CLASSNOTES 10

Blackbody radiation

There is one circumstance in which the spectrum of the light produced is quite independent of the matter producing it. I refer to black bodies and black body (thermal) radiation.

- **What is a blackbody?** We discussed the definition of a blackbody (BB) and why the *em* radiation emitted by it is just dependent on the body's temperature (and size).

- **Stefan-Boltzmann Law**. A hotter BB emits more radiation at all wavelengths than a cooler BB of the same area. The total amount -- all wavelengths considered -- scales as temperature to the fourth power: $E \propto T^4$.

- **Wien's Law**. The distribution of radiation with wavelength changes with temperature. Hotter BBs emit a larger fraction of radiation at shorter wavelengths than cooler BBs. This is expressed Wien's Law: $\lambda_{max} \propto 1/T$, where Fig. 6-6 defines λ_{max}. This law relates color to temperature provided that the emitting object is a BB or approximately so.

- **BB Laws and Stars**
  - Stars emit approximately as BB's
  - Color of a star indicates its temperature but . . . dust . . .
  - Luminosity (total energy output) of a star L is $L \propto$ (Area) x (T^4)
    $\propto R^2T^4$
    where R is the radius of the star.
    Often, we use the Sun as a reference or

$$\left(\frac{L}{L_\odot}\right) = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4$$

where the suffix $\odot$ is the traditional symbol for the Sun.

Here are some simple exercises:

1. Two stars of equal size have T = 3,000 K and 20,000 K.
   Which radiates more energy?
   How many times more?
   What color will each appear?
   Which radiates more energy in the red part of the spectrum?

2. A star has a surface temperature of 12,000 K and emits as much energy as the Sun (T = 6,000 K).

   Is the star smaller or larger than the Sun?
   By how many times?

3. The binary star UT-301 consists of a blue and a red star emitting the same total amount of energy. Which star has the larger radius?

Here are several questions and answers about stellar spectra:

Q.1. The absorption lines of metals, such as calcium, are prominent in the solar spectrum. Hydrogen lines are less prominent. Why does this not indicate that the Sun consists mostly of these elements instead of hydrogen?

To answer this question, we must recall the Bohr model of the atom in which the nucleus (very small and positively charged) is surrounded by an electron (negatively charged) cloud. The electrons are constrained to move only in selected orbits. They are not like objects in orbit around a star free to select any orbit. Indeed, electrons should be thought of as waves not particles in this context.

For our purposes, it should suffice to examine the hydrogen atom which consists of a single electron and a proton as a nucleus. We can number the allowed electron orbits 1,2,3,. . . beginning with the orbit closest to the proton.

If a hydrogen (H) atom is left undisturbed, the electron will drop down into Bohr orbit 1 within a small fraction of a second. It can absorb light only at frequencies corresponding to upward (outward) jumps such as 1 --> 2, 2 --> 3, 1 --> 4, ... The H atom's structure is such that all of these jumps are in the ultraviolet which is blocked by the Earth's atmosphere, and therefore, inaccessible to the ground-based astronomer. Result is that cool or cold H gas is not spectroscopically detectable from the ground.

Suppose now the H atoms are in a hot environment. Then the collisions with photons and energetic particles increase and the rate for upward jump 1 --> 2, 1--> 3, etc., increases. Downward jumps 2 --> 1, 3 --> 1, 3 --> 2, etc., occur much as before. But the population of H atoms with the electron in orbit, 2,3,. . ., increases slightly as the upward rate increases. In these circumstances, a photon traversing hot hydrogen gas may encounter a H atom with the electron in orbit 2 (say), and if the frequency is well matched, can induce the electron to jump from 2 --> 3 (say). Such jumps 2 --> 3, 2 --> 4,. . . are in the visible part of the spectrum (the Balmer series), and so hot H gas is detectable from the ground.

On the other hand, the metal atoms such as calcium have a different electronic structure. Their equivalent to the Bohr orbit 1 (the lowest orbit), 2, 3, etc., are such that 1 --> 2, 1 --> 3 jumps are in the visible part of the spectrum. Therefore, light at the appropriate frequencies is readily absorbed by the metals; essentially all of the metal atoms have an electron in the Bohr orbit 1 equivalent. As we have argued, only the very small fraction of the H atoms, which can be found with an electron in Bohr orbit 2, are capable of providing an absorption line in the visible spectrum. Therefore, although the H atoms outnumber the metals by about 10^5 to 1, the metals provide the strongest lines in the solar spectrum. Note $10^5 \equiv 100{,}000$.

Q.2. Why is the Balmer series the most commonly observed spectral series of atomic hydrogen?

The answer can be developed from the Bohr model H atoms just discussed.

The series of lines 1 --> 2, 1 --> 3, . . . is in the ultraviolet and 4 --> 5,. . . and so on are in the infrared. Detection of the former series requires access to a telescope above the Earth's atmosphere. The latter series are generally weaker than the Balmer series (2,3,4,. . .) for a variety of reasons: (i) the population of H atoms with electrons in orbit 3,4,. . . is less than that with electrons in orbit 2; (ii) the probability that the H atom will capture a photon and jump 3 --> 4, . . . is less than that for the Balmer series jumps. Also, the fact that the infrared is not so easily observed as the visible part of the spectrum also ensures the prominence of the Balmer series.

Q.3. Explain why the hydrogen absorption lines become weaker in the spectra of stars whose temperatures are (a) above 10,000 K and (b) below 10,000 K.

(a) At temperatures above about 10,000 K, the H atom collisions with particles and ultraviolet photons often lead to an ionization of the atom, i.e., the electron and proton are stripped apart. As the temperature increases, recall the blackbody laws tell us that more radiation is emitted, and an increasing fraction is emitted at high frequencies (short wavelengths). Therefore, increasing temperature leads to increasing numbers of ultraviolet photons with sufficient energy to ionize the H atom (strip the electron from the photon). Ionization can also occur through a collision with a particle. As the temperature increases, the average speed and energy of the particles increases. Then the rate of ionization through collisions increases.

The increasing ionization rate for temperatures in excess of about 10,000 K means the number of H atoms decreases. The decreasing atom density leads to a weakening of the hydrogen absorption lines.

(b) The answer is contained with Q1 above.

Q.4. If you looked at the spectrum of what appeared to be a single star and found lines of ionized helium as well as molecular bands, what conclusion could you draw? Why?

Molecules are the signature of cool gas. Ionized helium is a signature of very hot ($T \sim 40{,}000$ K) gas. Molecules and ionized helium cannot coexist in the atmosphere of a normal star.

The simplest explanation for the observation is to suppose that the single star is in fact a double star. One star is hot. The other is cool. Both have similar luminosities so that they contribute about equally to the spectrum. The hot star must be an O type and the cool star an M type.

Q.5. Describe the major characteristics of a neutral atom.

A neutral atom contains a number of electrons (negatively charged) in orbit around a positively charged center of nucleus. The number of electrons balances the number of positive charges on the nucleus, hence the atom is electrically neutral. The electron cloud has a radius of about 10^{-8} cm (1 Å). The radius of the nucleus is only about 10^{-13} cm, i.e., 100,000 times smaller than the electron cloud. The nucleus is composed of a number of protons (positively charged) and neutrons (no charge). Each proton and neutron is nearly 2,000 times more massive than an electron, and therefore, the atomic nucleus contains effectively 100% of the mass of the atom.

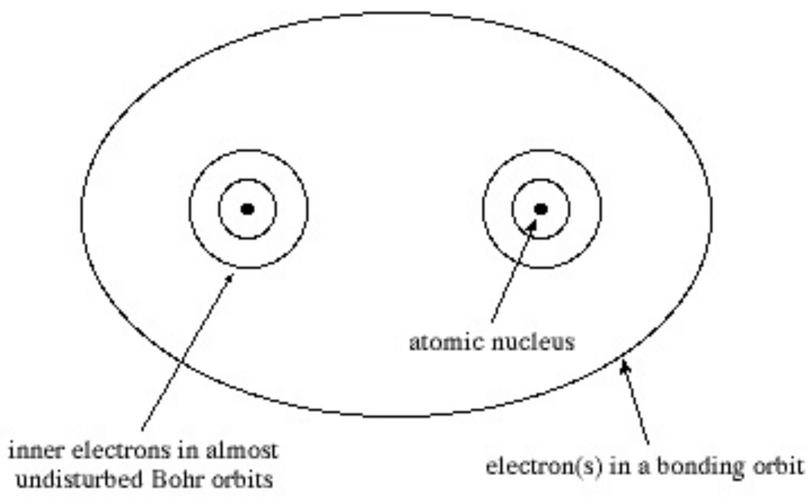
The chemical elements are distinguished by the nuclear charge, i.e., the number of protons in the nucleus. For example, hydrogen 1 proton, helium has a nucleus of 2 protons (and usually 2 neutrons), iron has a nucleus of 26 protons (and usually 30 neutrons).

Q.6. What is a positive ion?

If the electron cloud around a nucleus has lost one or more members, the "atom" will appear to the outsider to be positively charge. For example suppose the iron atom loses 1 electron as a result of a collision with an energetic particle or photon. The atom then has 25 electrons in orbit around a nucleus consisting of 26 protons and a number of neutrons. The combination of 26 positive charges (protons) and 25 negative charges (electrons) gives a net positive charge of 1. This is an example of a positive ion (in this case, a singly charged positive ion).

Q.7. What is a molecule?

A molecule consists of two or more atoms bound together. (The atoms are usually neutral atoms, but molecules can be made from an atom and a positive ion.) The size of a two atom (diatomic) molecule is about twice the size of an atom.



The equivalent picture of a diatomic molecule to that of the Bohr atom.

One to a few electrons from one or both atoms go into orbits around both nuclei. These are called bonding orbits for an obvious reason.

Q.8. Why is ultraviolet light needed in order to ionize a hydrogen atom in a cool interstellar cloud (i.e., remove the electron completely), whereas even the most intense red light will not do so? Could red light ionize the atom if the gas were at a higher temperature?

In a cool cloud, H atoms will be found with their electron in the first Bohr orbit. To strip such an electron from the atom requires a photon with (lambda) < 912 Å (deep ultraviolet). A red photon certainly cannot ionize the H atom. Bright red light consists of a stream of these low energy photons. (If the beam were exceedingly bright, there is a probability that two or more photons could interact simultaneously with an electron and collectively provide sufficient energy to ionize the atoms. For red light, about 7 photons would be required which probably demands an impossibly bright beam. Why 7?)

Suppose the H gas is heated. Now some H atoms will have electrons (for a brief moment) in the outer orbits 3,3, . . . Beginning from orbit 2, the energy required to remove the electron corresponds to $\lambda < 3600$ Å (deep blue) or from orbit 3, $\lambda < 8600$ Å (near infrared) is required. Clearly, red photons with $\lambda \sim 6{,}000$ Å have sufficient energy to eject electrons from orbits 3,4,5,. . . but not orbit 2.

What is science? Science is angling in the mud -- angling for immortality and for anything that may happen to turn up.

Aldous Huxley (1894-1963)

Being before the time, the astronomers are to be killed without reprieve; and being behind the time, they are to be slain without reprieve.

Anonymous (!) (before 250 BC)

Bohr's model of the atom was a marvellous invention. It was quickly appreciated as a great advance on J.J. Thomson's 'plum pudding' model.

Your theory is having a splendid effect on Physics, and I believe when we really know what an atom is, as we must within a few years, your theory even if wrong in detail will deserve much of the credit.

H.G.J. Moseley* (in November 1913)

*Moseley was killed in 10 August 1915 when, as second lieutenant in the Royal Engineers, he took part in the battle of Suvla Bay on the Gallipoli Peninsula.

In India one summer, I learned of the following experimental test of Newton's Laws of Motion:

A novice to Bombay's overcrowded traffic got into a train only to discover too late that it would not stop at his intended destination. A fellow passenger, more knowledgeable about the train system, however, advised him to stand near the door; for the train would surely slow down if not stop as the station approached and he could take a chance and get off the moving train. "Keep running for a while after you jump," the experienced one advised.

Our novice remembered the laws of motion and as the station approached and the train slowed down he jumped and kept running along with the train. However, the train slowed down further and he overtook a couple of compartments with the result that the passengers in the next compartment thought that he was trying to board a moving train. They gave him a 'helping' hand and pulled him up as the train gathered speed!