	Pa	mmHg	Torr	bar
pascal (N/m^2) =	1	6.5×10^{-3}	6.5×10^{-3}	9.9×10^{-6}
mm of mercury	133.3	1	1	1.33×10^{-3}
Torr	133.3	1	1	1.33×10^{-3}
bar	10^5	750	750	1

Table 1.1: Common units of pressure.

1. Equations are often simply quoted, not derived from first principles. This does not mean that you can skip the equations in these notes—you should always try to find out where they come from and how they are used in solving problems.
2. No formal definitions are given of technical terms or jargon words. When these come up, they are printed in *italics* and the meaning should be clear from the context.
3. No references are given to other books or articles. This is *not* because these are unimportant. You are expected to find them yourself! Of course there is a huge amount of (sometimes intimidating) published literature on plasmas, so specific references will be given from time to time during the module.

2 Plasma

What is a plasma? It's difficult to give a complete and correct answer to this question. For our present purpose it's enough to say that they are ionized (electrically conducting) gases—containing at least some electrons and ions—but there are many different things which can be called plasmas, and some phenomena which are typical of plasma behaviour also occur in other circumstances. Probably the most surprising fact is that plasma is by far the most common state of matter. Almost the whole universe is one huge and complicated plasma!

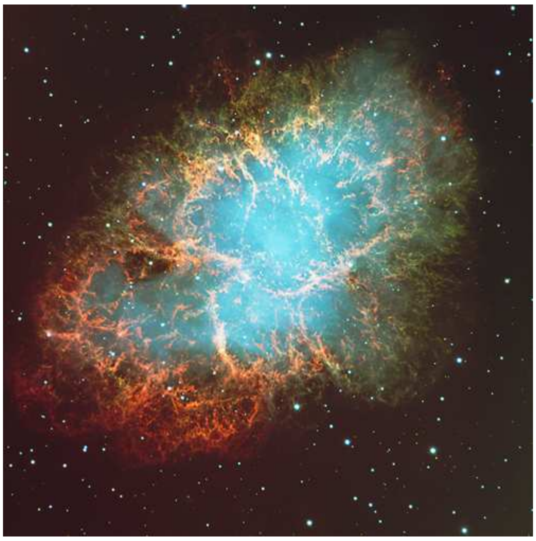

Figure 2.1: Everything visible in this photograph of the crab nebula is a plasma.

This is certainly not obvious from our point of view here on earth. Our planet is made of matter in the solid, liquid and gaseous states. Plasmas are unusual and exotic here. In fact plasmas have been studied systematically for less than two centuries, but in that time a whole range of uses for plasmas have been discovered—many in just the last three or four decades. Now is an exciting time to be looking at plasmas.

2.1 Plasmas in Nature

We will begin a more technical description of plasmas in the next part, but it may first be a good idea to have a quick preliminary look at plasmas in nature. Everyone is familiar with plasmas! One of the most spectacular examples is lightning. This awesome discharge involves megavolts and megawatts of electricity, so it is not very easy to reproduce, but the tiny sparks produced by small batteries (when the terminals are briefly connected together) are basically the same phenomenon on a microscopic scale.

Figure 2.2: The aurora or northern lights (there is an equivalent southern display, hence aurora borealis and aurora australis). Particularly spectacular displays occur when sunspot activity is high.

A more exotic example of atmospheric plasma is the aurora (see Figure **??**). This is less familiar because it is seen only close to the earth's poles. It is a fascinating coloured display caused by noising radiation from the solar wind liberating electrons which get trapped in the earth's magnetic field. The electrons penetrate the upper atmosphere near the poles and collide there with air molecules, causing the glow.

Natural plasmas go under lots of different names. Here are some which occur on or around the earth:

> spark, arc, corona, lightning, fireball, streamer, discharge, flame, St Elmo's fire, flash, ionosphere, aurora, ball lightning, solar wind, sprite

2.2 Plasmas in Technology

Wide industrial application of plasmas is very recent. While the first commercially significant processes were developed more than a century ago, pervasive use of the technology started growing rapidly only in the second half of the last century. During that time the basis of the world's leading economies shifted from transport and primary industries to energy and a range of secondary industries. Most recently information and communications technologies have grown very rapidly. These rely on integrated electronic circuits and mass storage devices for data and signal processing and storage. Plasma processing is one of the key technologies enabling the manufacture of the hardware needed in these high technology sectors.

The art of developing and optimizing plasma applications involves understanding how plasma properties can be controlled in order to achieve the best possible process results. Modification of surfaces by plasma is due to the particles from the plasma, so knowledge and control of their fluxes and energies is crucial.

Activation	Tailoring the surface properties of (typically) polymers by exposure to active plasma species which modify the near-surface chemical bonds. Two of the most important characteristics are surface wetability and adhesive properties.
Etching	Removal of surface material. This is most useful when it is selective, making it possible to fabricate fine patterns on a surface.
Cleaning	Removal of contamination or surface films with minimal effect on the underlying material.
Sputtering	Removal of surface material by high energy ion bombardment from a target. The material removed from the target may be subsequently deposited on a substrate.
Deposition	Deposition of a film from gas phase precursors onto a substrate.
Implantation	Insertion of impurity atoms into surface and subsurface layers in order to change properties such as hardness or electrical characteristics

Table 2.2: The most important types of low pressure surface processing applications

Table 2.2 lists the surface processing applications dealt with in this course. The emphasis is on low pressure processing for the microelectronics and other industries, although recent developments promise a growing importance for processes carried out at atmospheric pressure. Applications in energy generation and control, lighting, waste treatment and chemical conversion, and manufacturing processes such as plasma spraying, welding and cutting are not dealt with in detail.

2.3 Orders of Magnitude

Plasma science, perhaps more than any other, deals with a huge range of parameters. Stars are plasmas, as are tiny sparks. The processes which are important in plasmas range from the atomic scale all the way to the size of the universe! Compare this range to, for example, that of biology. Artificial plasmas used in applications are fortunately restricted to a much narrower range. Table **??** lists typical values for low pressure plasmas used in surface processing. You may like to compile similar tables for atmospheric plasmas.

Compared to the other parameters, the temperature is quite restricted. Exactly why this is will be explained later, but for now let's consider this temperature range. The lowest values are not much higher than room temperature. The upper end is also interesting. 10 eV is above the energy of many chemical bonds[1] and around the energy needed to remove electrons from atoms and molecules. This means that when these plasmas interact with matter, all sorts of chemical processes

[1]And, incidentally, the energy of photons in visible light.

parameter	**range**	**unit**
electron density	10^8 to 10^{13}	cm^{-3}
electron temperature	0.1 to 10	eV
neutral pressure	1 to 1000	mTorr
power input	1 to 10000	watts
size (volume)	1 to 10^6	cm^3

Table 2.3: Typical parameters for low pressure plasmas.

will happen. Whether we're dealing with the properties of some novel plastic, or the structure of living organisms, the chemical bonds are a key aspect of the forms of matter. Industrial plasmas are hot enough to change bonding patterns but not so hot as to destroy whatever comes into contact with them. This is the reason why there is such an enormous range of applications of low temperature plasmas.

Systematic investigation of plasmas started when the technology of electricity and vacuum developed sufficiently in the 19th century. The key was putting electricity and vacuum together. Almost immediately, fundamental discoveries were made (new emission lines, the electron, X rays, isotopes, a whole bunch of new elements, etc.). In search of ever more fundamental constituents of matter, vast effort was put into raising the energy, to MeV, and now GeV levels. Industrial plasmas are 'eV physics'—they will not teach us much more about the ultimate constituents of matter, but their temperatures are in the most immediately important range for both life and technology.

2.4 Creating Plasmas

To create a plasma we have to separate some of the electrons from their parent atoms or molecules. This means adding energy. The energy has to be concentrated and applied pretty quickly, before it is lost to the surroundings, and if we want the plasma to keep burning we have to keep up the energy supply.

There are two good ways to ionize a neutral atom: hit it with an energetic photon or electron. It turns out that the second is often the better option. Energetic electrons can be produced by acceleration in an electric field so the simplest way to make a plasma is to apply a voltage between two electrodes. It is much easier to create a plasma if we reduce the gas pressure down from normal atmospheric pressure[2]. At low pressure the electrons collide less often so their average energy can be raised to a much higher level. The loss of energy to the surroundings is also slowed down and much better control over the plasma can be achieved. What is needed then is an electrical power supply and a vacuum system. The pressure in the vacuum system must be controlled because there is normally an optimum pressure for plasma operation. These sorts of plasmas are called *gas discharges* or *low pressure plasmas.*

If we wish to make plasmas using light, we need to concentrate the light energy sufficiently and this means using a laser. Just shining a laser into a gas isn't enough[3], and what is normally done is to blast a solid surface with a short pulse from a powerful laser. A high density plasma forms and expands away from the surface. The expense of the lasers and difficulties in controlling the resulting plasma have kept these *laser plasmas* out of routine industrial use, but they have some specialist

[2]Plasmas are not difficult to produce at atmospheric pressure, but a lot of power is needed to keep them burning.

[3]Unless it's a *really* powerful laser!

applications and they make excellent light sources for atomic and molecular physics.

Some charged particles exist even in ordinary air. This is due to things like background and cosmic radiation which are constantly present in the environment around us. This energetic radiation interacts with the gas atoms and molecules, and can eject an electron resulting in the creation of a free electron and a positively charged ion in the gas.

Considering a gas in equilibrium, the density of ions in the gas is given by the *Saha equation*:

$$\frac{n_{j+1}n_e}{n_j} = \frac{2U_{j+1}}{U_j}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} e^{-e\mathcal{E}_{iz}/k_B T} \tag{2.1}$$

where $\mathcal{E}_{iz}$ is the ionization energy (in eV) needed to ionizes the j^{th} ion state, n_j is the number density of ions in the j^{th} state, n_{j+1} is the number density of ions in the next highest state of ionization, n_e is the free electron density and T is the gas temperature. The quantities U_{j+1} and U_j are known as the *degeneracy* of the respective ion species, and is related to the internal structure of the species. It usually has little effect on the overall result, changing the final value obtained by a factor of less than 10 typically, so it can often be ignored.

Numerical Example Consider a chamber filled with hydrogen gas at a temperature of 350 K. Calculate the H^+ density in the chamber given that the neutral density is 4×10^{15} cm^{-3}. You can assume that all the ions in the chamber are singly ionized.

Information on hydrogen required:

$U_1 = 1$. $U_0 = 2$. $\mathcal{E}_{iz} = 13.6$ eV

Note that the physical constants you require are available in the PRL notation document, or any basic physic book.

If all ions are singly ionized, then the number density of singly ionized ions n_1 equals the number density of free electrons n_e.

$n_1 = n_e$

The Saha equation becomes,

$$\frac{n_1 n_e}{n_0} = \frac{n_1^2}{n_0} = \frac{2U_1}{U_0}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} e^{-e\mathcal{E}_{iz}/k_B T}$$

Working out the pre-exponential factor we get:

$$\frac{2U_1}{U_0}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} = 1.6 \times 10^{25}$$

Similarly, for the exponential factor,

$$e\mathcal{E}_{iz}/k_B T = 450.5$$

Thus, the Saha equation becomes,

$$\frac{n_1^2}{n_0} = 1.6 \times 10^{25} e^{-450.5} = (1.6 \times 10^{25})(2.3 \times 10^{-196}) = 3.7 \times 10^{-175}$$

Thus,

$n_1^2 = (4\times10^{15})(3.7\times10^{-175}) = 1.48\times10^{-159} \Rightarrow = n_1 = 1.22\times10^{-79.5} \approx 0$

Thus we see that at normal temperatures, the charge density in a gas is a ridiculously small number. This is because of the large exponential factor. However, if the temperature increases, the exponential factor drops, and the ion density (and free electron density) increase.

Try the above calculation for a temperature of 3000 K and see how much raising the temperature to this value increases the number of ions.