Plasma physics: an introductory survey

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This paper describes what plasmas are, why their study is essential to our understanding of the universe, how plasma physics is applied to many scientific and technological areas of development, and how it possibly could provide the solution to the world's energy problems. In addition, the paper will briefly describe Australia's involvement in this research and development area.

KEYWORDS: fusion energy, fusion reactions, nucleosynthesis, physics, plasmas.

WHAT IS A PLASMA?

A plasma is an ionised gas in which the nearest neighbour interactions between the electrically-charged constituents (negatively-charged electrons and positively-charged ions, which are in equal numbers so as to maintain overall electrical neutrality) is dominated by the long-range interactions of many 'distant' particles. In fact, many plasmas contain a significant number of un-ionised neutral atoms, but the long-range interactions dominate.

The force (F) between isolated point electrical charges e_1 and e_2 which are separated by a distance r is

$$F = (e_1 e_2)/(4\pi\varepsilon_0 r^2) \tag{1}$$

where ε_0 is the permittivity of a vacuum. This is the so-called Coulomb interaction, and because it falls off relatively slowly with distance r, is a 'long-range' one compared to the shorter range forces between the particles which are constituents of the three other forms of matter—solid, liquid and gas. A plasma has been termed 'the fourth state of matter', because it has properties which are quite distinctive.

As electrically-charged particles are constituents of a plasma, the plasma can conduct electrical currents, it can be influenced by electric and magnetic fields, and currents flowing in the plasma generate magnetic fields. Plasma can support a whole range of wave motions.

In fact, the above (classical) definition of plasma has been extended to other situations where plasma properties can still be found, e.g. non-electrically neutral situations.

BRIEF HISTORY OF PLASMA PHYSICS

Plasma was first identified as a 'different' state of matter in the study of low-density ionised gases, which were formed in electrical discharge tubes (Crookes 1879). The term 'plasma' was introduced by Langmuir (1928) and Tonks & Langmuir (1929) in connection with their studies of oscillations of ionised gases. Such oscillations (which today we refer to as plasma oscillations) are due to the strong restoring electrical forces that act whenever there are charge separations, as can occur as a result of thermal fluctuations.

Why the term 'plasma' was used is unclear. One explanation does involve the similarity with blood plasma (both carry particles), while another explanation refers to the Greek word meaning 'anything moulded or formed', since plasma usually moulds itself to the shape of its container. Plasma physicists have, ever since, had to clarify this issue, and in most cases, to express an ignorance of the properties of blood plasma!

In 1920, A S Eddington realised that from atomic mass determinations made by F W Aston it is possible that hydrogen can be converted to helium (by the fusion or joining together of the hydrogen nuclei) under the right conditions, and that this could be the origin of the source of energy for all stars, in particular the sun. G Gamow, in 1928 derived (using quantum mechanics) the formula for the fusion of two nuclei with the associated release of energy (as matter and energy are equivalent according to Einstein). R Atkinson and F G Houtermans (in 1929) then used Gamow's results to calculate the rate of energy production arising from thermonuclear fusion reactions in hydrogen plasma in stellar cores. H Bethe (in 1939), elucidated the processes whereby the energy of stars is produced, for which he received the 1967 Nobel Prize in Physics. This theory worked well for stars with masses up to about the mass of the sun. In 1938, C F von Weizsecker identified processes which were important in more massive stars. The study of the creation of heavier nuclei in such fusion processes was initiated by F Hoyle in 1946. This interesting story is described in more detail in the history section of the Wikipedia article on nucleosynthesis (http://en.wikipedia.org/wiki/Stellar_nucleosynthesis). Nucleosynthesis is the formation of the chemical elements by nuclear reactions occurring in the cores of stars. Fusion is thus a fundamental process in the establishment and maintenance of the universe.

The first fusion reactions performed in the laboratory were carried out by the 'fathers of fusion' M OIiphant, P Harteck and E Rutherford in the early 1930s (Oliphant *et al*. 1934).

ABUNDANCE OF PLASMA

Plasma is the most common state of visible matter in the entire universe. It is estimated that over 99% of the visible matter in the universe is in the plasma state (Figure 1a) e.g. intergalactic medium, interstellar medium, and the solar system [the sun (Figure 1b), the solar wind and the
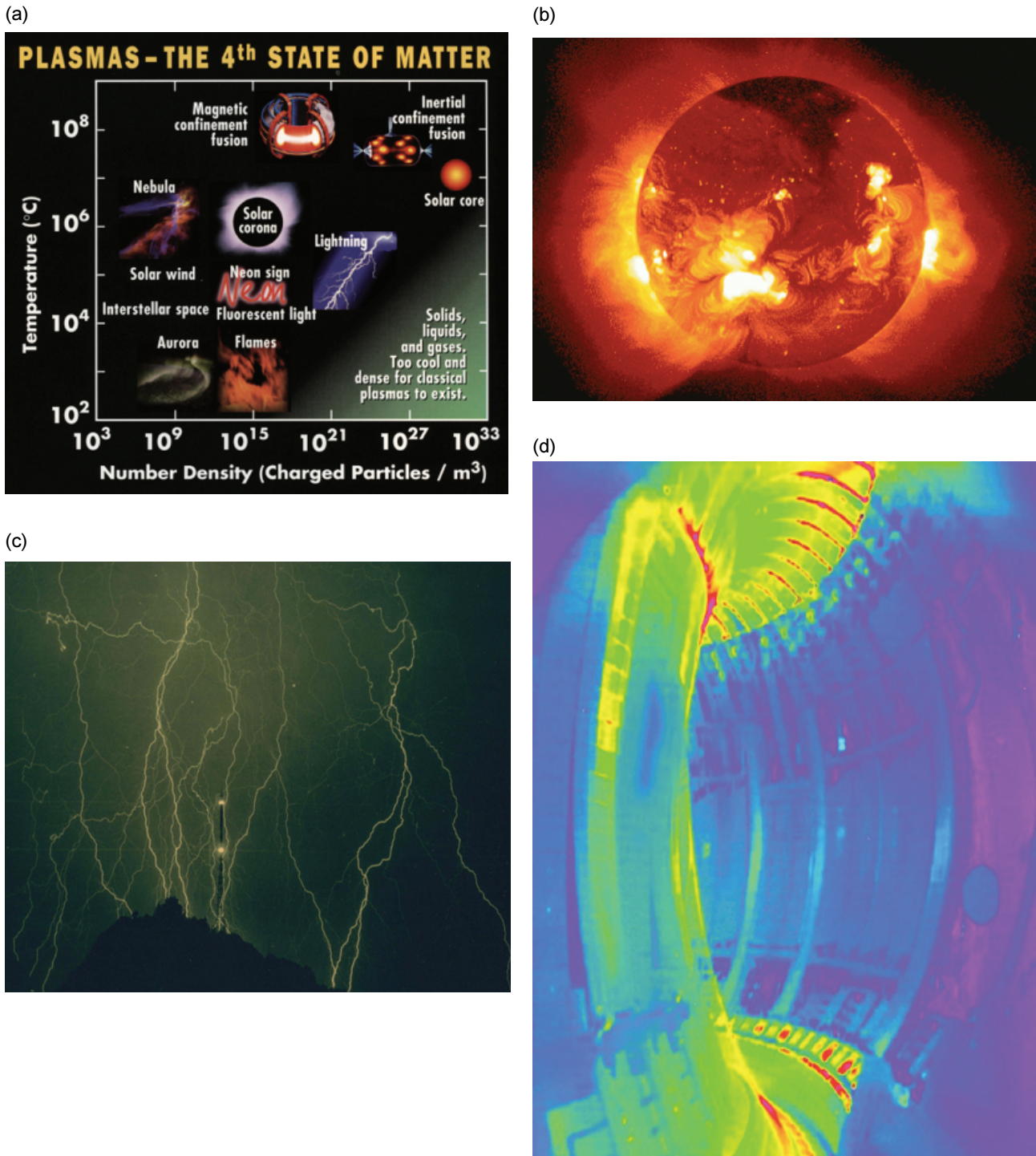
(a)

(b)

(c)

(d)

Figure 1 (a) This shows different plasmas in terms of their temperature in K, and the number density (no. of charged particles/m³). The range of temperatures spans more than six orders of magnitude, while the number density spans more than 30 orders of magnitude. <http://fusedweb.pppl.gov/cpep/chart_pages/5.plasma4statematter.html>. (b) The sun—a functioning fusion reactor. (c) Lightning, a dramatic natural, terrestrial, plasma occurrence. (d) The interior of the JET tokamak. The infrared camera reveals the heat loads on the wall and sometimes the radiation from the very cold areas of the plasma. The experiments in JET done with the brand new ITER-Like -Wall (the JET wall has been constructed to resemble the ITER one in its material aspects) help to develop the best experimental routine for ITER. JET's successor ITER aims to demonstrate that it is possible to produce commercial energy from fusion. EFDA - JET <http://www.efda.org/2011/09/iter-like-wall/?view=gallery-265>.

interplanetary medium]. Near the Earth we have natural plasmas [the polar aurorae, the Van Allen belts, the ionosphere and lightning (Figure 1c)]. Only here on Earth plasma is not a normal state and has to be produced [flames, neon signs, fluorescent lights, rocket exhausts, plasma displays (e.g. TV), electrical discharges (arc lamps, arc welders, plasma torches, sparks), and fusion-energy experiments].

Plasma is characterised by its temperature [related to the energy of its constituent particles, so it is sometimes measured in energy units (eV) rather than temperature (K): 1 eV is about 1.1×10^4 K], and by the number density (charged particles/m^3) of its constituent particles. From Figure 1a, it can be seen that both temperature and density span many orders of magnitude for plasmas.

Clearly, because of the great abundance of plasma in the universe, an understanding of its behaviour, i.e. plasma physics, is of fundamental importance.

PLASMA DESCRIPTION

There are two main descriptions of plasma.

(1) Macroscopic (large scale) – this treats the constituents of a plasma (ions and electrons) as fluids, with average properties e.g. density, temperature and mass velocity. In a fully ionised plasma there may be only one species of ion, and electrons, but in more complicated cases there may be several species of ions, and even un-ionised atoms, as well as the electrons. This is the plasma-fluid model, sometimes known as the continuum or magnetohydrodynamic (MHD) model.

(2) Microscopic (small scale) – where the velocity distributions of the different types of particles are used to describe the medium at each space and time location. This is clearly a more detailed view than in (1) but does not follow the individual identity of every single constituent particle. This is the plasma-kinetic model. It should be noted that a useful fluid model can be derived from the microscopic one under certain conditions, and that the so-called transport coefficients of the fluid model (e.g. viscosity, thermal conductivity) can be calculated from the microscopic model.

An alternative approach is to use the enormous computing power at present available and to follow the motion of individual charged particles making up the plasma. However, even with present computer performance, the number of particles able to be treated in this way is limited.

There is a parallel here with the description of a neutral gas. In order to describe such a gas in macroscopic (fluid) terms, the mean free path for collisions (the average distance travelled by the particles making up the gas between collisions) must be smaller than all other lengths of interest. In the opposite limit of very large mean free path, the motion of individual particles can be considered. The intermediate regime is treated by considering the velocity distribution functions of particles. For plasma the situation is more complex, because there are more lengths of interest: (i) the Debye length which is a radial measure of the sphere of influence of a positively charge particle in the plasma (for a plasma this length must be small compared with other lengths of interest and there must be many particles inside the so-called Debye sphere); and (ii) when there is a magnetic field present (as there often is) the radii of gyration of the electrically-positive ions and negative electrons in the magnetic field.

The model to be used to describe a plasma depends on the problem under consideration.
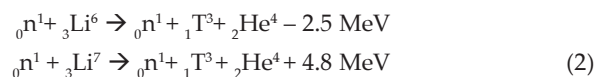
PLASMA PHYSICS STUDIES

Plasma physics is required for many different areas: (i) astrophysics, dealing with subjects such as the core of the sun and the transport of energy from it to the solar corona, the solar wind (which is a continuous stream of particles impinging on the earth's magnetosphere), the Van Allen belts which are made up of charged particles trapped in the earth's magnetic field), and space exploration by means of rockets with ion thrusters; (ii) closer to earth, plasma physics is required for lightning studies, and communications (e.g. the propagation of electromagnetic waves in the ionosphere); and (iii) on earth, plasma physics is required for studies of MHD energy conversion, solid-state plasmas, low-temperature plasmas and plasma chemistry, and atomic physics. As indicated above, one of the main areas of plasma physics has been the study of plasmas relevant to fusion-energy production.

FUSION-ENERGY PRODUCTION

This section covers some of the material given in a talk delivered to the Royal Society of Western Australia on 15 October 2012 (Green 2012). One of the significant areas of plasma study has been that of thermonuclear plasmas, where 'thermonuclear' means that significant fusion reactions may take place by virtue of the high temperature of the fuel. In other words, the energy of the fuel particles (say the nuclei of deuterium, an isotope of hydrogen) is sufficient to overcome the electrical repulsion between the positively charged nuclei (see equation 1). The temperatures for this to occur are very high (of the order of 100 million K), and matter at this temperature is in the plasma state.

There are many possible fusion reactions (Table 1) but the one most easily accessible (i.e. requiring the lowest temperature for significant fusion reactions to occur in the plasma fuel) is that involving a fuel made up of the isotopes of hydrogen; deuterium (D) and tritium (T). Deuterium exists naturally, and 1 part in about every 7000 atoms of hydrogen is deuterium, so there is an enormous abundance of it, and it is easy to extract from seawater. However, tritium is non-naturally occurring and has to be generated. This can be done by allowing the neutrons produced in DT fusion reactions to interact with the isotopes of lithium (Li) (see equation 2). In these equations energy is required for the reaction with Li6 to proceed, whereas energy is produced in the reaction with Li7.

$$_0n^1 + _3Li^6 \rightarrow _0n^1 + _1T^3 + _2He^4 - 2.5 \text{ MeV}$$

$$_0n^1 + _3Li^7 \rightarrow _0n^1 + _1T^3 + _2He^4 + 4.8 \text{ MeV} \qquad (2)$$

Lithium occurs naturally, is abundant and easily mined or extracted from seawater. This means that fusion

Table 1 Some of the many possible fusion reactions.

	Reactant 1	Reactant 2	Product 1	Energy of 1 (in MeV)	Product 2	Energy of 2 (in Mev)
1a	$_1D^2$	$_1D^2$	$_2He^3$	0.82	$_0n^1$	2.45
1b	$_1D^2$	$_1D^2$	$_1T^3$	1.00	$_0n^1$	3.03
2	$_1D^2$	$_1T^3$	$_2He^4$	3.52	$_0n^1$	14.08
3	$_1D^2$	$_2He^3$	$_1P^1$	14.7	$^2He^4$	3.7

Chemical symbols: D, deuterium; T, tritium; p, proton; n, neutron; He, helium.

Subscript is the atomic number i.e. the number of protons in the nucleus e.g. 2 for He.

Superscript is the number of protons and neutrons in the nucleus e.g. He has 2 protons in the nucleus and there are 2 isotopes; $_2He^3$ with one neutron in the nucleus, and $_2He^4$ with two neutrons in the nucleus.

Unit of energy, MeV, is approximately 1.6×10^{-13} J. While each reaction produces an apparently small amount of energy, there are a large number of such reactions (of the order of 10^{23}) in each mole (molecular mass in grams) of the reacting material.

1 g mass of D undergoing reactions 1a +1b (each with 50% probability) releases about 25 000 kWh/g mass of the reacting nuclei: cf. hydrogen and oxygen which release 4.4×10^{-3} kWh/g mass of the reactants.

fuel is readily available for millions of years, and indeed, if DD fusion could be achieved, there is no necessity for lithium fuel, and the source of energy is essentially unlimited.

However, to achieve the conditions necessary to produce and extract fusion power for useful purposes (electricity production, high-temperature heat for industrial processing, desalination, or the production of hydrogen for use as a clean fuel in fuel cells) is a huge challenge. It is a most seductive challenge, because its solution appears to promise an unlimited source or energy, with significant positive environmental features.

Since the late 1950s, many schemes have been studied to extract fusion power from a plasma of hydrogen isotopes, but the main two approaches at present are: (i) magnetic confinement; and (ii) inertial confinement.

Approach (i) uses a magnetic 'bottle' (mainly formed by electric currents in coils outside the reactor, but sometimes supplemented by magnetic fields arising from plasma currents) to confine the plasma, while it is heated and the fusion energy extracted, in a steady-state manner.

Approach (ii) uses energy-dense beams (e.g. lasers, ion beams) to irradiate targets made of fusion reactant materials (e.g. deuterium and tritium). This irradiation causes the target to be heated and the constituent matter to fuse in a 'pulsed' manner. The confinement (the state in which the reacting plasma stays together) is determined by the inertia of the fuel.

The plasma temperatures required for a reactor plasma have been achieved, and significant fusion power has been produced (16 MW peak), but the production of more energy than is required to establish the fusion plasma, and the maintenance of reactor conditions for times of reactor interest, remain to be established.

The magnetic confinement scheme which is, at present, closest to achieving reactor-like plasma conditions is the so-called tokamak. This is a scheme, first developed in the Soviet Union, and the word 'tokamak' is a Russian anagram for toroidal magnetic chamber. One of its main features is that it requires a significant current flowing in the plasma to establish its confining magnetic field. However, another scheme

called the stellarator has potential advantages (in that it does not require a significant plasma current to flow), and research in this area continues and provides support for the tokamak studies.

The international project ITER (www.iter.org), which involves a tokamak, is at present being constructed in the south of France, and aims to provide information necessary for the construction of a prototype/ demonstration fusion reactor.

The development of special plasma measurement systems (so-called plasma diagnostics) has been necessary to understand plasma behaviour. For example the measurement of the properties of these extremely high-temperature plasmas in fusion energy studies presents a challenge because no material probe can survive being placed in such a plasma. One active measurement of electron temperature uses an intense laser beam, which is fired into the plasma. This highly monochromatic light is scattered by electrons in the plasma. and the scattered light is collected and measured. The absolute scattered signal strength depends on the number of scattering centres (electrons) per unit volume i.e. the plasma density, and the broadening of the incident laser light is the result of the Doppler effect (electron motion affecting the frequency/wavelength of the laser light in the scattering process). Thus the mean velocity (energy) of the electrons in the scattering volume can be determined, and this is essentially the electron temperature.

JET is the world's largest tokamak at present and has achieved conditions closest to those required in a fusion reactor. Figure 1d shows the interior of the JET device and how infra-red diagnostics can be used to understand the impact of the hot plasma on the material walls of the material container. Of course, the confining magnetic field is arranged to reduce this impact so that it is tolerable.

SCIENTIFIC AND TECHNOLOGICAL APPLICATIONS

There are many ways in which plasma-physics knowledge has been applied. Some are: plasma

processing (plasma-based materials processing technology which aims to modify the chemical and physical properties of surfaces e.g. spraying, and etching in microelectronics); improved lighting (fluorescent lights); the production of ion beams (e.g. for ion implantation to change material bulk properties as in semiconductor device fabrication); plasma processing of waste; metal cutting and welding; the new therapeutic techniques of plasma medicine; plasma acceleration (to improve on conventional particle accelerators); non-thermal plasmas used in food processing; MHD generators for directly generating electricity from the thermal and kinetic energy of plasma; and solid state plasma (electron-hole plasmas, atomic physics) and plasma chemistry.

Knowledge gained in the study of plasma physics has wide application in other scientific and technological areas. One major example involves the computational modelling of plasma. Fluid codes, which attempt to model the many fluids making up a plasma (e.g. different species of ions and electrons) have been used in studying the propagation of fire. Such fluid codes already existed in fluid studies (e.g. weather and climate codes) but dealing with the complexities of plasma description has led to advances in numerical computation techniques.

For fusion research, many different technologies are required, and the development of them has had applications in other fields. Some of the technologies involved are: ultra-high vacuum; remote handling; computerised control and data acquisition (one development led to the control of in-line strip production of stainless steel); pulsed power supplies and switching; instrumentation and measurement systems (in particular laser systems); electromagnets; thermal shielding and cryogenics; and the development of high heat-flux resisting materials (applications in brakes and clutches in aviation, trains and motor racing, and actively-cooled components for space vehicles). Perhaps one of the largest spin-offs (or technology transfers) comes from the

requirement of producing high-magnetic fields and maintaining them for long periods of time (a requirement also shared by particle accelerators). This has led to the development of advanced superconducting strands which are now used in the magnets of magnetic resonance imagers (MRIs) in hospitals all over the world to carry out body scans (Figure 2).

Knowledge transfers occurs through researchers who move to other areas bringing with them the skills they have developed in plasma-physics research. This kind of cross-fertilisation and inter-disciplinary studies are important forces driving scientific and technological progress.

BRIEF REVIEW OF AUSTRALIAN INVOLVEMENT

An Australian, M Oliphant, was one of the 'fathers of fusion' (see above) in the early 1930s. P Thonemann (Australia) and G Thomson (UK) pioneered, in the mid to late 1940s, magnetic-confinement research in the UK. M Oliphant returned to Australia in 1950 and commenced plasma-physics research at the Research School of Physical Sciences and Engineering at the Australian National University (ANU) in 1958. This work continues to this day and now involves a national experimental stellarator facility as well as theoretical studies. C Watson-Munro established (1961) a department of plasma physics in the School of Physics at the University of Sydney, and this work also continues. In the 1960s B S Liley built and operated the first tokamaks outside the Soviet Union at ANU. This work continued into the 1970s and 1980s but the experimental work was subsequently altered to that involving a novel stellarator.

Flinders University became involved in magnetic confinement studies, the University of New South Wales carried out an inertial confinement research program, theoretical work was carried on at the University of
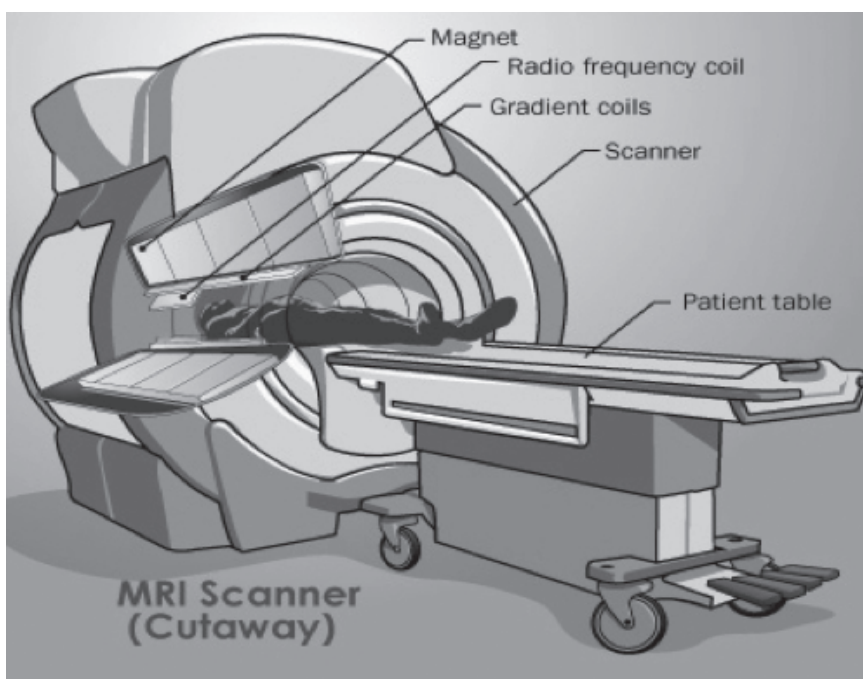

Figure 2 Magnetic Resonance Imager showing the (super-conducting) magnet <http://www.magnet.fsu.edu/education/tutorials/magnetacademy/mri/>.

Melbourne, and by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The Australian Nuclear Science and Technology Organisation (ANSTO) has also been involved in fusion-related studies, in particular in the study of materials required to withstand the hostile environment of a fusion reactor interior. Such materials studies are also being carried out elsewhere, e.g. at the University of Newcastle. Fundamental studies on plasma processes are being carried out at the Curtin University.

This brief summary does not properly describe all the individual contributions made by the different Australian research groups, but one thing is clear, plasma research in Australia has produced a significant number of scientists who have participated/are participating in the international research and development program involving plasma studies, many of them in the fusion program.

At present, Australian fusion researchers are looking for the opportunity to participate in the ITER Project and subsequent fusion-reactor development. They have established an interest group, the Australian ITER Forum, and have prepared a document 'Powering Ahead: A National Response to the Rise of the International Fusion Power program' (http://fusion.ainse.edu.au/iter/australian_fusion_strategy2). This document will hopefully persuade the Australian Government to negotiate with the partners of the ITER organization to allow Australians researchers to participate.

CONCLUSIONS

1. Plasma is the most common form of visible matter in the universe and as such, the study of plasma physics is fundamental to an understanding of the universe.

2. Not only is plasma physics of basic interest, but there are also also many applications which have been developed based on our understanding of plasma behaviour.

3. The study of plasma physics has many possible applications in other areas of research and development.

4. The realisation of fusion energy from plasma fuel could solve the world's energy crisis in that it could provide an environmentally-friendly source of energy, with essentially a limitless supply of fuel.

5. Australian researchers are looking for support to continue their fusion studies as part of the international program. Without appropriate government support, this area of research will not be sustainable in Australia.

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