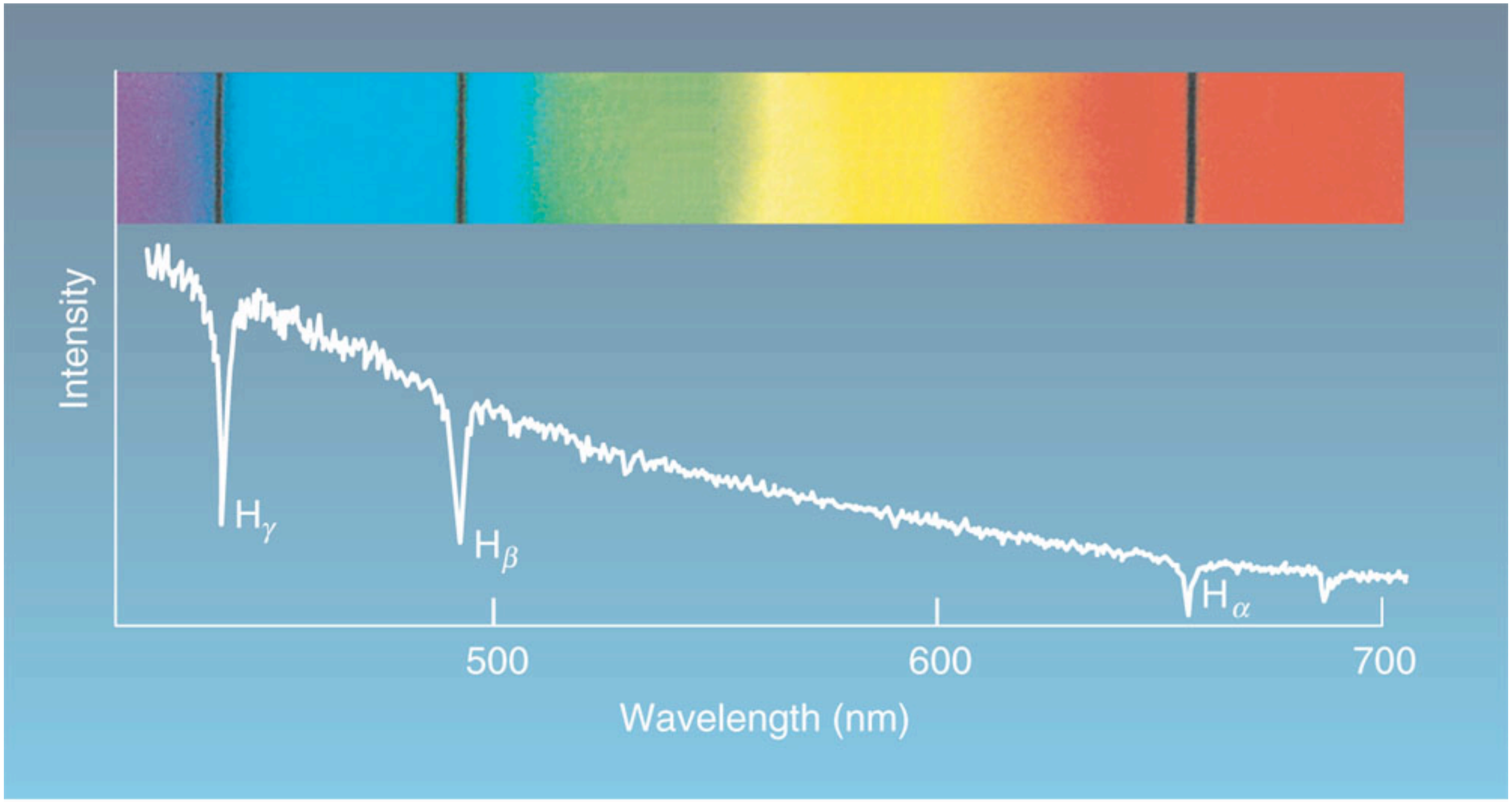
1000 nm is the same a 1μ m (1 micron), so 9677nm = 9.7 μm , which is in the infra-red.



In addition to continuous and emission spectra, there is a third type of spectrum: an absorption spectrum. This occurs when light from a blackbody passes through a cold gas. Atoms in the cold gas absorb light at wavelengths that correspond to the electron’s orbital transitions. The dark lines show where light from the continuous spectrum has been ‘used up’, so is a sort of ‘inverse emission spectrum’

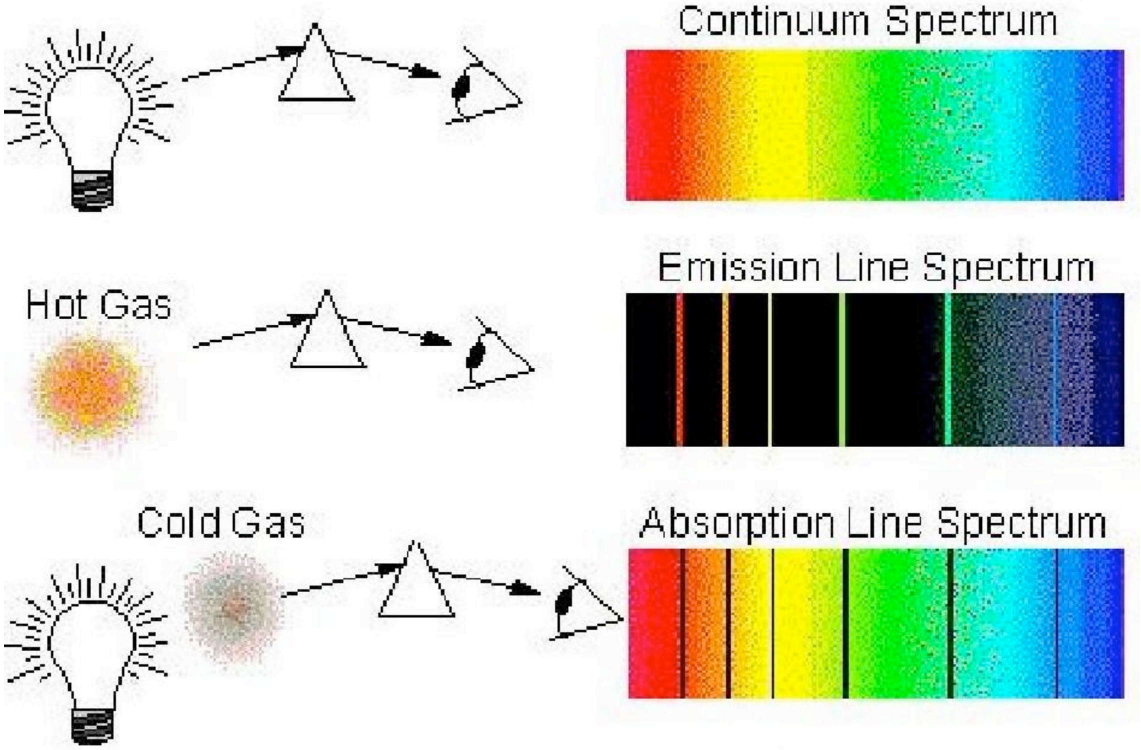


Although we said that stars like the sun produce blackbody radiation, their spectra actually show absorption lines. This is because cooler layers of gas near a star's surface absorb certain wavelengths of the blackbody (continuous) spectrum. Some of the strongest lines are those from hydrogen

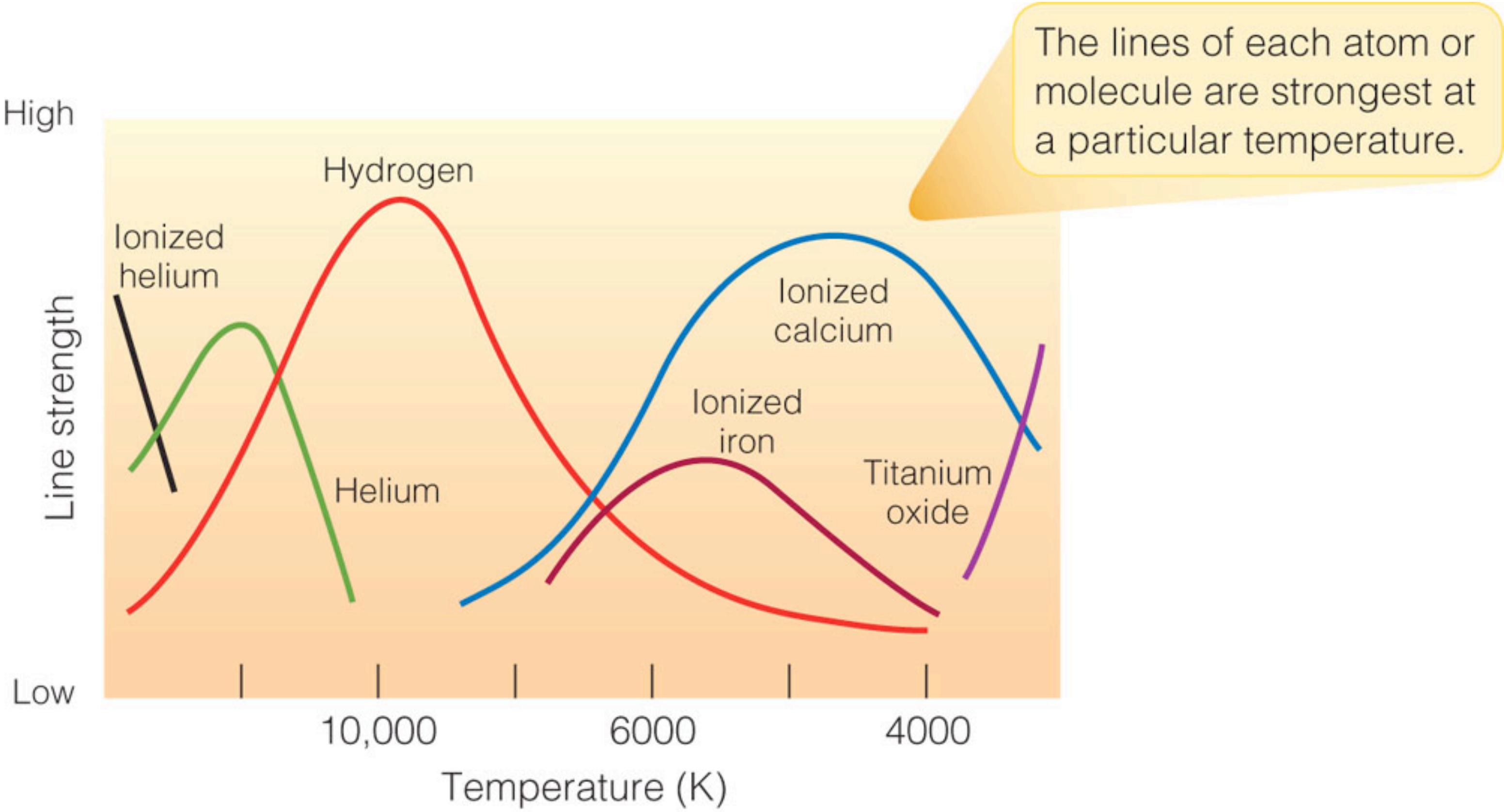


These 3 types of radiation are summarised by Kirchoff's laws

1) A solid or dense gas will produce a continuous spectrum
2) A hot low density gas will produce an emission spectrum with lines at fixed wavelengths
3) A cold gas in front of a continuum source will produce an absorption spectrum

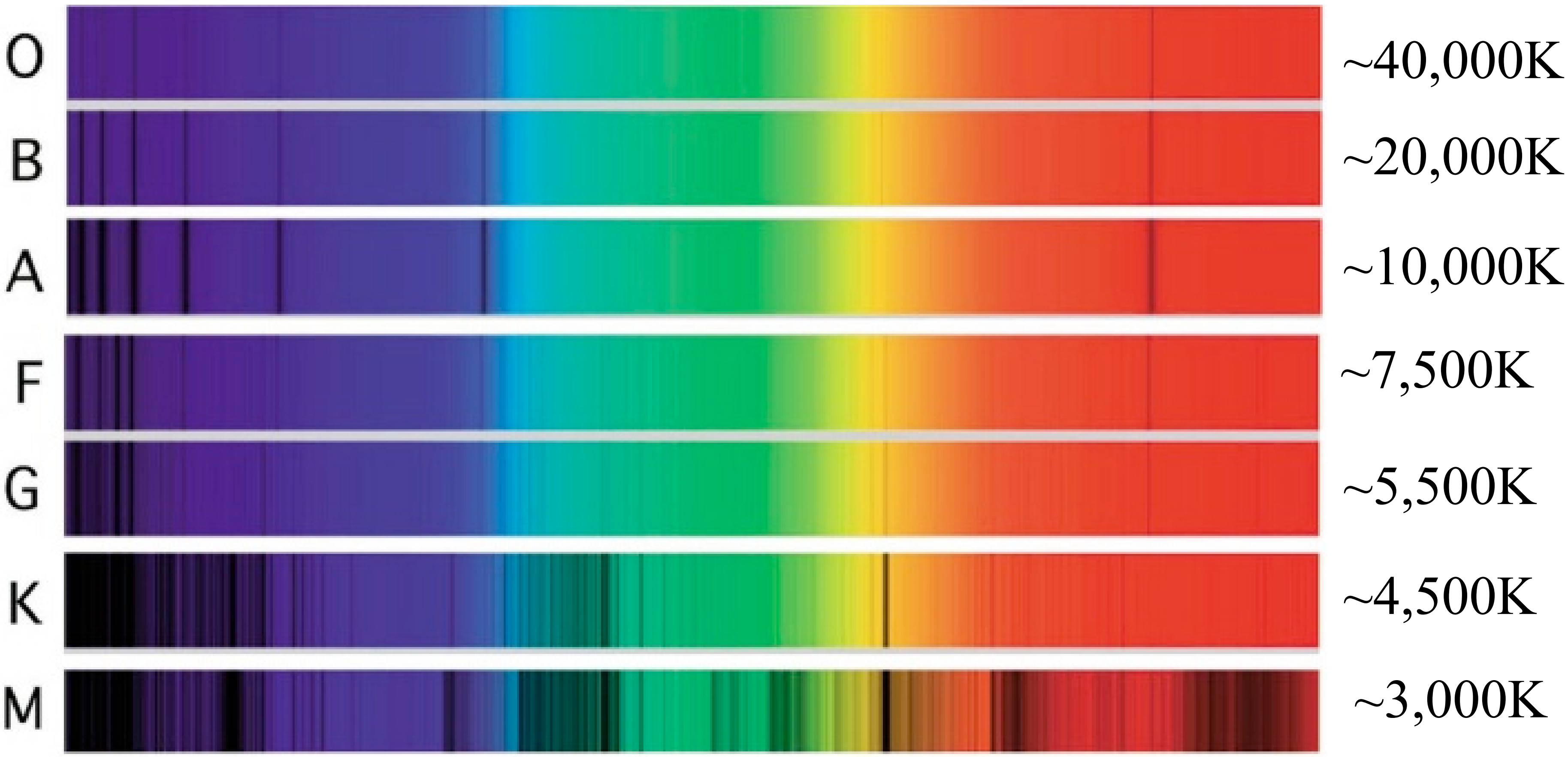


The spectrum of a star tells us how hot its surface is. We figure out the temperature by measuring how strong different absorption lines appear. Spectral lines are an accurate thermometer because they tell us how many electrons are in the different orbits of an atom/ion/molecule which in turn tells us about the temperature.



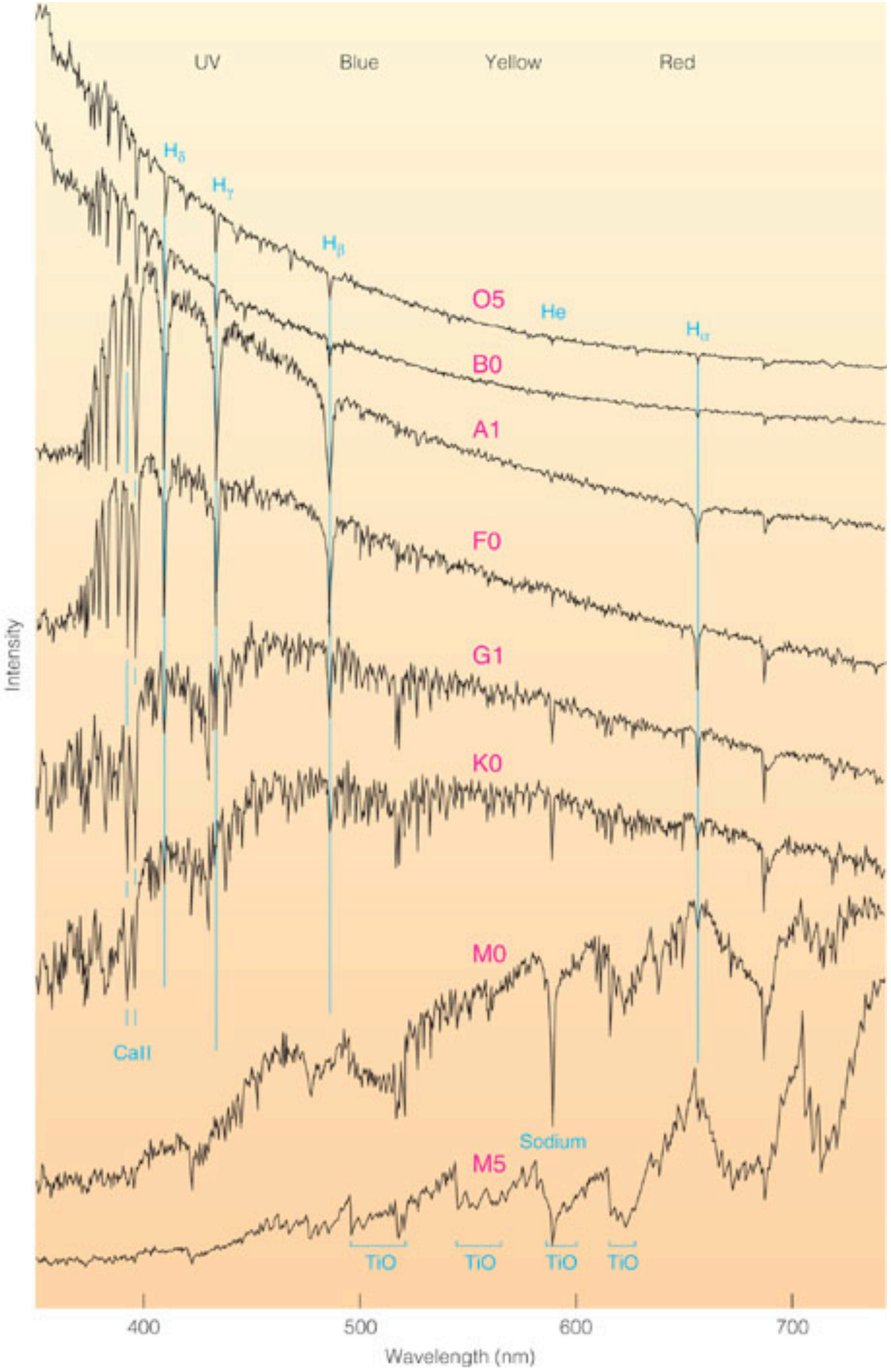
The lines of each atom or molecule are strongest at a particular temperature.

For convenience, we refer to stellar types (classified by temperature) by a letter



Oh Be A Fine Girl/guy Kiss Me !!

We can also sub-divide these letter classifications with a number from 0-9 where 0 is the hottest and 9 is the coolest. In very cool stars (e.g. M-stars) the atmosphere is cool enough that molecules like TiO (titanium oxide) can form. In hotter stars, molecules are destroyed by the very energetic photons.



In addition to telling us the temperature of a star, the strength of its absorption lines tell us the abundances of different chemical elements in that star's atmosphere. Cecelia Payne Gaposchkin was the first person to untangle the effects of temperature and abundance in the sun.

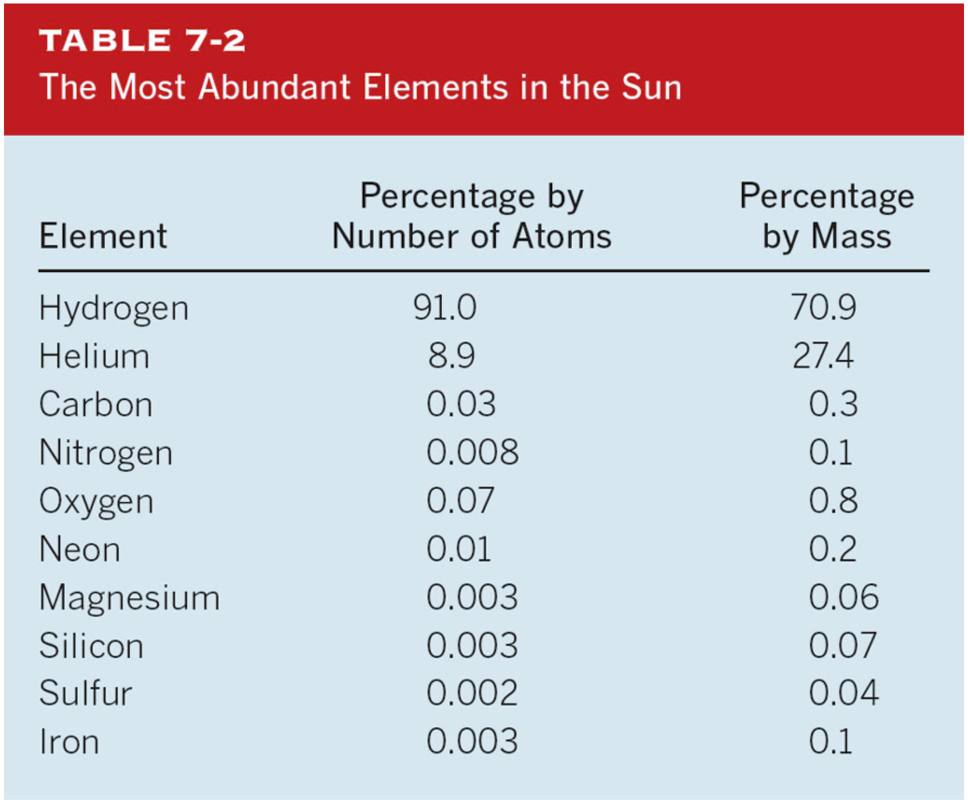
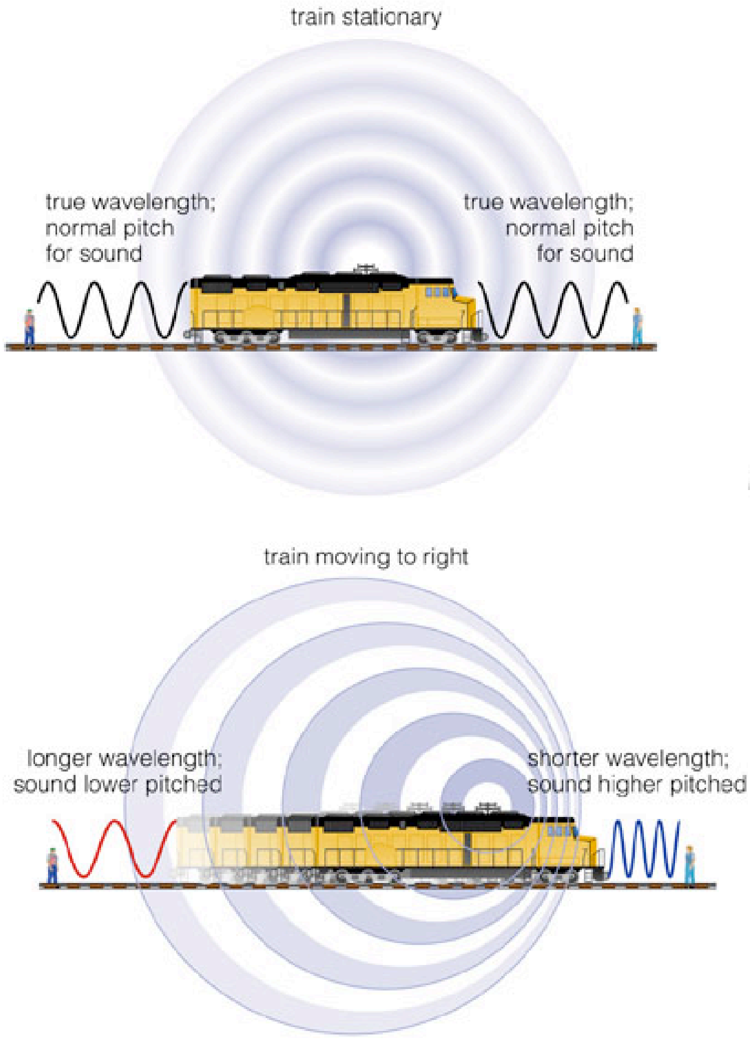


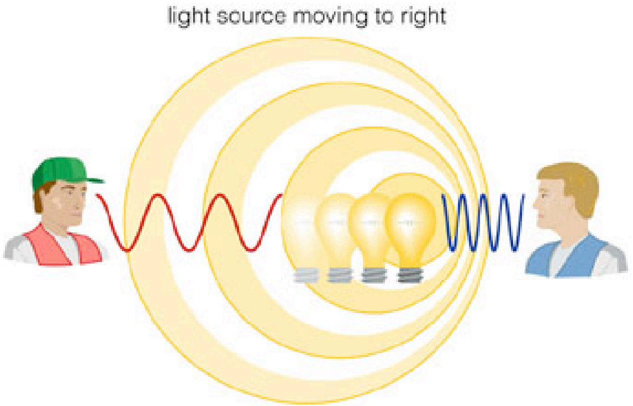
TABLE 7-2

The Most Abundant Elements in the Sun

Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	91.0	70.9
Helium	8.9	27.4
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.07	0.8
Neon	0.01	0.2
Magnesium	0.003	0.06
Silicon	0.003	0.07
Sulfur	0.002	0.04
Iron	0.003	0.1

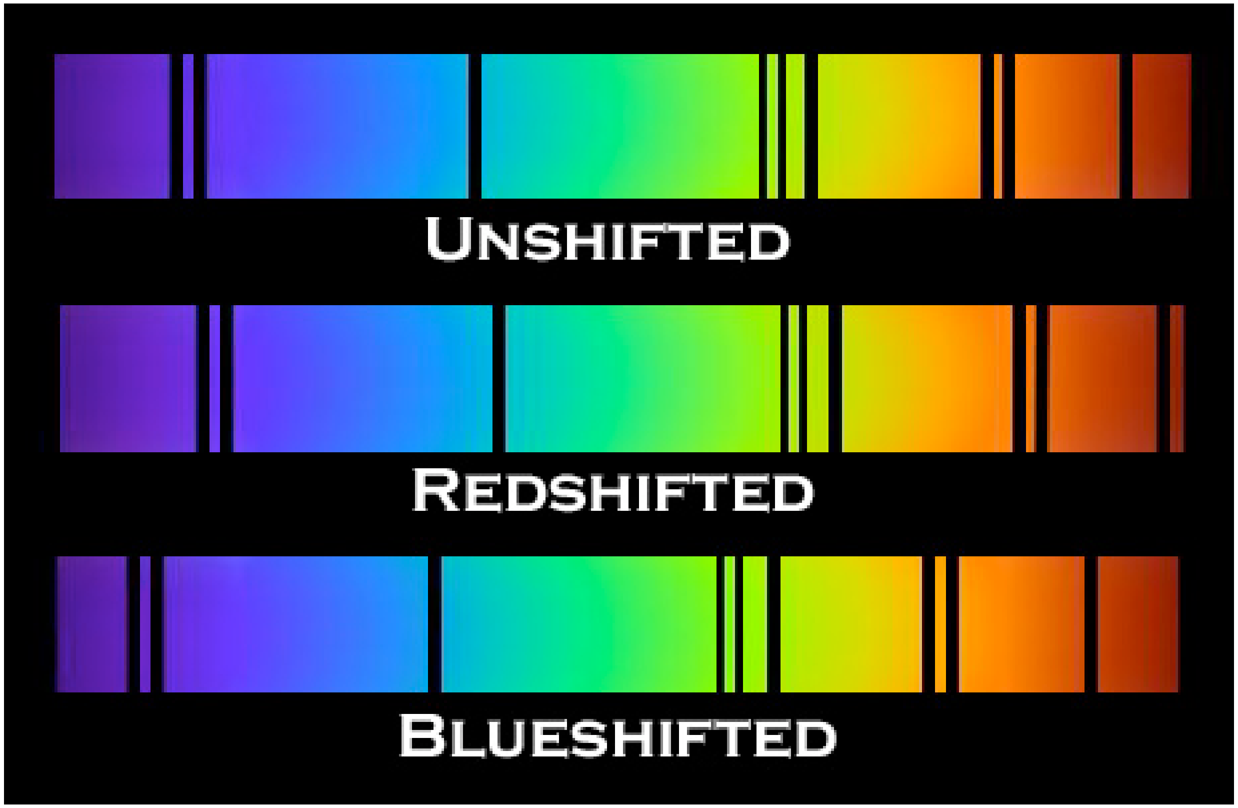
Finally, we can also figure out the velocity that the light source is moving at relative to us. We do this by measuring the Doppler shift of the spectral lines.



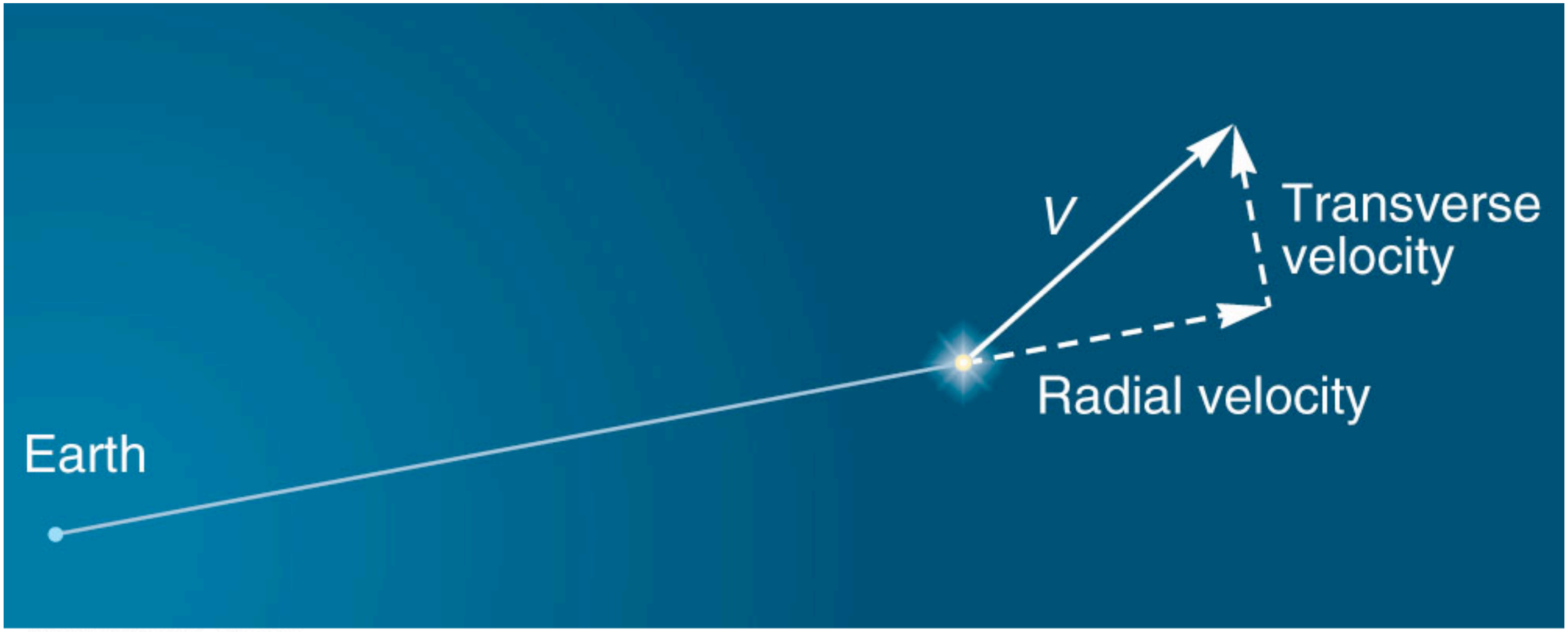


If a light source is approaching us, we see its spectral lines shifted towards the blue end of the spectrum: blueshift. A blueshift results in spectral lines having a shorter observed wavelength

If a light is receding from us, we see its spectral lines shifted towards the red end of the spectrum: redshift. A redshift results in spectral lines having a longer observed wavelength



The shift in wavelength only tells us about the stars velocity towards or away from us (its radial velocity), we can't infer anything about its motion across our line of sight (transverse velocity) because this doesn't cause a Doppler shift.



We calculate the radial velocity with this simple formula:

$$\frac{\text{velocity}}{\text{speed of light}} = \frac{\text{change in wavelength}}{\text{original (rest) wavelength}}$$

A shorter way of writing this is: $\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$

Example: You take a spectrum of a star and notice that the Lyman alpha line is shifted from its rest wavelength of 121.6 nm to 121.8nm. What is the velocity of the star?

In this example, λ=121.6 nm and we know that c=300,000 km/s.

$v = (121.8-121.6)/121.6 \times 300{,}000$

$= 493$ km/s because the observed wavelength is larger than the rest wavelength, this is a REDSHIFT.

Doppler shifts also contribute to the shape of stellar absorption lines. Every atom absorbs light at a particular wavelength, but that wavelength shifts depending on the velocity of the gas. If the gas is cool, the atoms move slowly and don’t have a wide range of velocities so the absorption line is narrow. If the gas is warm, the atoms move faster, have a wider range of velocities, so the absorption line looks broad.