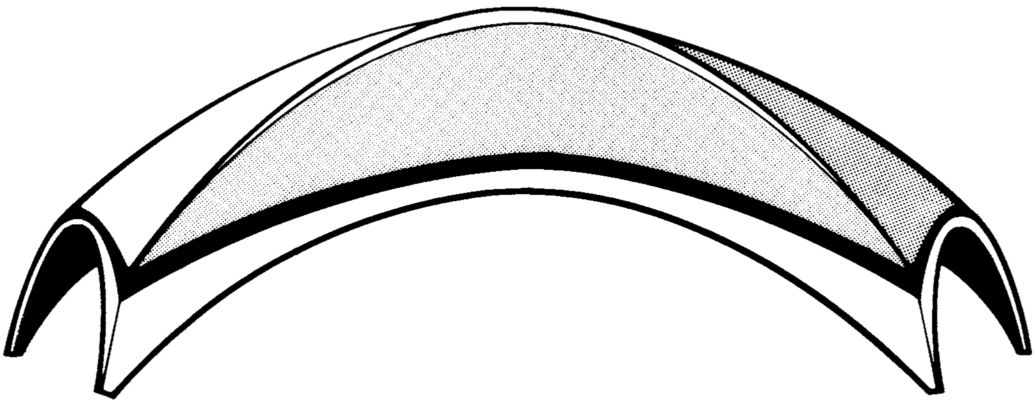
UNIVERSITY OF ABERDEEN

# DEPARTMENT OF PHYSICS



# Electromagnetism

## CPD Day for Physics Teachers

**25th May 2004**

**ELECTROMAGNETISM FOR PHYSICS TEACHERS**

## CONTENTS

### Lecture notes

*Fundamentals of Electromagnetism*

*Magnetic Resonance Imaging*

*Our Invisible Environment: electricity and magnetism in the solar system*

### Laboratory Notes

*Voltages and currents in inductors and capacitors*

*Induced voltages*

Datalogging experiment

Demonstration

Appendix on setting up the dataloggers

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**G. Stuart Leadstone**, Banchory.

UNIVERSITY OF ABERDEEN

**Professional Development for Physics Teachers**
**Electromagnetism**
**25th May 2004**

# PROGRAMME

| | |
|---|---|
| *09.00 – 09.30* | *Registration and Coffee in Foyer of Fraser Noble Building* |
| **09.30 – 10.30** | **Fundamentals of Electromagnetism**<br>Dr Iain S Mackenzie, Department of Physics, University of Aberdeen |
| *10.30 – 11.00* | *Coffee* |
| **11.00 – 11.30** | **Magnetic Resonance Imaging**<br>Dr Thomas W Redpath, Department of Bio-Medical Physics & Bio-Engineering, University of Aberdeen |
| **11.30 – 12.30** | **Practical Work**<br>(group a) induced emfs; (group b) voltages and currents in L and C |
| *12.30 – 13.30* | *Buffet lunch in the 'Seminar Room'* |
| **13.30 – 14.00** | **Our Invisible Environment:** *E & M in the solar system*<br>Dr John S Reid, Department of Physics, University of Aberdeen |
| **14.00 – 15.00** | **Practical Work**<br>(group a) voltages and currents in L and C; (group b) induced emfs |
| **15.00** | **Discussion & Feedback**<br>*In the lab* |

- **Lectures** will take place in Lecture Theatre 2 off the foyer in the Fraser Noble Building, King's College

- **Practical work** will take place in laboratory F002 of the Fraser Noble Building

**Principles of Nuclear Magnetic Resonance and Magnetic Resonance Imaging**

# Thomas W Redpath

## 1.1 Brief historical introduction

Nuclear magnetic resonance (NMR) was discovered independently by Bloch and Purcell in 1946, work which led to their joint award of the Nobel Prize for physics in 1952. Chemists were quick to see the potential of NMR, as the NMR signal gives valuable information about the chemical environment surrounding the nuclear spins. This is because the atomic electrons which determine the chemical properties of materials, interact with the nuclei which give rise to NMR signals. It has only been since Lauterbur's seminal paper in Nature in 1973, that NMR has been applied to forming images of the hydrogen nucleus in vivo, leading in turn to a major new application of NMR in medical imaging.

## 1.2 Nuclear spins

Nuclei are positively charged. Some have the quantum mechanical property termed spin. If an object is both charged and spinning, it will generate a magnetic field in the same way that a current circulating round a loop will generate a magnetic field. Physicists call this type of magnetic field distribution a dipolar field. It is the same sort of field distribution as that produced by a magnet with two poles, north and south (di- is a prefix meaning two). Thus, each spinning nucleus can be thought of as being a tiny bar magnet. Some nuclei do not have spin, and do not produce a nuclear magnetic field. These nuclei do not undergo nuclear magnetic resonance. In magnetic resonance imaging (MRI) images are normally formed from signals arising from hydrogen nuclei ($^1H$), mainly because they are so much more abundant in the body than any other nucleus capable of yielding an NMR signal.

Normally, nuclear spins do not have any preferred direction of alignment. If, however, they are placed in a strong magnetic field $\mathbf{B_0}$, they will tend to align with it, in much the same way as a set of compass needles will align with the earth's magnetic field. We do not observe the effects of individual nuclei, we observe the averaged effects of many billions of nuclei (in a single millilitre of water, there are $3.3\ 10^{22}$ water molecules, and therefore $6.6.10^{22}$ hydrogen nuclei). The most abundant form of hydrogen has an atomic mass of 1, so that its nucleus is a proton. The symbol for this form of hydrogen is $^1H$.

The alignment brought about by the strong magnetic field produces an observable bulk nuclear magnetisation (Fig. 1). Bulk means averaged over a volume. Magnetisation $\mathbf{M}$ is a measure of dipole density per unit volume of the sample, or per unit volume of tissue. Until the nuclei are placed in the strong magnetic field their magnetic dipoles are randomly oriented, so that their average effect, or their bulk magnetisation, is zero. As we will see in section 1.4, when the average magnetisation is zero, no NMR signal can be produced. In other words, a powerful magnet is the first prerequisite for an NMR experiment.

## 1.3 A quantum description of NMR

This section can be omitted without loss of continuity. It is intended to give additional background to those with some knowledge of basic quantum mechanics.

Figure 2

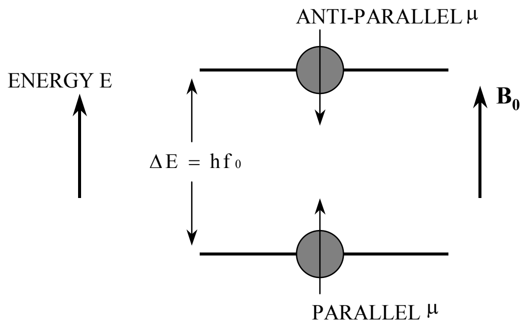
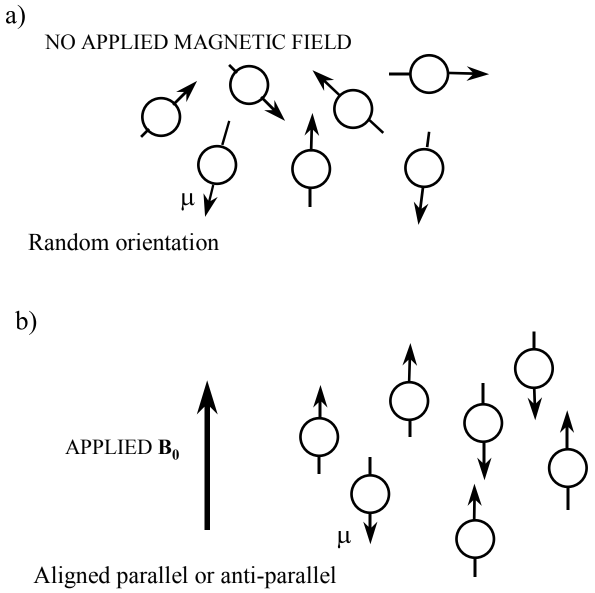



Figure 1




The z-direction in NMR is conventionally taken to be that of the applied static magnetic field $\mathbf{B_0}$. The magnitude of the angular momentum of each spin equals I.h/2π, where I is an integer, or a half-integer, and h is Planck's constant. The nuclei of different elements, and of different isotopes of the same element, may have different I values. Protons, the nuclei of hydrogen with atomic mass 1 ($^1$H) have an I value of 1/2. The nuclei of P $^{31}$ (phosphorus with atomic mass 31), which give an NMR signal often used for *in vivo* NMR spectroscopy, also have I=1/2.

The z-component of the angular momentum $I_z$ is also restricted to particular discrete values. These are -I.h/2π, (-I+1)/2π,.....,+I/2π. There are therefore (2I+1) possible orientations of a nuclear spin to the z-axis. There are 2 possible orientations of spin 1/2 (that is I=1/2) nuclei. These orientations are called spin-up and spin-down, parallel and anti-parallel to $\mathbf{B_0}$ respectively.

If γ is positive, spin-up nuclei have a lower energy than spin down nuclei (Fig. 2). The nuclear spin energy E is given by

$$E = -\gamma h B_0 I_z / 2\pi \qquad 1.3.1$$

where γ is the gyromagnetic ratio, which is different for different elements, and for different isotopes of a particular element. In other words γ depends on the nuclear charge and mass, and on nuclear angular momentum I.

In the equilibrium state, when the nuclear spins are in thermal equilibrium with their surroundings, there are slightly more spins in the lower energy level than in the higher level. The relative populations in the high and low energy states are given by the Boltzmann distribution

$$N_{HIGH} / N_{LOW} = \exp(-\Delta E / kT) \qquad 1.3.2$$

where ΔE is the energy difference between the 2 states, k is Boltzmann's constant, and T is the absolute temperature of the sample. From equation 1.3.1, for spin 1/2 nuclei

$$\Delta E = \gamma h B_0 / 2\pi \qquad 1.3.3.$$

For protons at a field strength of $B_0$=1.0 Tesla (T), $\gamma=2\pi.42.6.10^6$ radians per Tesla, so that the ratio of $N_{HIGH}/N_{LOW}$ is only about 0.999993. There is only a tiny population difference between the 2 states, so that the alignment discussed in section 1.2 is weak.

If the spins are subjected to a short burst of a radio-frequency (RF) magnetic field, oscillating at the NMR resonant frequency, at right angles to the static field $\mathbf{B_0}$, then spin-up nuclei absorb energy from the external field to transfer to the higher energy spin-down state, while spin-down nuclei are stimulated into giving out energy in transferring to the spin-up state. The NMR resonant frequency $f_0$, or Larmor frequency, is given by

$$\Delta E = hf_0 \qquad 1.3.4$$

so that

$$f_0 = \gamma B_0 / 2\pi \qquad 1.3.5$$

The RF frequency has to match $f_0$ otherwise there is no effect.

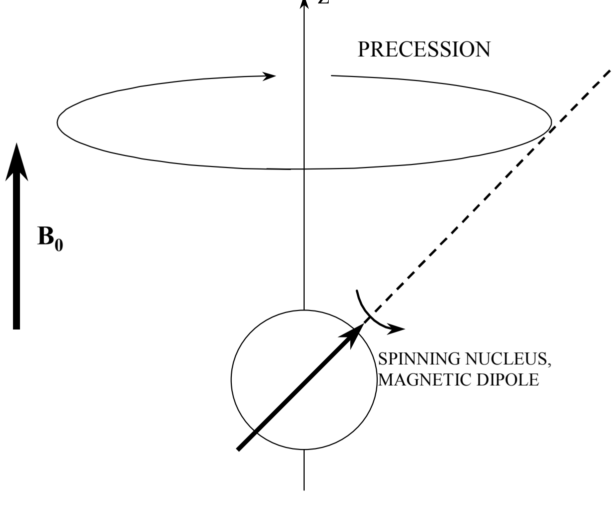
During the burst of RF energy, the probabilities of a spin-up nucleus transferring to the spin-down state, and vice-versa, are equal. However, before the RF pulse, there are slightly more spins in the lower energy spin-up state so that more spins transfer out of this state than enter it from the higher energy state. Therefore, the nuclear spin system absorbs a small amount of energy from the RF magnetic field.

### 1.4 A classical vector description of NMR

Classical physics describes the behaviour of the world at the macroscopic level. Quantum physics describes the world at a microscopic atomic level. Descriptions of individual nuclei require a quantum approach. Such descriptions are mathematical and, for most scientists, and many physicists, give little intuitive grasp of the physical processes involved. As we are dealing with the average, or bulk properties of many billions of nuclear spins, the classical picture is often sufficient to give a good representation of the NMR process. This is highly convenient, as the classical model of NMR is much easier to visualise than the quantum one. The vector model of NMR is quite sufficient to explain the physical basis of NMR imaging, or MRI as it is now known.

As was outlined in section 1.2, when randomly orientated nuclei (or to be more precise, nuclear magnetic dipoles) are placed in a strong external static magnetic field $\mathbf{B_0}$, they tend to align with it, thus producing a nuclear magnetisation $\mathbf{M}$. The magnetisation vector $\mathbf{M}$ has a preferred alignment along the z-axis, parallel to $\mathbf{B_0}$.

Figure 3




The gyroscope, or spinning top, is a good analogy to the behaviour of the nuclear magnetisation in $\mathbf{B_0}$. If the top is perturbed from its initial alignment with the earth's gravitational field, then it precesses around a vertical axis through its point of contact with the table. The precession is a much slower (in terms of revolutions per second) motion than the spin of the top around its own axis. Similarly, if the nuclear magnetisation **M** is perturbed from its alignment with $\mathbf{B_0}$, it precesses around the z-axis, the direction of the static field. The precession frequency $f_0$ is often referred to as the Larmor frequency and is given by

$$f_0 = \gamma B_0 / 2\pi \qquad 1.4.1$$

where $\gamma$ is a constant of proportionality called the gyromagnetic ratio. For those who read section 1.3 on a quantum description of NMR, this is identical to equation 1.3.5. Different nuclei have different values of $\gamma$. Protons have a gyromagnetic ratio of $2\pi$ radians times 42.6 MHz per Tesla. Thus protons precess at 42.6MHz in a magnetic field of strength 1 T, at 21.3 MHz in a field of 0.5 T, and 63.9 MHz in a 1.5 T scanner, and so on. Other nuclei have very different values for $\gamma$. For instance the nuclei of $P^{31}$ (phosphorus with atomic mass 31), which give an NMR signal often used for *in vivo* NMR spectroscopy, have a gyromagnetic ratio of $2\pi$ radians times 17.2 MHz per tesla.

Whereas the spinning top can be pushed from the vertical by a tap of the finger, the magnetisation **M** has to be pushed by an oscillating magnetic field applied at right-angles to $\mathbf{B_0}$. The RF magnetic field is applied by means of a tuned RF coil surrounding the patient's body or head, with power supplied by a radio-frequency power amplifier. The oscillation frequency has to equal the Larmor precession frequency $f_0$, or nothing happens. This is what is meant by resonance. The energy input into the system has to be applied at precisely the correct frequency for there to be any effect. The oscillating magnetic field is applied for only a few milliseconds, so that it is usually referred to as an RF magnetic field pulse, as imagers use field strengths which give $f_0$ values in the radio-frequency range. An RF pulse which rotates **M** through $90^0$ from its initial position aligned with z is called a $90^0$ pulse. M will then precess around z. If the amplitude of the RF magnetic field pulse is doubled, or alternatively, if it is left on for twice as long, then M is rotated by $180^0$. In this case we have applied a $180^0$ pulse. Thus if M is initially parallel to $\mathbf{B_0}$, it will be rotated to be anti-parallel with $\mathbf{B_0}$.

## 1.5 Relaxation

The magnetisation **M** will naturally align itself to be parallel with $\mathbf{B_0}$. If it is moved away from this alignment by applying an RF pulse, it will begin to re-align itself as soon as the RF pulse is switched off.

The physical mechanisms which cause the re-alignment are called relaxation processes. They happen because, when the magnetisation is away from its natural position of alignment with $\mathbf{B_0}$, the nuclear spins can be said to have a higher temperature than the surrounding electrons and atoms. Therefore, over time, the natural tendency of the spins is to lose their excess thermal energy so that the magnetisation **M** eventually regains its preferred, or equilibrium, alignment parallel to $\mathbf{B_0}$. The spins exchange energy with their surroundings because they have an intrinsic magnetic dipole field, so that they interact with those neighbouring electrons and atoms which have magnetic fields of their own.

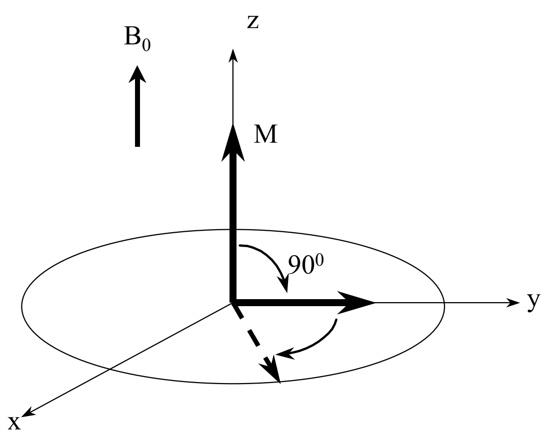
Whereas soft-tissues in the body have similar water, and hence proton densities, they have very different relaxation properties. Furthermore, while many disease processes have little effect on water densities in the affected tissues, relaxation properties can be significantly altered. The NMR signal strengths from different tissues are affected by relaxation properties, and therefore MRI is very good at producing images with excellent contrast between different anatomical structures and organs in the body, and is sensitive to the changes caused by disease.

### 1.6 The NMR signal

The discussion so far has not covered how the phenomenon of NMR might be detected. The use of a tuned RF coil to apply RF pulses to the patient was briefly mentioned in section 1.4. The same coil, or a coil used for signal reception only, is used to detect nuclear magnetic resonance, as discussed below.

Faraday's experiments with magnets and coils of wire in the 19th century demonstrated the principle of electromagnetic induction. He showed that, while a stationary magnet close to a coil produced no voltage in it, moving the magnet induced voltage and current in the wire coil. The stronger the magnet, and the faster its motion, the larger the voltage.

Figure 4




Consider what happens if a coil of wire is placed around a sample which is subjected to a RF pulse which rotates the magnetisation $90^0$ away from the z-axis i.e. a $90^0$ RF pulse (Fig. 4). Initially the magnetisation M is aligned with +z, so that its associated magnetic field is unchanging so that no voltage is induced in the coil. After the RF pulse it precesses rapidly in the x-y plane, at right angles to $\mathbf{B_0}$. The magnetic dipole field associated with **M** is now rapidly rotating, and this induces a voltage in the coil. The voltage induced in the coil alternates at the same frequency as the precession frequency of **M**, so that the loop picks up an RF signal at the Larmor frequency. The z component of magnetisation $M_z$ is only slowly changing compared to the very high frequency oscillation of the transverse components $M_x$ and $M_y$, so that $M_z$ does not give rise to an observable NMR signal voltage.

NMR signals are more efficiently collected if they closely fit the sample, and if they are tuned to the Larmor frequency. Therefore MRI systems are usually equipped with a wide range of signal reception coils, tailored to different parts of the body. Both transmitting and receiving RF coil axes must have a particular orientation with respect to the static field $\mathbf{B_0}$ in order to work.

### 1.6 Brief history of magnetic resonance imaging

In 1973 Paul Lauterbur published a method of NMR imaging which proposed the use of magnetic field gradients to encode position. Lauterbur had been inspired in 1971 by observing Leo Saryan, a graduate student at Johns Hopkins, investigate *in vitro* increases in NMR relaxation times in cancerous tissues previously reported by Raymond Damadian. Much of the work needed to develop this new imaging technology to a level capable of clinical application was done in the UK in the late 1970s and early 1980s, at the universities of Nottingham and Aberdeen, and at EMI's laboratories in Wembley. Damadian has been in the news recently because of his contention that he should have been awarded the 2003 Nobel Prize for Medicine - only Lauterbur and Mansfield, a professor at Nottingham, were honoured. Since then NMR imaging, renamed magnetic resonance imaging (MRI), has continued to develop technically and expand its clinical applications, such that it is now a major imaging modality, with thousands of MR scanners in use world-wide.

### 1.7 Magnetic field gradients

The essence of Lauterbur's proposal is that the Larmor precession frequency be used to mark the position of an object within the scanned volume. We recall that the nuclear magnetisation precession frequency $f_0$, and the frequency of the NMR signal induced in the receiving coil, is directly proportional to the strength of the static magnetic field $B_0$

$$f_0 = \gamma B_0 / 2\pi \qquad 1.7.1.$$

Suppose that a coil is constructed which, when it is carrying a steady current, can modify the strength of $B_0$ depending on the horizontal left-to-right position within the scanner. This can be expressed mathematically as

$$B_0(x) = B_0(0) + x.G_x \qquad 1.7.2$$

where $B_0(0)$ is the static field strength at the centre of the magnet corresponding to x = 0, x is the distance from the magnet centre in metres, and $G_x$ is the size of the magnetic field gradient in teslas per metre. The size of the gradient $G_x$ is directly proportional to the current flowing through the gradient coil, and its direction can be reversed by reversing the direction of current flow. Figure 5 shows an example of such a coil, the Maxwell pair. The field lines add to the main magnetic field at the left of the diagram, and subtract from it on the right. In the centre the coil has no effect. Since the field gradient coil produces fields which are much weaker than the main magnetic field $\mathbf{B_0}$, the magnitude of $\mathbf{B_0}$ is unaffected by the gradient field where it is at right angles to $\mathbf{B_0}$. Like the Maxwell pair, all gradient coils have to have effective currents (NI) of many hundreds of amperes in order to produce fields which are the order of 10 milliteslas in regions away from the centre of the MRI scanner.

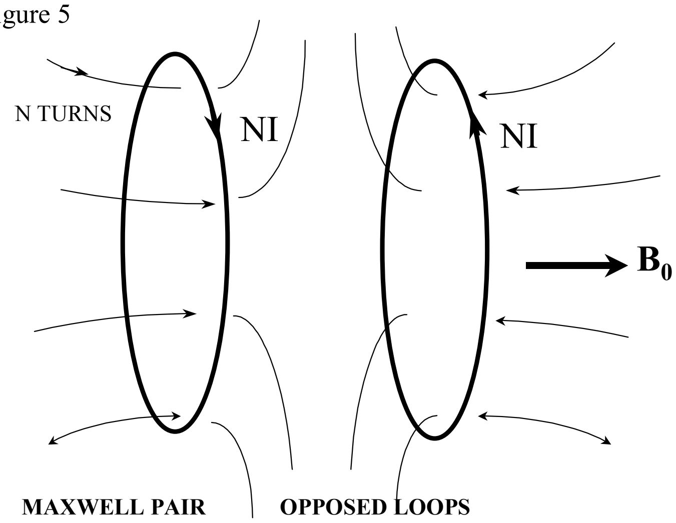
The Larmor precession frequency must also vary in a similar way, with it changing steadily from a value below $f_0$ at negative values of x, to a value above $f_0$ at positive values of x, assuming $G_x$ to be positive. From equations 1.7.1 and 1.7.2 we have

$$f_0(x) = f_0(0) + \frac{2\pi.x.G_x}{\gamma} \qquad 1.7.3.$$

In order to encode the x position of an object into the NMR signal, the $G_x$ gradient coil is switched on while the signal is being observed. The signal is then mathematically analysed by a technique called Fourier transformation. This process requires the use of a powerful computer, as many signals have to be analysed to form the final image. Fourier transformation sorts the signal into its different frequency components. A reasonable analogy is the use of a prism to split sunlight into its constituent colours, where each colour corresponds to a different frequency of the electromagnetic spectrum. In our case, each frequency component of the NMR signal corresponds to a particular x position. The observation of the NMR signal in the presence of a magnetic field gradient, and the use of signal frequency effectively to mark position, is called frequency encoding. The gradient used to do this is usually called either the frequency-encoding or the read-out gradient - the latter because the signal is observed, or read out while it is on.

The human body is, of course, 3-dimensional, so that MRI scanners are fitted with 3 separate magnetic field gradient coils which can be independently controlled, one each for the x, y and z directions. The process of image formation is not straightforward. There are 3 dimensions to be encoded, and yet equation 1.7.1 allows only one dimension to be encoded at any one time. The imaging process therefore encodes each direction sequentially. The first stage of the process is often to select out a thin slice, reducing the imaging problem to 2 dimensions. A brief description of the methods used in a modern MRI scanner will be given in the lecture.

Figure 5



**Our Invisible Environment:**
**Electric and magnetic fields in the solar system**

**John S. Reid**

(*Half hour talk to Advanced Higher Physics Teachers – not given verbatim. Accompanies PowerPoint slides*)

# Preamble

30 minutes is a short time to cover a subject that attracts a lot of space science interest. I want offer a taster of the relevance of E&M to the 3 subjects of: cosmic rays, the Van Allen belts and Aurora.

# Above the Earth

Most of our weather, the clouds, the wind and the rain, is confined to the first 8 km of the atmosphere above us. The next 80 km has an important influence on the lowest region of the atmosphere, the troposphere, but by the time you reach 100 km the density of the atmosphere is not much different from a moderate school lab vacuum (about $3\times10^{-3}$ Torr). Anyone would be forgiven for thinking that between there and the Sun there wasn't much of interest or relevance to everyday life. Far from it. At 100 km or a bit below you enter the realm of where electric and magnetic fields play a controlling role in what goes on – and what goes on is very relevant to everyday life.

The next layer up is the ionosphere, the region responsible for reflecting radio waves back down to Earth to make long distance communication possible in the short and medium wavebands. The ionosphere was discovered if not so named by that famous son of Brechin, Robert Watson Watt, Scottish inventor of radar. There's scope with here to interest pupils in both radar and the ionosphere. Why the ionosphere reflects some radio waves but lets through the higher frequencies used in satellite communications is a topic that more advanced pupils might like to investigate. Above the ionosphere is the plasmasphere, a region where many satellites orbit in a plasma of energetic ions and electrons, a region that leads up to the Van Allen radiation belts, sufficiently damaging to cause satellite operators serious concern. Above that is the magnetosphere, extending a couple of hundred Earth radii on the night side of the Earth.

*The bigger picture*

I've included this picture just to show the scale and some of the complexity of the magnetic field surrounding the Earth. Close to the ground the magnetic field approximately resembles the field of a bar magnet. Further from the Earth its characteristics are different. Outside the umbrella like region in the diagram lies the interplanetary magnetic field, another IMF, generated by the Sun and stretching beyond the orbit of Pluto.

*Charged particles and a uniform magnetic field - 1*

Can you illustrate any physics in the school syllabus with interesting examples from 'space'? Yes.

The magnetic force on a charged particle moving in a magnetic field is well known to be proportional to all 3 quantities involved, namely the particle's charge, the speed of the particle and the strength of the magnetic field. In addition, the force is at right angles to both the speed of the particle and the magnetic field. This last condition is very important in the context because it means that the force can do no work on the particle and change its energy. All it can do is change the direction of a particle, not its speed.

The slide shows that the force on a charged particle acts just like the tension in a string when you're whirling an object around your head. The string keeps the object at a constant distance from you; only the direction of motion changes as the object goes around in a circle. Likewise for the charge circling around in a uniform magnetic field. You'll be able to work out that the frequency of rotation is given by $f = qB/(2\pi m)$. Applying this to a field of $10^4$ nT, gives a frequency of over $10^5$ Hz. The radius of the circle depends on the energy, i.e. the velocity of the particle and is inversely proportional to the frequency of vibration. This follows from the basic relationship that $2\pi rf = v$. We'll need this result in a minute.

*Cosmic Rays*

Cosmic rays cause Geiger counters to 'click' even in the absence of any obvious radiation source. Cosmic rays are the background radiation we are all exposed to. It was Victor Hess who showed that the origin of this background radiation was cosmic. He won the Nobel Prize in Physics in 1936 for his earlier pioneering work.

Nowadays we believe that primary cosmic rays are the products of violent accelerations in the exploding atmosphere of a star going supernova. It turns out that there are just about enough supernova in our galaxy to account for the frequency of cosmic rays received on Earth.

Cosmic rays contain almost all the elements in the periodic table, though with a slightly different distribution from that found in the solar system. This is another clue about their cosmic origin.

*Deviation of cosmic rays*

Do cosmic rays come straight to us from identifiable supernova sites in the galaxy? In fact they don't. Hess and subsequent investigators showed that you get pretty well the same amount of radiation coming from all directions, and the same by day and by night. This is at first puzzling until you remember about the interplanetary magnetic field.

The IMF (interplanetary magnetic field) isn't that big but it is easily sufficient to bend the path of a cosmic ray. A very rough calculation goes like this:

The gyration frequency, $f$, of a charged particle in a magnetic field is given by:

$$\boxed{f = \frac{qB}{2\pi m}}$$

As seen two slides back. First we work out what frequency the cosmic ray particle has around the IMF and then what radius of circle it travels in. If this is smaller than the distance between planets, then we know that such a particle will follow the field lines in big circles and not come straight in. Take the case of a heavy, energetic particle, an $Fe^{26+}$ nucleus travelling near the speed of light, $c$. For this particle: $q = 4.165\times10^{-18}$ C; B = 10 nT (say); m = $9.37\times10^{-26}$ kg. These figures give $f = 7\times10^{-2}$ Hz.

If such a particle is travelling in a circle with speed close to $c$, the speed of light, then the radius $r$ of the circle is such that $2\pi rf = c$. Since $c = 3.0\times10^{8}$ m s$^{-1}$, $r = c/2\pi f = 6.8\times10^{8}$ m, or $6.8\times10^{5}$ km, about the diameter of the Moon's orbit. Hence even an energetic heavy particle will spiral round the interplanetary field lines as it comes into the solar system. In this way we lose all track of where it came from.

The influence of the field lines is greater than just destroying a way of satisfying our curiosity. The field lines to some extent trap the cosmic rays. As the field lines are deflected around the Earth, so are some of cosmic rays, shielding the Earth in a way that doesn't happen for the planets Mars and Venus that have no magnetic field.

You can hear from this Geiger counter that in spite of some shielding life has evolved in an environment with cosmic radiation and we are to some extent 'radiation hardened' as the technologists put it. There are natural mechanisms in life for discarding faulty molecules and replacing them with new ones. Not so, of course in electronic circuitry that we send up in satellites. It's not self-repairing. Radiation, basically energetic ion bombardment, is an important hazard for all Earth orbiting satellites.

The first person to discover that there was a lot more radiation up there where the satellites roam was James Van Allen, a year before the first satellite was launched. I'll say some more about Van Allen's discovery shortly.

*The physics of motion in magnetic and electric fields*

You have to work hard to understand the plasmasphere and magnetosphere. Charged particles in there exhibit 3 types of motion in the presence of magnetic and electric fields found around the Earth.

1. They spiral around magnetic field lines. This is known as gyration. Around the Earth there is enough space for the electrons to go around in rapid circles.
2. If the field lines come together then the particles can be reflected back along the field line they came on. Since the field lines come together at both poles, then particles end up spiralling from pole to pole
3. Less obviously, if an electric field is present at right angles to a magnetic field, then the particles drift at right angles to both fields. This leads to a drift of particles around the circumference of the Earth.

*Charged particles and a uniform magnetic field - 2*

In real life, the charged particles don't just move around the field lines, they move up or down them. Since the force on the charges is at right angles to both the velocity and the field, there is no component of the force parallel to the field lines and hence no force to alter the motion up or down the field lines. Hence the gyration in combination with the motion along a field lines produces a spiral motion of charged particles.

*Charged particles spiralling down converging field lines*

We have to treat the complexity of the world as we find it. We haven't reached the end of the story yet. The convergence of the field lines towards the poles mean that the field lines down which the particles are spiralling gradually converge. It's a serious problem to work out what happens to the spiralling charges in this circumstance. The result isn't that obvious. As the lines converge, the field increases and the particles gyrate in smaller, faster circles. That you'd expect. However, since the total energy of the particle isn't changed, then if the velocity in a circle is increased, there must be less velocity to keep travelling down the converging field. This is so and eventually the velocity down the field becomes zero when the gyration speed consumes all the available speed from the particle's initial energy. Remember that kinetic energy is just $\frac{1}{2}mv^2$. The slightest wiggle in the backward direction sends the particle gyrating at a slightly slower speed again and the motion along the field line starts to pick up. So the particle is reflected back along its tracks. The phenomenon is known as the **magnetic mirror**. It really works.

*Add an electric field **E** perpendicular to the magnetic field B*

That's still not the end of the story for our particles in the magnetosphere. Electric fields also exist in the magnetosphere, which is perhaps not surprising because electric fields are produced both by charges and by the motion of magnetic fields. There is a hand-waving argument that says that the electric field is mainly at right angles to the magnetic field. Lets accept that this is so.

We're accustomed to electricity flowing in what you would call an 'obvious' way, parallel to the electric field generated by a voltage. In most domestic appliances, we provide the conducting path using wires. The current generates heat in the wire, which might be the whole purpose of passing the current, as in a cooker, or perhaps the current generates a magnetic field that operates a motor to drive some DIY equipment like an electric drill. It's strange but true, the electric fields in the magnetosphere have a different effect on charge. When the electric field **E** and the magnetic field **B** are at right angles to each other, the result is a motion of the charge that is at right angles to them both, a drift of charge at speed of the magnitude of E/B. This drift operates to make the charge circle around the poles in a **ring current**.

*Van Allen radiation belts*

James Van Allen discovered the lower of these radiation belts when he organised the first of a series of rocket probes during the IGY, the International Geophysical Year, that started in 1957. Van Allen was responsible for the instrumentation aboard Explorer 1, all of one single Geiger counter on board. To his and the team's astonishment, the Geiger counter sent back higher and higher counting rates as it climbed, eventually cutting. "My God, space is radioactive" was the comment, according to scientific folklore. We know a lot more about the Van Allen belts now and space isn't radioactive. The belts do though contain substantial amounts of high energy particles.

Electrons with energies over 1 MeV have a flux above a $10^{10}$ $m^{-2}$ $s^{-1}$ from 1-6 earth radii (about 6,300 - 38,000 km), and protons over 10 MeV have a flux above $10^{9}$ $m^{-2}$ $s^{-1}$ from about 1.5-2.5 Earth radii (9,500 km - 16,000 km). The radiation dosage from these particles is significant for any one, or any thing, that stays in the belts for some time.

*Detail of the Van Allen belts*

The inner belt is around 1.5 $R_E$, mainly energetic protons produced from cosmic rays. The trapping of particles by the Earth's field is very effective and the protons spiral backwards and forwards for a very long time (years have been quoted). Although the supply from cosmic rays is not very big the loss mechanism is very small so pretty substantial fluxes build up.

The outer belt at 3 – 9 $R_E$ is trapped magnetospheric plasma. The drift of the particles around the Earth contributes a so-called ring current that can rise to millions of amps. This space current induces ground currents that upset long electricity transmission lines, sometimes to the point of causing huge surges. The main contributor to the ring current is low energy protons, at least low energy compared with those that may cause radiation damage.

*Motion of electrons in the magnetosphere*

The ring current isn't the only flow of electrons. This slide shows a current of solar wind particles, a current across the plasma sheet and a current involving charged particles, mainly electrons, flowing towards the poles. These later produce the aurora when they get close enough to the Earth to impinge on a significant density of upper atmospheric ions and atoms, as is sketched in the inset. This collision process between energetic electrons and the constituents of the upper atmosphere excites some of the atoms and molecules present, giving them more internal energy. Notice that it's internal energy the molecules have, not extra kinetic energy. This raises the electrons to higher energy levels within the atom. Excited atoms don't stay excited for long, because they can give up their energy by emitting a packet of electromagnetic radiation, namely a photon. If the photon is in the visible part of the spectrum, then we will see it as light. I'll say about more about this shortly.

*Permanent auroral oval around both poles*

The aurora is generated at heights between 300 km and 80 km. Although we only see it on occasions at Aberdeen, there is a permanent **auroral oval** around both poles of the Earth. The slide shows the intensity of the auroral superimposed on both the dark and illuminated side of the globe. Notice that it is more intense on the dark side, particularly where it is late evening but not yet midnight. This is the time you will most likely see the aurora at

Aberdeen, from say 8 pm to midnight, though certainly not exclusively within these hours. The auroral oval increases in intensity at times of high geomagnetic activity, initiated by solar wind events. It particularly expands southward (in the Northern hemisphere) and it is only then that we are likely to see it if the night is cloud-free. If the Sun is the cause, why is the aurora so strong on the night side of the Earth? The slide shows that it's not just that it's dark here and we can see light that's always faint compared with sunlight much better. The auroral intensity really is much higher on the night side of the Earth.

*Auroral colours*

Auroral light is mainly confined to spectral lines whose location in the spectrum is characteristic of the molecules and atoms emitting the light. What are they? Mainly $N_2$ and atomic oxygen, O. At the lower heights involved molecular nitrogen $N_2$ is excited and ionised by the incident electrons. It emits characteristically in the blue and green. At higher altitudes, the meteorologists in the class might remember than UV below about 250 nm in wavelength is capable of breaking oxygen molecules $O_2$ into atomic oxygen, O. Excited atomic oxygen emits strongly in the green. When atomic oxygen is excited at even higher altitudes it emits strongly in the red? Why the difference? You're not likely to guess but it has to do with the even lower pressures at higher altitudes. Very low pressures mean even longer between atomic collisions.

The fundamental lines from aurora at different heights are suitable primary colours that when mixed together in a whole range of ratios can produce almost any colour sensation you than think of. The net result is that you can get a very wide range of coloured auroras.

*Example Auroras*

Here are a few examples of auroras. The one on the upper right shows the characteristic green from lower altitude atomic oxygen, with magenta showing through from low level $N_2$. The lower slide shows a red auroral glow from high altitude atomic oxygen that can pretty well cover the sky at times. You can find many excellent auroral pictures taken near Aberdeen in the book *The aurora: an introduction for observers and photographers* by Jim Henderson & John MacNicol (Crooktree Images, Kincardine O'Neil, 1997).

Final message: My slides were taken from our course on *Space Science & Remote Sensing* that we give to science students in general. There's a lot of very good physics in this area that is relevant to everyday life but doesn't get into an Honours course. Much of it centres on Electricity & Magnetism.