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Earth's Proximal Space

Plasma Electrodynamics and the Solar System

Chanchal Uberoi

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Plasma Electrodynamics and the Solar System

Chanchal Uberoi
Department of Mathematics
Indian Institute of Science
Bangalore 560 012

Jawaharlal Nehru Centre for
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Dedication

Our views of the Space Environment of the Earth, the Solar System and our relationship with this system have changed tremendously. This book is dedicated to those who have brought about this change.

Desire in the beginning came upon that (the unevolved universe), (desire) was the first seed of mind. Sages seeking in their hearts with wisdom found out the bond of the existent in the non-existent.

Rig Veda 1200–900 B.C.
(Translated by Arthur A. Macdonell)

Contents

Foreword

The Jawaharlal Nehru Centre for Advanced Scientific Research was established by the Government of India in 1989 as part of the centenary celebrations of Pandit Jawaharlal Nehru. Located in Bangalore, it functions in close academic collaboration with the Indian Institute of Science.

The Centre functions as an autonomous institution devoted to advanced scientific research. It promotes programmes in chosen frontier areas of science and engineering and supports workshops and symposia in these areas. It also has programmes to encourage young talent.

In addition to the above activities, the Centre has undertaken a programme of publishing high quality Educational Monographs written by leading scientists and engineers in the country. These are short accounts of interesting areas in science and engineering addressed to students at the graduate and postgraduate levels, and the general research community.

This monograph is one of the series being brought out as part of the publication activities of the Centre. The Centre pays due attention to the choice of authors and subjects and style of presentation, to make these monographs attractive, interesting and useful to students as well as teachers. It is our hope that these publications will be received well both within and outside India.

C N R Rao
President

Preface and Acknowledgements

There are numerous books for non-scientists and young students giving information about the Sun, Stars, Galaxies, Nebulae, Black Holes and many other astronomical objects, millions of kilometers away from the Earth. However, there are very few popular books which describe the interesting features and processes that exist in the space immediately surrounding our planet Earth — a space that extends out to a distance of just about 64 000 kilometers. The reason could be that the study of our neighbourhood space is a new subject and this study is more abstract, in the sense that it lies outside the realm of daily experience and has not aroused our curiosity. *The space surrounding us is literally invisible to the naked eye.* However, with the advent of the satellite age, we can see this space with the eyes of the satellite vehicle which has enabled us to acquire enormous amounts of data and knowledge about our space. This book aims at publicising the recent, amazing new findings about the plasma and magnetic environment of the space surrounding our planet Earth.

The material in this book is mainly based on my scientific writings for young people trying to build a career in science and for non-scientists interested in science, in various science magazines both in India and abroad. Some of these ideas were also used for Radio Programmes and U.G.C. Television programmes. Many letters and responses from young students and friends inspired me to consider writing this book, compiling the ideas expressed in my earlier scientific articles.

I have tried to tell the story of our space environment with the help of pictures. I am greatly indebted to Lou Lanzerotti of AT&T Bell Labs., N.J., U.S.A., for providing me with some valuable and informative photographs. My collaboration with Lou Lanzerotti in writing scientific articles and discussions with him and other colleagues at Bell Labs, especially Dr. A. Wolfe and Dr. Carol G. MacLennan has given me great insight into the understanding of our space.

The idea of writing this book came up while discussing various topics on space environment at home. My special thanks go to my young son Sameehana Gargeya for suggesting the title of the book and elaborate discussions about the material which should go into each chapter. The book could not have been completed without encouragement from my husband Prof. S.N. Balasubramanyam. I also thank my daughter Vibhavaree Gargeya and her husband Kenneth Miller for critically reading the manuscript.

The writing of this book became possible with the financial support from Indian Space Research Organisation (ISRO) through the ISRO-IISc Space Technology Cell, Indian Institute of Science, Bangalore.

I thank Mr. Ancil J. D'Coutho and Mr. Ramesh Babu for the preparation of the illustrations. Last, but not the least, I thank Mr. M. Renugopal, who with great enthusiasm and competence, not only organized a seemingly endless series of versions and revisions, but managed to greet each one of them pleasantly.

C. Uberoi

1. Introduction

"A satellite vehicle with appropriate instrumentation can be expected to be one of the most potent scientific tools of the twentieth century. The achievement of a satellite craft by the United States would inflame the imagination of mankind and would probably produce repercussions in the world comparable to the explosion of the atomic bomb ......"

— *Project RAND: Preliminary Design of an experimental world circling spaceship, May 1946.*

The purpose of this book is basically to reveal the new ideas which have been acquired over the past forty years about the proximal space environment of planet Earth and to point out the deeper understanding of the Sun–Earth relationship we have arrived at, although there has been an awareness of this link since ancient times.

The rapid progress in understanding our space environment can be attributed to the amazing advances in space technology and to the development of the science of plasma, the fourth state of matter. The solar physicists and geophysicists working together, with the help of data obtained from the space experiments have now found a very important plasma link between the Sun and the Earth. It is not just the visible light which links us with the Sun, but the Earth and the entire *solar system* is embedded in the *solar plasma*, called the *Solar Wind.* The interaction of the solar wind plasma with the Earth's magnetic field forms the basis for the understanding of our space environment. The first part of the book is therefore devoted to plasma and the Sun–Earth relationship.

Not long ago, several physical phenomena occurring on the Earth, as manifestation of plasma processes in the near-Earth space, were attributed to supernatural happenings. It is the endeavour of this book to show how the knowledge of plasma matter and the physical conditions in the space surrounding our planet has helped us overcome our ignorance about these natural physical phenomena.

The study of our plasma environment has another advantage. Earth's proximal space acts like a large plasma physics laboratory provided by nature. Understanding of this naturally occuring plasma is relatively easier as it can be probed by the in-situ instruments flown on rockets and spacecrafts. The study of plasma is not only basic to every aspect of astronomy, but it is also important to overcome the difficulties faced by the scientists trying to achieve thermonuclear fusion , one of the most potentially viable sources of energy for the future.

With the advances in space technology, man is beginning to depend on the space systems especially for weather forecasting, communication systems and navigation. The satellites orbiting around planet Earth move into the plasma medium with attendant complicated physical conditions created by the Earth's magnetic environment. It is important, therefore, to know our space and the effect of it on the technical systems in the space close to the Earth. Besides the man-made systems placed in space, the geospace impact on man-made technical systems on the Earth, especially those that use electric power grids, are often dramatic. This book hopes to cover these aspects.

1.1 Measure of Our Space

What is the measure of our space? What are the distances we are dealing with? Looking towards the sky, we become aware that the planet Earth has an atmosphere which gives us the changing seasons and, most important and vital for life, the rainfall. The Earth is unique in the sense that it is the only planet in our solar system which receives rain. The atmospheric layer of the Earth consisting essentially of neutral gases almost symmetrically surrounds the Earth. From the direct evidence of aircraft and aerial projectiles and from the indirect evidence supplied by *twilight*, *cosmic rays*, *meteors* and *auroras*, we know that the atmosphere extends up to about 80–90 km. We have also come to realise that it can be divided into various layers based on temperature variation with altitude, which are given definite names; though there is no sharply defined border-line between these layers, and one merges gradually into the other [Fig. 1.1].

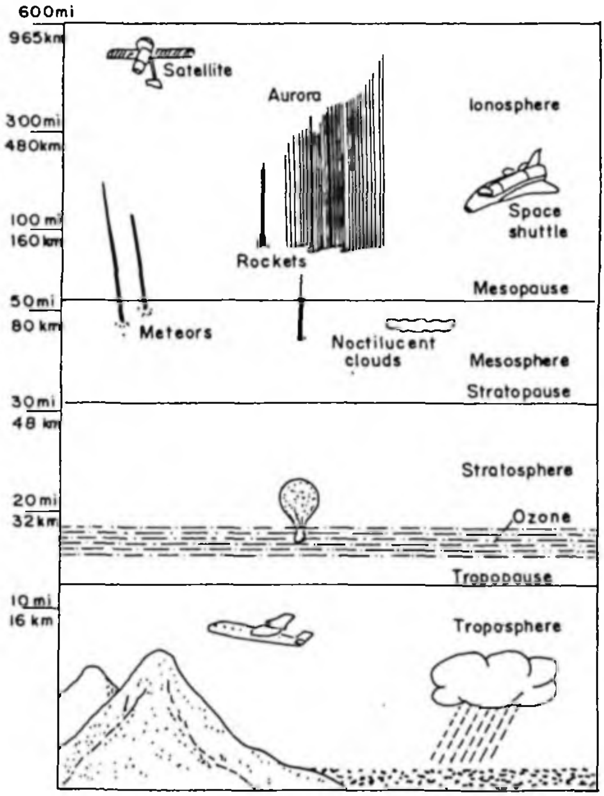


Fig. 1.1 This figure gives an idea of the altitude at which some familiar natural phenomena and objects are seen. We see here the different layers of the Earth's atmosphere; the *Troposphere, Stratosphere* and *Mesosphere* are shown. The ionosphere extends up to altitudes of 1 500 to 2 000 km leading into the magnetosphere . Note that the satellite (INSAT) shown here is at approximately the lower limit of its stable operation; most have higher orbits (illustrated by Eric A. Lord).

The visible light from the Sun passes directly through the atmosphere, but the *Ultraviolet* and *X-rays* from the Sun interact strongly with the upper atmosphere air, producing ionospheric and ozone layers. With increasing altitude, the air becomes more and more ionised and above a height of about 100 km, ionised matter dominates the neutral form; and the region from thereon up to 1 500 km is called the *ionosphere*. The matter in the ionosphere is in the plasma state. This is the layer which reflects radio waves in the broadcast band, allowing short-wave communication to be carried out on a worldwide scale. The understanding of the ionosphere began in the very early part of this century, after the wireless transmission of radio waves was invented. The radio waves could be used as probes to determine the physical condition on the ionosphere. What is there above the ionosphere? This is the story which will be related in this book.

Probing the Ionosphere

On December 12, 1901, Guglielmo Marconi, transmitted a simple Morse Code signal from England to Newfoundland, a distance of 2 900 km. The scientists were amazed as they could not fathom how the waves travelled around the curvature of the Earth. In 1902, after a year, Arthur E. Kennelly proposed that radio waves overcome the curvature of the Earth by reflections from an electrically conducting layer at a height of about 80 km., Oliver Heaviside made a similar proposal almost simultaneously; the ionised layer came to be called the Kennelly–Heaviside layer.

In 1925 Edward Appleton and his student Miles Barnett, from England, set out to determine the height of reflection of a continuous wave from the Heaviside layer. Appleton prevailed on the BBC to provide him with a continuously varying wavelength from London at the end of the broadcast day, so that he could detect the interference pattern of ground and sky waves at Oxford. Along with Barnett he observed the elapsed time between emission and reception of the same frequency as the broadcast frequency was oscillated back and forth. Early experiments used lower frequencies that only probed the lowest portion of the reflecting layer. Later,

Continues...

Continued...

as Appleton increased the frequency, he found a higher region of reflection. By 1927 he could discriminate three regions that he labelled D, E and F layers in order of increasing height. For these experiments Appleton subsequently received the Nobel prize.

The name "ionosphere" was proposed by R.A. Watson-Watt, in a letter to the United Kingdom Radio Research Board, dated November 8, 1926. Although this name did not enter the literature till almost 1929, it has now virtually suppressed the older term Kennelly–Heaviside layer.

1.2 MAGNETOPAUSE: EARTH'S MAGNETIC *LAKSHMAN REKHA*

It was believed until thirty-five years ago that the matter in space above the ionosphere was very diffuse, and the Earth with its atmospheric and ionospheric layers rotated around the Sun in harmony with other planets of our solar system in a space which was a near-vacuum. It was also believed that the Earth's magnetic field extended indefinitely into interplanetary space, becoming gradually weaker with distance from the Earth. This picture of the Earth's space environment and the magnetic field organisation in the space has changed drastically since 1957, when the first artificial satellite *Sputnik I* was launched. The dawn of the satellite era has brought us a very different and surprisingly new picture of the space in the neighbourhood of our planet. Before the exploration of space by satellites and spacecrafts, we no doubt had balloons to probe up to 30 km and radio waves to study the ionosphere. The meteor trails and auroras up to 100 km and higher could be observed, but we were essentially living in a two-dimensional world. It was thought that the Earth's atmosphere was just a few hundred kilometers and then it ended. Now we know where our space ends and the outer space begins. The space near the Earth has its own boundary. We own this space! The boundary is marked by the magnetic field of Earth organising itself as a closed cavity called the magnetosphere [Fig. 1.2]. The magnetopause, marking

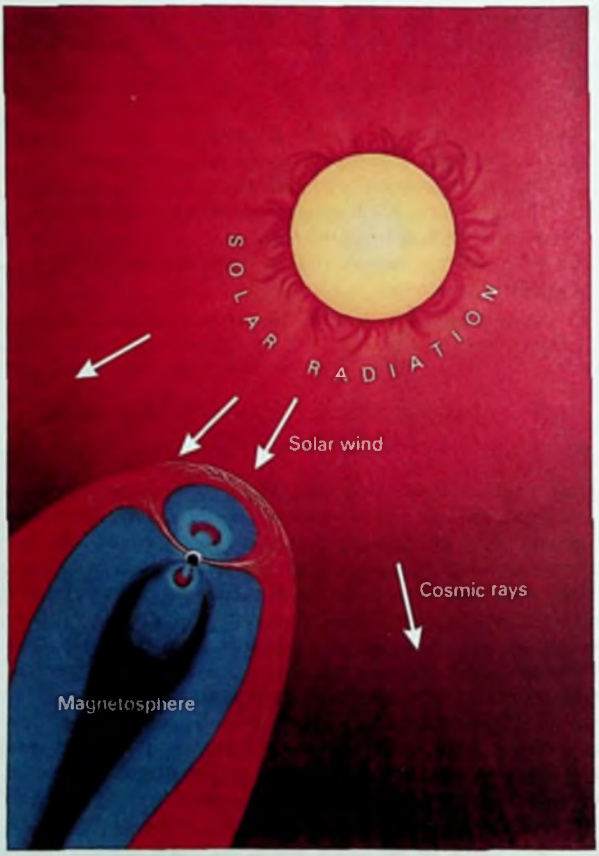


Fig. 1.2 Sun–Earth Relation, an artist's sketch. The solar wind organises the Earth's magnetic field enclosing the Earth's magnetic environment in a closed cavity, the Magnetosphere (illustrated by Eric A. Lord).

the actual outer boundary of the magnetosphere is at a distance of about 10 R_E (R_E, the Earth radius is approximately 6 400 km) away from the centre of the Earth on the side facing the Sun. In fact, the magnetosphere protects the Earth from various harmful radiations from the Sun. The magnetopause is thus a *Lakshman Rekha*[1] for the Earth.

Actually, the term magnetosphere was coined by T. Gold in 1959[2] to describe the region of space, wherein the principal forces on a plasma are electrodynamic in nature and are a result of the planet's magnetic field. The magnetosphere results from the solar energy in the form of solar wind interacting with the magnetic field of the Earth.

1.3 Magnetically Organised Systems in the Universe

You can now ask a question: Why is it that the magnetosphere which is just 10 R_E away from the Earth can never be seen, whereas for thousands of years man has been studying the distant stars in the outer space millions of kilometers away from the Earth? It is strange that we have been watching and understanding distant objects for many years now, but have begun to understand the space in the neighbourhood of our planet just less than two decades ago. This strange paradox can be explained as follows: In the case of the Sun, other stars and galaxies, the plasma matter is organised by gravity. The gravitationally organised systems have a feature of emitting an appreciable amount of radiation in the visible range and so we can often see these distant objects with the unaided eye.

The plasma matter in the immediate neighbourhood space around the Earth is mainly organised by the Earth's mag-

[1] This word seems to have originated from the following story in the Indian epic *Ramayana*. Lakshmana, the younger brother of Rama, was assigned the duty of protecting Rama's wife Sita, when Rama was away capturing the deceptive 'golden' deer. On sensing that Rama was in danger, Lakshmana decided to go in search of his brother. But he could not leave Sita unprotected, and so he devised a magical circle which he drew around the cottage. Within the boundaries of this circle no danger could befall Sita but a step outside could remove the magical power of this line. Such a protective line has come to be known as Lakshman Rekha.

[2] In a fall AGU (American Geophysical Union) meeting in 1994, Gold humourously recalled that when he introduced the term "magnetosphere" in the title of a paper in 1950, several people told him that the terminology would never be adopted because the structure was not a sphere. Gold also recalled that as late as 1956, Wooley, the Astronomer Royal of Great Britain, regarded space physics as "utter bilge", a viewpoint that was instrumental in Gold's subsequent departure to the United States.

netic field. Unlike the gravitationally organised systems, the magnetically organised systems radiate primarily at radio and micro wavelengths, but not in the optical wavelengths. Thus, magnetosphere-like systems are not visible to the human eye by merely looking towards the sky, but can be studied only by lifting our instruments above the Earth's ionosphere. This was the main reason that we did not give any importance to the space environment around us, until the sophisticated instruments carried by the spacecrafts gave us an interior view of these regions. We can now study the three-dimensional structure and behaviour of the magnetosphere with the help of the data given by these instruments. This is discussed in detail in the fourth chapter.

Are we alone in having a closed space or the magnetosphere surrounding our planet? This question has been answered by observations from spacecrafts which have revealed that not only other planets in our solar system but also the Sun, other normal stars and galaxies too are surrounded by magnetically organised matter in the form of a magnetosphere. It is now becoming more and more obvious to the scientists that large-scale magnetic organisation of matter in the plasma state may be as common as the more familiar gravitational organisation. The last part of this book aims at describing the near space surrounding other planets in our solar system and points out how the study of our own magnetosphere has opened up avenues for a deeper understanding of the basic physical characteristics of other large-scale magnetic organisations of matter in the universe.

1.4 Space Age: Revolution in Science

The sky, when we look up at it, looks the same today as it did thousands of years ago, but now we can look at it with different eyes, the eyes of the satellite vehicle through which we can see an entirely new picture of the space around us.

This reminds me of Hannes Alfvén, the father of modern space plasma physics. Alfvén regarded the space age as a revolution in science comparable to the introduction of the telescope by Galileo. The spacecraft is capable of observing a wide range of physical parameters in comparison to the limited "visual light universe" dependent on ground-based telescopes.

2.

Plasma : The Fourth State Of Matter

"The resulting mixture of free ions and free electrons known as plasma, has bewildering properties unfamiliar to those on Earth, though it is the prevailing state of matter in the universe".
— *J. L. Tuck, 1972*

The planet Earth is capable of supporting three states of matter namely; solid, liquid and gas. In other words, conditions are appropriate for these states to exist. To understand this, consider the most important life-sustainer, water, which is the liquid state of matter. If the conditions on the Earth were to change such that the Earth became very cold, then the rivers, seas and other water resources would all freeze to ice and we would not have known the liquid state of water. On the other hand, if the Earth were to become very hot, all the water sources would evaporate to form steam and water would exist in the form of vapour or in the gaseous state. The temperatures of the atmosphere of the planet Earth are therefore suitable for matter to exist in any of the three states: solid, liquid and gas. Does the matter in the vast universe outside the atmosphere of our planet Earth occur commonly in these states? The answer to this question which scientists explored and found out recently is very different from what we expected. The most prevalent matter in the universe is neither solid, liquid nor gas, but it is in the form of *plasma, the fourth state of matter.* The solids, liquids and gases form only one percent of the matter in the universe, the remaining ninety-nine percent of the matter is in the plasma state.

What is this state of matter which is called plasma? Once again, consider the familiar example of water which is a liquid consisting of molecules formed by two hydrogen atoms and one oxygen atom. When water freezes to ice, the molecules arrange themselves in a closely packed manner, thus forming the solid state. On the other hand, when water is heated, the bonds of hydrogen and oxygen weaken and the continuous packing of molecules break and are separated from each other giving off steam. Now, suppose we further heat the water in the gaseous form to a very high temperature, say to a million degree kelvin, then what changes take place? The atoms consist of a central nucleus. The electrons revolve around this nucleus. When the hydrogen or oxygen atoms are heated to a very high temperature, they cannot retain all their electrons. With the increase in temperature, the outermost shell of the atom is removed. On one hand we are left with electrons which are negatively charged particles, and on the other hand we have atoms which on losing electrons become positively charged and are called ions. The ionised gas consisting of an equal number of positively and negatively charged particles is called plasma.

You can ask a question: Can the electrons and ions recombine to again form a neutral gas? It is seen in nature and in the laboratory that under suitable physical conditions this assembly can exist as a stable and a natural state of matter.

This can be explained by the important fact that plasma is a collection of charged particles and so the interactions of particles is by long-range forces, unlike the case of neutral gases where the molecules interact with short-range forces only. Actually, the principal phenomena in plasma physics can be traced to the simple fact that charged particles interact with one another by long-range Coulomb forces. For instance, the electric field due to a point charge decreases only as the cube of the linear dimension, so the dominant interactions in plasma are such that a charged particle interacts with many or all other particles simultaneously. Thus, it is possible for the electric (and magnetic) fields of an assembly of charged particles to act together in a coherent way giving rise to strong cooperative plasma behaviour which does not exist in ordinary gases where molecules interact with short-range forces only. The dominance of collective particle interactions over the close binary collisions allow an ionised gas to exist as plasma. The most important criterion for an assembly of charged particles to behave like plasma is, therefore, that it should be sufficiently dense so that space charge effects can result in strongly coherent behaviour. By coherent behaviour, we mean that if the system is disturbed at a particular point then this disturbance should be transmitted to all other points of the system.

The temperature requirement for the ionisation of a gas depends on the nature of the gas. The relationship between the temperature and ionisation of a gas was first given by the Indian physicist Meghnath Saha in 1920 in his studies related to the nature of matter in the interior of the stars. The application of *Saha's equation* allows us to arrive at the important result that when the temperature is high enough, the gas is no longer neutral, but contains both positive ions and free electrons. The number of ions and electrons in the gas increase very rapidly with increasing temperature. (Here, it is necessary to mention that the degree of ionisation depends not only on the temperature, but also on the density of the gas, though less sensitively.) Most of the atoms will become ionised by the time temperatures of the order of 10 000 to 1 00 000° K have been reached and there will be practically no neutral atoms left [Fig. 2.1].

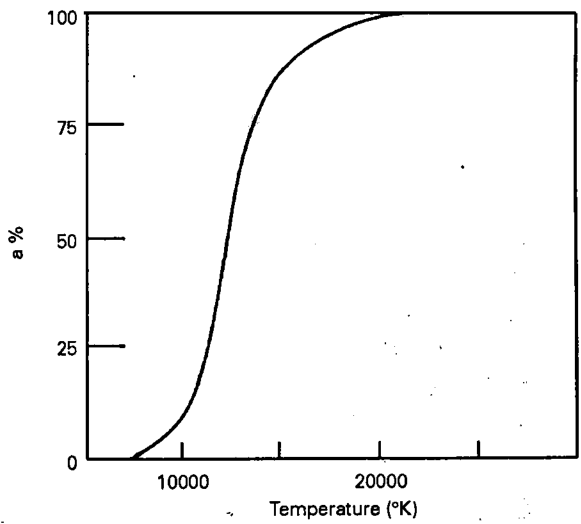


Fig. 2.1 Degree of hydrogen ionisation as a function of temperature. The density taken here is 7×10^6 neutral atoms per unit volume, the pressure corresponding to this density is about 1 mm Hg. It is noted that when T = 10 000° K, the number of ionised atoms is less than 10% of the total number of hydrogen atoms, while at 30 000° K there is only one neutral atom for every 2×10^4 positive ions (protons).

2.1 Natural Plasmas

As it requires such high orders of temperatures, million degrees and above to ionise a gas, it is understandable that the plasma state is not a natural state of matter on the Earth. Plasma, however, is the most widespread matter in the universe. The Sun and the other stars can be considered as lumps of hot plasma. The matter in the solar corona, interstellar space [Fig. 2.2] and, nearer home, all the matter surrounding our atmosphere at a

Fig. 2.2 Interstellar gaseous plasma.

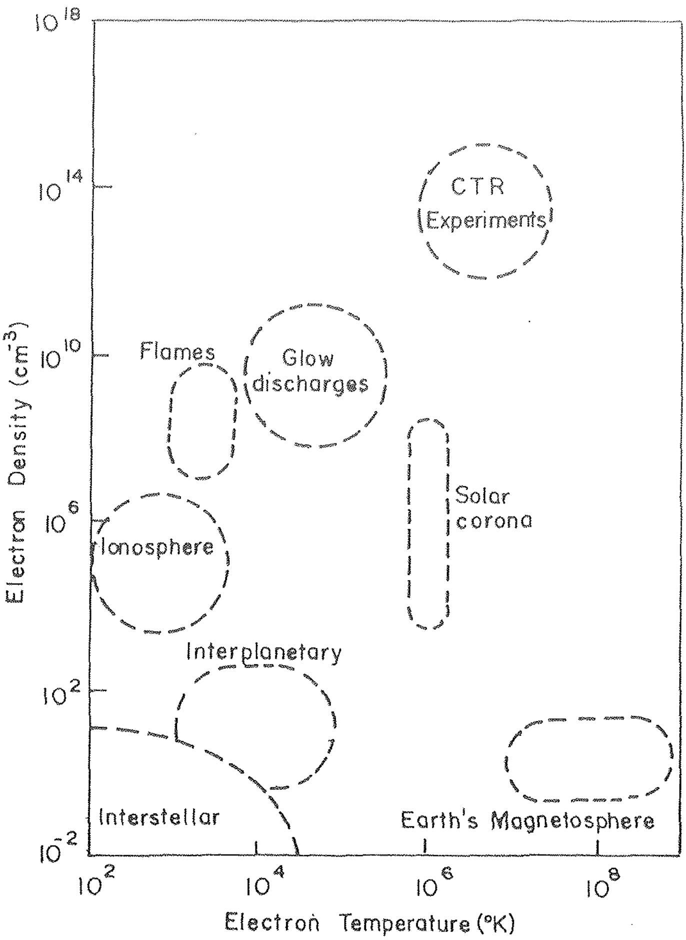


Fig. 2.3 Plasma parameters for a variety of natural plasmas in terms of electron density and temperature. For comparison, laboratory plasmas used for Controlled Thermonuclear Reaction (CTR) experiments are also shown.

distance of about 90 km from the surface of the Earth and above, is in a plasma state.[1] Nature's plasmas cover a broad range of

[1] A passage from *Scientific American*, 1846, 150 years ago.
"Jean-Baptiste Fourier, a French philosopher, established that there are three states in which material bodies exist and proved that when a solid body or a liquid (such as molten iron) becomes incandescent, the light which it emits is polarised and that the light of incandescent gases, such as flame, is unpolarised. Now M. Francois Arago has, with most beautiful sagacity, established that the light from the Sun is not polarised; the conclusion is inevitable, that the surface

temperatures and densities. Figure 2.3 shows typical parameters that are characteristic of some of the plasmas in nature.

Interestingly *Auroras*, [Fig. 2.4] the spectacular displays of luminous radiation in the sky near polar regions, and lightning [Fig. 2.5] are the oldest studied effects of the plasma environment of the Earth.

Fig. 2.4 Auroral plasma in action.

of the Sun is covered by an atmosphere of flame." [Editor's note: Plasma, the fourth state of matter, was not recognised until 1952. The surface of the Sun does give off unpolarised light, but is actually composed of plasma.]

Fig. 2.5 Lightning discharge: The earliest example of plasma phenomenon in nature. A Badlands storm [The Badlands Collection].

2.2 Man-Made Plasmas

As already noted above, the conditions on the Earth which are suitable for existence of life are certainly not suitable for the fourth state of matter to exist naturally on Earth, though we can use man-made plasmas for laboratory and industrial purposes. When we are in a market with huge neon signs, we are actually looking at 'plasma lights'. Similarly, a fluorescent lamp which is common in many homes is a plasma light. In all these cases, the plasma is produced in a glass tube filled with gas, by passing a high-voltage current through it. Traditionally, a current passing through a gas is called a *discharge* [Fig. 2.6]. The production of plasma in the discharge tube can be understood in terms of the concept of plasma produced by the simple process of heating a gas as introduced above. In the case of a discharge, the energy provided by the current flow, is used to ionise the gas. Scientists are interested in understanding laboratory plasmas as they have many technological applications [Fig. 2.7]. An important application is to obtain cheap energy sources. Scientists think that by producing certain reactions in plasmas, just like in the interior part of the

Sun and other stars, we can generate energy at a very low cost. These reactions are called *Thermonuclear Fusion Reactions.*

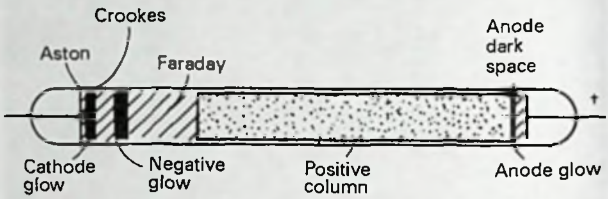


Fig. 2.6 The physical appearance of a glow discharge.

Fig. 2.7 Application of plasma in industry. The plasma is used for surface hardening of a gear wheel kept in the discharge chamber by the process of Nitriding (courtesy: P.K. Kaw, Institute of Plasma Research, Gandhinagar, Gujarat).

What is Thermonuclear Fusion Energy? We are quite familiar with the term *fission energy.* Fission means splitting of a heavy nuclei element into two components. This process releases a vast amount of energy, which is the fission energy. Fusion, on the other hand, uses the light nuclei element. If the light nuclei can fuse together, again a vast amount of energy can be released; now this is called the fusion energy. But, the main difficulty is that when two nuclei are apart, they are acted upon by electrostatic forces. To bring these nuclei together, one has to overcome those forces. Suppose these nuclei are a constituent of plasma as positive ions, they will have random thermal motion due to the high temperature of plasma. In this case, there is a probability that these ions can come very close and fuse together. We are familiar with the production of fusion energy in the hydrogen bomb but, unfortunately, the energy is uncontrolled and so can only be used for destructive purposes and not in a constructive way. Plasma physicists are trying for controlled nuclear fusion with high temperature plasmas.

The most suitable fuel for fusion is considered to be Deuterium, which is an isotope of hydrogen. We know that ordinary water consists of hydrogen and oxygen, whereas if we take heavy water, which we are familiar with in the case of fission reactors, instead of ordinary hydrogen it has its isotope, Deuterium. It is a suitable fuel as it occurs in ordinary sea-water and other water sources on the surface of the Earth and so it can be obtained almost for free, making fusion energy cheaper than fission energy. Compared with gasoline energy, the calculations show that one liter of water can give us the energy equivalent to 300 liters of petrol!

2.3 The Name Plasma

The word plasma certainly reminds us of blood plasma, a medical term. Then why is the name plasma used for an assembly of positively and negatively charged particles in equal numbers? The name plasma was first used by the American Nobel Laureate, Irwin Langmuir, in 1928 to describe the glow in the positive column region of the discharge which contains ions and electrons in about equal number. This name was borrowed from the medical term blood plasma, as Langmuir noted a very fascinating property of this assembly of charged particles. He found that this group of charged particles as a whole showed a characteristic oscillatory behaviour or a jelly-like movement similar to that of blood plasma, which led him to use the name 'plasma'. The characteristic frequency of oscillations is now called the *Langmuir frequency* or more commonly *Plasma frequency*. It appears that in plasma the electrons, which are lighter particles, execute a simple harmonic motion with the heavy particle ion as the centre. The plasma can be viewed as a huge assembly of harmonic oscillators, oscillating with the plasma frequency.

The plasma frequency is proportional to the plasma density of electrons. For example, if there are one million particles in a unit volume, the plasma frequency will be about 50 million cycles per second; and if the density is a hundred million, the frequency will be five hundred million cycles in a second.

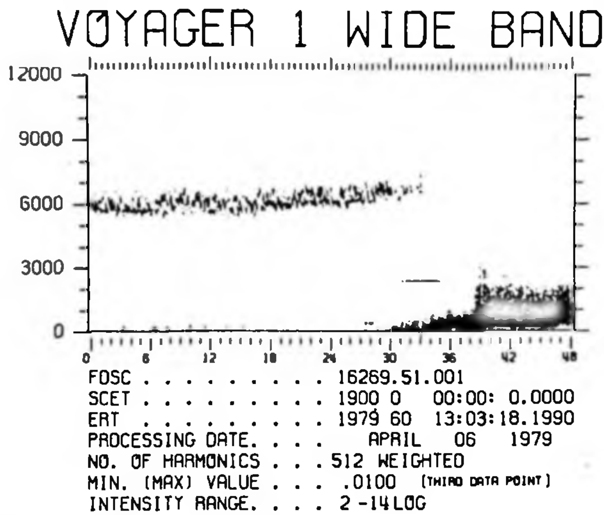


Fig. 2.8 Jovian plasma oscillations: Frequency-time diagram of the electron plasma oscillations detected in Jupiter's magnetosphere by the spacecraft *Voyager*. The plasma probe picked up the signals on March 1, 1979 which, when plotted on the frequency-time graph, showed constant frequency oscillations. The frequency of 6 000 Hz was calculated to be the plasma frequency of the plasma in the vicinity of the spacecraft. After 33 sec. mark, plasma turbulence features are seen.

The plasma oscillations arise due to strong interactions between the charged particles constituting the plasma. Plasma consists of an equal number of positive and negative particles and the important property of plasma is that it tries to remain electrically neutral. The oscillations in plasma are the consequences of this property. Imagine a small volume of plasma with an equal number of electrons and ions. Ions, being heavy, form more or less a uniform background. If one electron is pulled out from this volume, this region becomes positively charged and so tries to draw the electron back to its original position so as to restore neutrality. As electrons are light and have inertia, many electrons will overshoot in this region so that this volume has now an excess of electrons, thus becoming a negative region and so once again the electric fields build up and try to expel the excess of electrons to restore neutrality.

Thus, a slight initial disturbance in a region of plasma sets up systematic longitudinal oscillations in the plasma. This also shows that it is the electric fields between the positive and negative charges which gives the plasma a cooperative behaviour, by which the whole assembly shows the characteristic oscillations with a specific frequency.

A very interesting example of the existence of plasma oscillations in space plasmas was seen by the *Voyager* spacecraft, on its journey towards the outer planets, on entering the space environment of Jupiter [Fig. 2.8]. We shall read more about the *Voyager* mission later.

2.4 Oddities of Plasma

Plasma is the fourth state of matter. What are the odd properties of this state of matter which makes it different from the other three states: solid, liquid and gases? The oscillations of electrons in a plasma about their equilibrium position as discussed above give a unique property to plasma. This property of plasma has some interesting consequences which makes plasma an oddity among the four states of matter. For example, if we calculate the *refractive index* n, which is the ratio of the velocity of light in vacuum, to that in the plasma medium, it is found that:

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2}$$

where ω is the frequency of the light beam travelling in the plasma and ω_p is the *plasma frequency*. Two points are to be noted. First, that the refractive index of the plasma is not a constant, but depends on the frequency of light, which means that plasma is a dispersive medium. It disperses light just as a prism disperses a beam of white light into spectrum of colours. The second very important and singular property is that the refractive index of plasma is always less than one.

The refractive index of waves in the visible range are shown for different substances in Table 2.1. We find that the refractive index of solids, liquids and gases is greater than one. Plasma is unusual in having a refractive index of less than one. An interesting consequence of this is that if a convex lens of plasma was used for refracting light, it would be divergent and not convergent as with a lens of glass [Fig. 2.9]. We now realise that this effect plays a very important role in the operation of gas lasers.

Table 2.1 Index of refraction

Substance	Index
Air	1.00
Water	1.33
Ethyl Alcohol	1.33
Glycerine	11.47
Benzene	1.50
Glass, Crown	1.52
Glass, Flint	1.63
Quartz	1.46
Zircon	1.92
Diamond	2.42

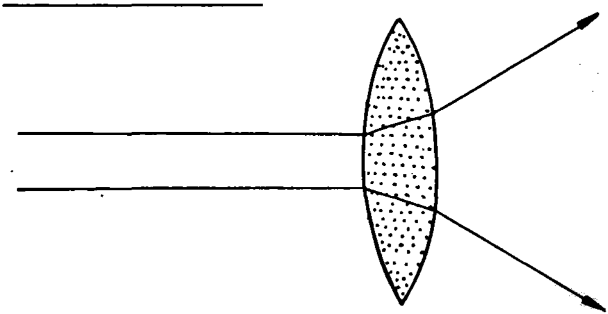


Fig. 2.9 A divergent plasma convex lens: The unusual optical properties are a consequence of the plasma index of refraction being less than unity.

This understanding of the plasma refractive index enables us to understand why a radio wave gets reflected from the ionosphere allowing the possibility of radio communication. The expression for the refractive index n, becomes an imaginary quantity for all frequency less than ω_p. This means that plasma does not allow any radio wave or, for that matter, any electromagnetic wave with frequency less than the plasma oscillation frequency to pass through it. So these waves get reflected. The plasma frequency ω_p is thus a *cut-off frequency*.

So, when a radio wave reaches an altitude where the plasma density is sufficiently high, it is reflected. This makes it possible to send radio signals between points on the Earth's surface, not visible to each other, by 'bouncing' them off the Earth's ionosphere.

If we take the maximum density of ionospheric plasma to be 10^6 per cm^3, that is a million particles per cubic volume, the critical or cut-off frequency is of the order of 10^7 Hz. Hence, the frequencies used for radio communication should be less than this. For the same reason, in order to penetrate the ionosphere, it is necessary to use frequencies higher than this, to communicate with space vehicles. However, during the re-entry of the spacecraft into the Earth's atmosphere, the density of the plasma generated by the intense frictional heat is so high, that the operational frequencies used for communications becomes very much lower than the cut-off frequency of the plasma surrounding the spacecraft, resulting in a total communication blackout [Fig. 2.10].

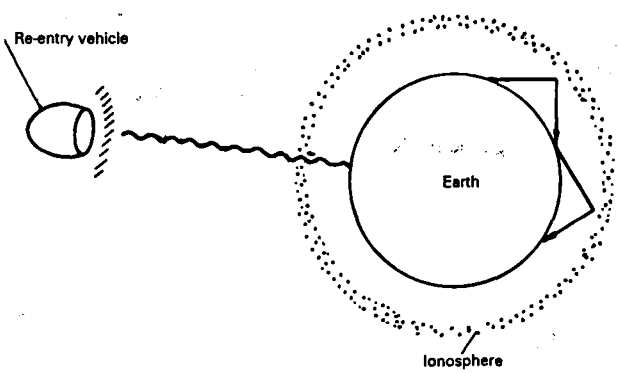


Fig. 2.10 The effect of the Earth's ionospheric plasma on radio communications and the communications blackout (see Chapter 7 for more examples).

2.5 Interaction with the Magnetic Fields

We are familiar with the gravitational forces in the universe. It is the gravitational force of the Earth which makes the objects fall downwards. If not for this force, we would all be floating in space! Gravitational force plays an important role in the behaviour of astronomical systems. In fact, it is this force which keeps the Sun, Moon, planets and other stars as a stable rotating system. Even the overall structure of the universe appears to be governed by this force.

Besides the gravitational force, there is another more prevalent, though less familiar, force in the cosmos, the magnetic force. This force arises due to the presence of magnetic fields, caused by the magnetism of the various celestial bodies like the Earth, the Sun, numerous other stars, many planets, interstellar space and galaxies. As of now, we know that magnetism is a common phenomenon in the cosmos. Plasma, being a conducting gas, has an important property in that it interacts in remarkable ways with magnetic fields giving rise to various current systems. No wires are needed! The understanding of the interaction of the plasma, the most common matter in the universe, and the commonly occurring magnetic fields, is therefore of great importance to understand the electrodynamics of not only our neighbouring space, but also of the outer space.

Plasma consists of innumerable positively and negatively charged particles and it tries to remain neutral and exhibits cooperative behaviour, which results in plasma oscillations. Hence, plasma can display behaviour of a charged particle motion in a magnetic field or it can behave like a conducting fluid interacting with the magnetic fields.

2.6 Charged Particle Motion in a Magnetic Field

When an electric current flows in the presence of a magnetic field, then an electromagnetic force, called the Lorentz force, acts on the conductor carrying the current and the magnetic field [Fig. 2.11].

Consequently, any charged particle in a magnetic field is subjected to a force acting at right angles, both to the direction of the field and to that of the particle motion. As a result,

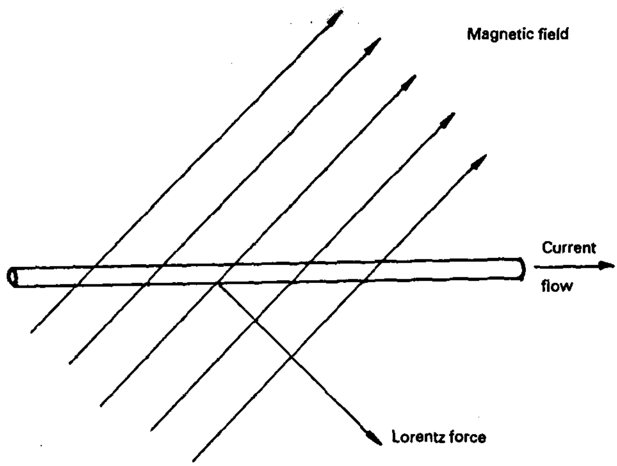


Fig. 2.11 The Lorentz force: The electromagnetic force of the magnetic field on the conductor carrying the current. This force is at right angles to the direction of the magnetic field and the current flow.

a charged particle moving in a uniform magnetic field, which is directed along the magnetic field direction initially, follows a helical (or spiral) path of constant radius about a line of force [Fig. 2.12]. This constant *radius of gyration* is the gyromagnetic radius, sometimes called the *Larmor radius*.

In a magnetic field of uniform strength, the lines of force are parallel, but if the field is non-uniform, i.e., its strength changes from one point to another, the field lines are no longer parallel. Suppose, for example, that the field strength increases from left to right, then the lines of force will converge. The path of a charged particle in such a field is then a spiral of decreasing radius with tighter turns. Moreover, the turns of the helix become closer and closer to being perpendicular to the field lines. In other words, the pitch angle, the angle of a turn the helix makes with the field direction, approaches 90°. The magnetic field then causes the direction of motion of the particles to be reversed, so that it now commences to spiral back in the opposite direction.

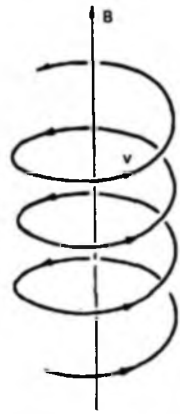


Fig. 2.12 Charged particle in a magnetic field: The general motion of a particle in a uniform magnetic field is a constant velocity parallel to the magnetic field direction and a circular motion at right angles to it. The trajectory is a cylindrical helix and the frequency of the circular motion is the gyrofrequency ω_c.

The reversal in motion of charged particles in a magnetic field of increasing strength is described as 'reflection' in a *magnetic mirror*, and the point where the reversal occurs is called a 'mirror point'. If the magnetic field is stronger at both ends than in the middle, there will be two 'conjugate' mirror points, one at each end [Fig. 2.13]. A charged particle can then be reflected at each mirror point and as a result it will, in principle, spiral back and forth continuously from one conjugate point to the other. In other words, the charged particle is trapped or confined by the magnetic field. Actual theory tells us, with reference to the magnetic field direction, that for trapping to result certain conditions have to be met by the velocity direction of the charged particle.

The idea of particles trapped in a magnetic field was understood in the early 1950s. Much effort was devoted during this time to produce controlled thermonuclear reactions in the laboratory. To accomplish this, as we have already seen, a temperature of 10^8 degrees kelvin or an energy of 10 KeV, or more, is necessary. Particles of such energy cannot be contained in a vessel

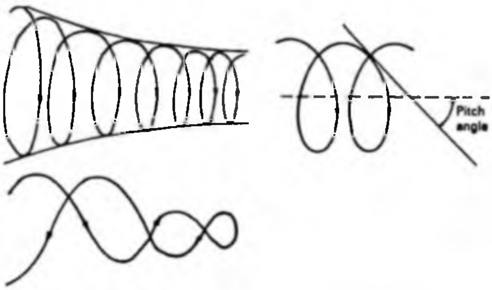


Fig. 2.13 The motion of an electrically charged particle in converging lines of force. a) Spiral of decreasing radius with tighter turns. b) Pitch angle: The angle a turn of the helix makes with the field direction. c) Reversal of motion or reflection of charged particle by the magnetic field.

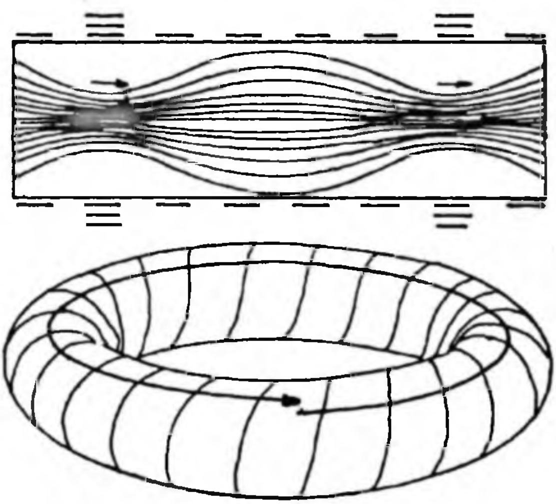


Fig. 2.14 An attempt to confine a plasma: The two types of 'magnetic bottles' are shown here. The 'mirror' device is at the top in which the magnetic field is made stronger near the end so that most of the particles can be reflected back to the plasma in the interior of the bottle. The lower figure is a kind of toroidal device. The magnetic lines of force are bent into closed loops and given a slight twist.

because the walls of the vessel will melt and, therefore, magnetic fields are used to hold the particles and keep them away from the walls of the system. During the past thirty to forty years, all kinds of 'magnetic bottles' have been devised to confine plasma. One such confinement machine is the magnetic mirror machine which can contain charged particles because a particle inside the machine moving towards the end where the magnetic field is stronger will be reflected from the magnetic mirror, thus confining the plasma [Fig. 2.14].

Since the Earth's magnetic field is stronger near the surface than it is at a distance, the lines of force are close together near the Earth at one hemisphere, then become farther apart as they move outward and finally are close again at the other hemisphere. Thus, there are mirror points at both ends, i.e., in each hemisphere, and charged particles entering the geomagnetic field can be trapped [Fig. 2.15]. They will spiral back and forth,

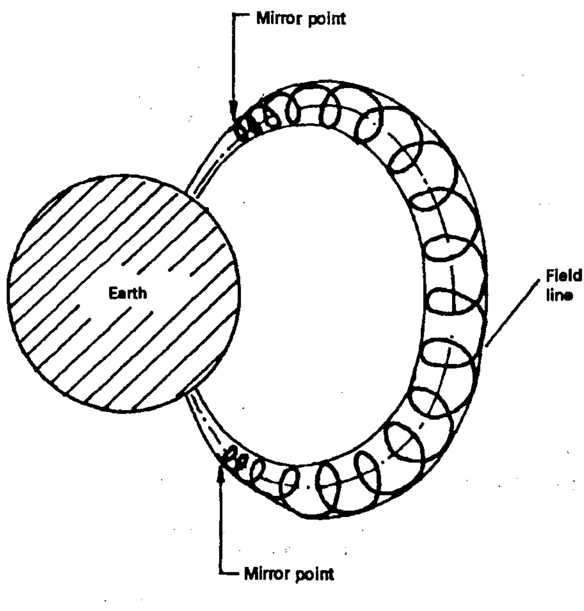


Fig. 2.15 Mirror devices in nature: Spiral motion and mirror points of charged particles in the Earth's magnetic field.

around the lines of force from one hemisphere to the other. The Earth's magnetic field is thus a naturally occurring mirror machine similar to the thermonuclear machine in the laboratory, but curved into an arc. The geometry of the Earth's magnetic field is such that is can trap particles. This fact was realised before Van Allen's discovery of intense radiation (which we shall discuss later) on *Explorer I* and *II* and the source of the radiation was soon recognised to be geomagnetically trapped particles. The ability of the geomagnetic field to trap charged particles was also directly verified experimentally by injecting high-energy charged particles by the explosion of a nuclear bomb at high latitudes. Especially in 1958 and 1962, high altitude, nuclear explosion-induced artificial radiation belts were seen persisting for many months.

In addition to the back and forth spiral motion of charged particles between the conjugate mirror points in the northern and southern hemispheres, there is another type of movement caused by the decreasing strength of Earth's magnetic field with increasing altitude, that is, in the radial direction. The effect of this radial gradient in the geomagnetic field is to introduce a force on a charged particle in a direction perpendicular to the field lines. The result is that the particles drift around the globe — the positively charged particles (protons) from east to west, and those with negative charges (electrons) from west to east. Since this drift of particles is due to the gradient in the magnetic field, it is called the *grad-B drift.*

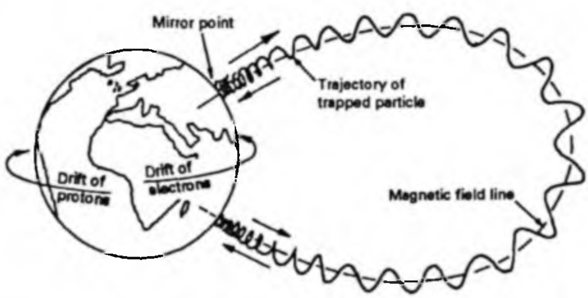


Fig. 2.16 General behaviour of charged particles in the Earth's magnetic field: Particles are trapped by the Earth's magnetic field and undergo three types of motion. There is a circling around a magnetic field line (Cyclotron motion), a bouncing back and forth between the mirror points in either hemisphere, and a drifting around the planet.

The motion of a charged particle in a dipole field can be broken down into three components with certain approximations made by the theorists. The particle rotates rapidly around a field line, it bounces back and forth along a line between its two mirror points, and it slowly drifts around the Earth [Fig. 2.16]. The speeds of these three motions are so different that they can be separated. Another very important drift, especially in naturally occurring plasmas is in the presence of an electric field. This drift is always in the direction perpendicular to the electric field direction and the magnetic field direction, and so is called the $\vec{E} \times \vec{B}$ drift (E cross B drift) [Fig. 2.17].

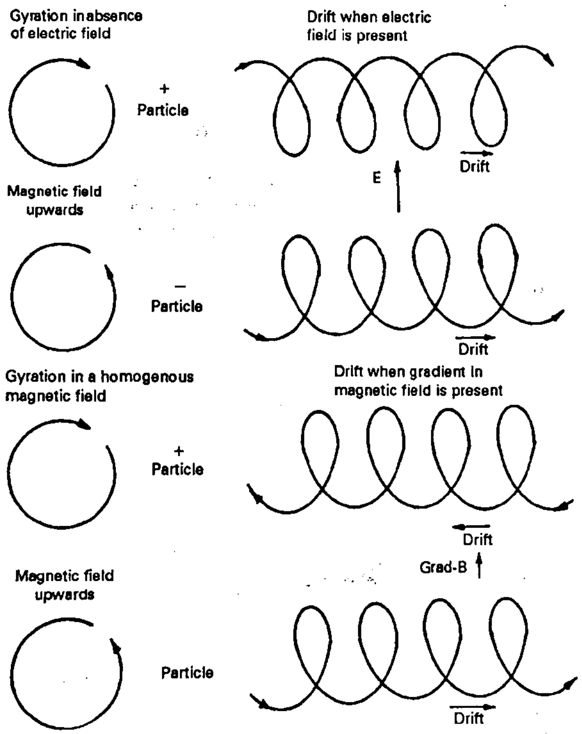


Fig. 2.17 Drift due to the presence of an electric field and due to the gradient in the magnetic field ($\vec{E} \times \vec{B}$ and grad-B drift).

Considering the fact that plasma is an assembly of charged particles, we can easily see now why the properties of plasma are radically altered when it is placed in a strong magnetic field. The main reason being that in a strong magnetic field, the electrons and ions cannot move freely in the direction perpendicular to the lines of force. The trajectory of each particle takes the form of a helix with its axis parallel to the magnetic field, and the motion is therefore highly directed. The drift of particles in non-uniform magnetic fields can also give rise to different types of current systems in the plasma.

2.7 Refractive Index of the Magnetic Plasma

The magnetic fields introduce an additional characteristic frequency besides the plasma oscillation frequency — the Larmor or Gyrofrequency ω_c. The refractive index of the plasma thus gets modified and consequently so do the cut-off frequencies for the electromagnetic waves propagating in the plasma medium. The fact that the refractive index of the plasma not only depends on the frequency of the waves and plasma density but also on the magnetic field, makes the plasma a very complex medium with the nature of propagation of electromagnetic waves varying in the choice of direction with respect to the magnetic field. Plasma can support a variety of electromagnetic waves. A very important mode of propagation along the magnetic field direction in space plasmas is the Whistler mode, which will be discussed later.

2.8 Fluid-like behaviour: Magnetohydrodynamics of Plasma

1. Basic Concept

The study of individual particles, as we have seen, gives us an insight into the behaviour of an ionised gas. However, plasma is a collection of charged particles and a fluid theory should be developed to describe the collective behaviour of the group of particles. It is fortunate, that with some restrictions, a collection of charged particles can be treated as a fluid, a magnetohydrodynamic fluid. The study of the dynamics of fluids like water, honey, etc. deals with macroscopic phenomena and treats the fluid as a continuum and deformable. Similarly, magnetohydrodynamics is a branch of continuum mechanics that deals with the motion of electrically conducting fluids in the presence of electromagnetic fields. The individual particle identity is ignored and only the motion of a group or an ensemble of particles is considered.

The important element of the MHD theory is that it incorporates the effects that arise from the motion of an electrically conducting fluid across magnetic fields. It is well known that when a conductor is moved across a magnetic field, an electromotive force appears in the conductor. Currents driven by this electromotive force will then flow in the conductor. Two processes happen. Firstly, the magnetic field associated with these currents will modify the original magnetic field that created them. Secondly, we again have the situation of current flow in the presence of the magnetic field. The fluid motion is modified as it experiences the mechanical force of electromagnetic origin, the local force for conduction fluid. This is also referred to as the Maxwell's coupling between the motion, currents and magnetic fields and characterises the general behaviour of magnetohydrodynamic fluids.

2. Diffusion or Leakage of Magnetic Fields

Another important aspect of the interaction of magnetic fields with conducting fluids arises due to the finite conductivity or the resistance of a conducting medium to the penetration of the magnetic fields. Consider the fluid to be at rest. Due to the finite conductivity of the conducting fluid the interacting magnetic field diffuses or 'leaks' through the plasma from point to point. A decay of the field results in time. This process of change of the magnetic field in time relative to spatial changes, ascribes diffusion of the magnetic field similar to change in temperature during the diffusion of heat in a fluid.

The role of resistivity is the same as the coefficient of heat conduction in a fluid. The finite conductivity results in Ohmic or resistive losses and the currents that are responsible for the magnetic field will decay. If initially there is a magnetic field trapped in the fluid, it will steadily decay. The time of decay is proportional to the conductivity and the square of the dimensions of the region in which the current flows. Hence, for cosmic conductors where the conductivity is large and with huge dimensions, the diffusion time for the magnetic fields can be very long. For example, supposing that the Earth's core consists of molten iron, Elsasser calculated the time of free decay of the Earth's field to be 15 000 years. Cowling estimated that for a sunspot magnetic field the time of decay is at least 300 years and, for a general magnetic field in the Sun, it is 10^{10} years, for a field in interstellar gas in the galaxy it is much longer still. Generally speaking, lines of magnetic force in a large conducting mass can leak only very slowly through the material.

3. Frozen-in-Field Concept

Now consider the opposite case when conducting fluid is in motion, but offers no electrical resistance, or has an infinite conductivity. In this case, magnetic field lines can 'leak' only very slowly through that and so the decay of magnetic field in time is negligible. But now it is seen that the changes in the magnetic field are such that it appears as if the magnetic field lines of force are constrained to move with the material. This is expected when the material moves in a magnetic field. The induced electric force is, roughly speaking, due to the motion of the material relative to the lines of force. Since here the electrical resistance is taken to be negligible, the induced electric force must vanish, and with it the motion of the material relative to the lines of force. Following the Nobel laureate Alfvén, this is now known as Frozen-in-Field. This concept was given by Alfvén in 1942.

4. The Alfvén Wave

The Lorentz force, in the case of conducting fluid, can be interpreted as being equivalent to a hydrostatic pressure combined with a tension in the lines of force. In an incompressible fluid the hydrostatic pressure can be balanced by the pressure of the fluid, so that only the tension remains.

As already seen, when the conductivity of the fluid is very high, the magnetic field lines can 'leak' only very slowly through the fluid and the magnetic field can be considered as practically 'frozen' into the fluid. In this case, the elastic properties of the magnetic field are very effectively communicated to the fluid. Hence, drawing an analogy with the theory of stretched strings which vibrate in the direction perpendicular to the string, suggests that this tension may lead to the possibility of transverse waves along the lines of force in the highly conducting, magnetised plasma. The possibility of such waves in an incompressible fluid was first established by the Swedish Nobel Laureate, Hannes Alfvén in 1942. Now these waves are commonly known as *Alfvén waves* or, in general, the Magnetohydrodynamic waves. Before the discovery of these waves, only sound or acoustic waves were known to exist due to compressibility of a fluid. The discovery of this wave in an incompressible medium, therefore, became very important as energy could be transmitted without large-scale exchange of the fluid elements [Fig. 2.18]. We shall see later

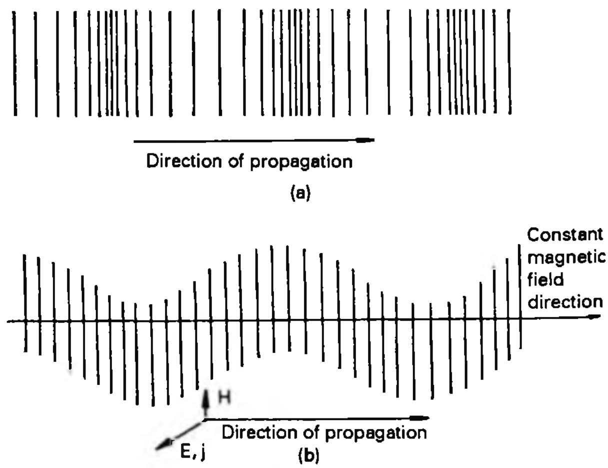


Fig. 2.18 (a) Familiar acoustic waves (longitudinal) arise by compression of the fluid. (b) Alfvén waves in a uniform magnetic field. These waves arise (without any compression of the fluid) due to extra tenacity given to a conducting fluid by the presence of the magnetic field. Here H, E and j represent the perturbed magnetic-electric field and current density, respectively.

how Alfvén waves play a very important role in the physics of various phenomena in space. When compressibility is taken into account, in addition to Alfvén waves, a modified form of acoustic waves, called the Magnetoacoustic waves, propagate in the plasma. The hydrostatic pressure due to fluid and magnetic pressure added together give rise to these latter waves.

An important property of Alfvên waves is that the energy is transmitted partly as magnetic and partly as kinetic energy. The electric field is small and insignificant for Alfvên waves which are low frequency waves, lower than the Larmor frequency. Looking at the table below, we see that the velocity of Alfvên waves is often nine powers of ten lower than the velocity of light.

2.9 Magnetic Reconnection

A geyser, a common sight, or a shishiodishi (a bamboo contrivance) which is a familiar sight in Japanese Gardens, releases energy in an off-and-on or intermittent fashion. There are many phenomena in natural plasma systems which are manifestations of the intermittent burst-like energy release, like geysers or shishiodoshis. As we will discuss later, the most important of these phenomena are the solar-flares and geomagnetic storms. In both these processes, an enormous amount of energy is released in a few seconds making it a burst-like energy release. It is now forty years since the idea that such energies are stored in the magnetic fields of the plasma systems, and the magnetic reconnection or magnetic fields merging processes convert the magnetic energy into the motion of plasmas or acceleration of charged particles constituting the plasma, have been discussed and studied by the scientists.

Space plasmas can often support configurations in which the magnetic fields are oppositely directed. These magnetic fields then contain a neutral line or neutral sheet, which is a region in which magnetic field intensity vanishes [Fig. 2.19]. Since Faraday had shown that currents can exist when magnetic field intensity varies, a current can exist in this neutral sheet. As shown in the figure, consider two plasmas with oppositely-directed magnetic fields. Then, a current sheet lies in the neutral sheet separating these two plasmas. The current sheet shields the two plasmas from one another. If some kind of breakdown can be created in this bounding current sheet, the oppositely directed magnetic field lines of two plasmas can join and form a new topological arrangement; one that allows the two plasmas to intermingle [Fig. 2.20]. The new topological arrangement of the magnetic

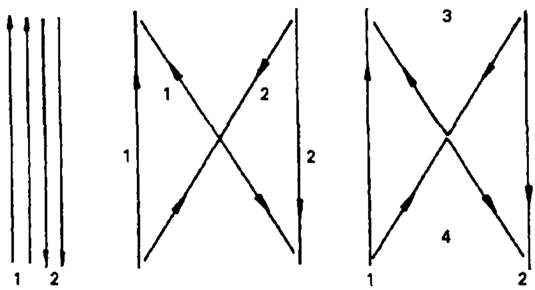


Fig. 2.19 The geometry of magnetic field merging. Two oppositely directed magnetic lines are brought together and allowed to merge. The merging process leads to a complete change in the original geometry. In the final figure the magnetic field lines are seen to have an X-type neutral point.

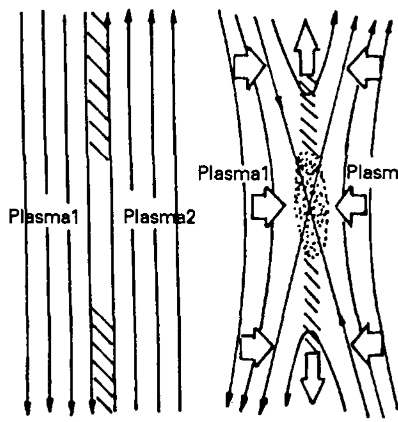


Fig. 2.20 A simple way to understand the magnetic reconnection process. Two plasmas with oppositely directed magnetic fields as in the figure are brought together. A boundary current sheet is formed between them, which shields the plasmas from one another. Some disturbance in the current sheet can lead to a breakdown of the shielding current and the two plasmas go through the merging process. In the mixing of these plasmas, the kinetic energy for plasma in-flow and out-flow (marked by the directed arrows) is drawn from the magnetic field energy.

fields can be a highly stressed magnetic configuration, so the reconnection or merging process transfers an enormous amount of energy to the plasma being transmitted through the boundary. Thus, magnetic reconnection can be loosely defined as a change in magnetic field topology accompanied by either plasma jetting or heating.

2.10 Dynamo Theory

The magnetohydrodynamic theory predicts that the motion of conducting fluid in the presence of a magnetic field induces currents which can then lead to the generation of additional magnetic fields. W.M. Elsasser, in 1908, recognised the importance of this dynamo action and suggested that it might be responsible for the persistence of the Earth's magnetic field. The dynamic concept is a very basic one in the studies of the origin of planetary and stellar magnetic fields.

The Dynamo theory, based on this concept, is a specialised topic closely associated with how currents are generated and amplified in nature.

3.

The Sun: Sun–Earth Plasma Couplings

"Crossing space, you are the maker of light, seen by everyone, O Sun, you illumine the whole, wide realm of space"
"You cross heaven and the vast realm of space, O Sun, measuring days by nights, looking upon the generations"
"The constellations, along with the nights, steal away like thieves, making way for the Sun who gazes on everyone"
"Seven bay mares carry you in the chariot, O Sun god, with hair of flame, gazing from afar"
— *Rig Veda, 1200–900 B.C.*

Looking at it scientifically, the Sun is a very insignificant star compared to many other stars in the universe which have a diameter of 109 times the Earth radii. The surface temperature is close to 6000°K and there is a general magnetic field on the Sun, with a strength of about 1 to 2 Gauss. However insignificant the Sun may be in the universe, we know that it is the most significant star for our solar system. Especially in the case of the Earth, which is just 15 00 00 000 km away from the Sun, (Jupiter is about five times the distance from the Sun and Saturn) it is the source of energy and maintains life on this planet. Interestingly, the Sun produces this energy by thermonuclear reactions taking place in the Sun's interior. Man is still unable to achieve such controlled thermonuclear energy!

Man has been aware of the close link between the Sun and the Earth for thousands of years. It is the visible radiation from the Sun which produces the heat and light crucial for life on Earth. The Sun regulates days, nights, twilights, months and years. It is no wonder, therefore, that this powerful, life-sustaining, heavenly source was attributed with god-like qualities in almost all the mythologies of ancient civilisations [Fig. 3.1 and Fig. 3.2].

Fig. 3.1 The representation of the Sun God by ancient Hindu tribes in the Bastar region of Madhya Pradesh, India [Personal collection].

Fig. 3.2 The Aztec calender. The Sun god in stone and other natural forces represented as gods from Mexico (original in Archaeological Museum, Mexico City).

Table 3.1 Physical data for the Sun

Mean distance from Earth	1.5×10^8 km
Mass	1.99×10^{30} kg
Diameter	1.39×10^6 km
Rotation (as seen from Earth)	26.8 days
Magnetic Field Strengths:	
Sunspots	3000 G
Polar Field	1 G
Prominences	10 to 100 G
Earth (for comparison)	0.7 G at poles
Temperature:	
Interior (center)	1.5×10^6 K
Surface (Photosphere)	6050 K
Corona	8×10^5 to 3×10^6 K

3.1 Sunspots and Solar Storms

The belief that the Sun was a god and therefore perfect, was so strong that people refused to believe when Galileo's telescope in 1610 showed irregularities on the surface of the Sun. The most important controversy was about the darkened areas on the surface of the Sun which appeared as dark spots through the telescope. The opposition was so strong against these blemishes, now commonly called *sunspots*, that scientists and people refused to look through the 'wicked instrument', namely the telescope, lest they be forced to change their views about the Sun. They believed that the Sun was perfect; perhaps these spots were dark objects circling the Earth itself [Fig. 3.3].

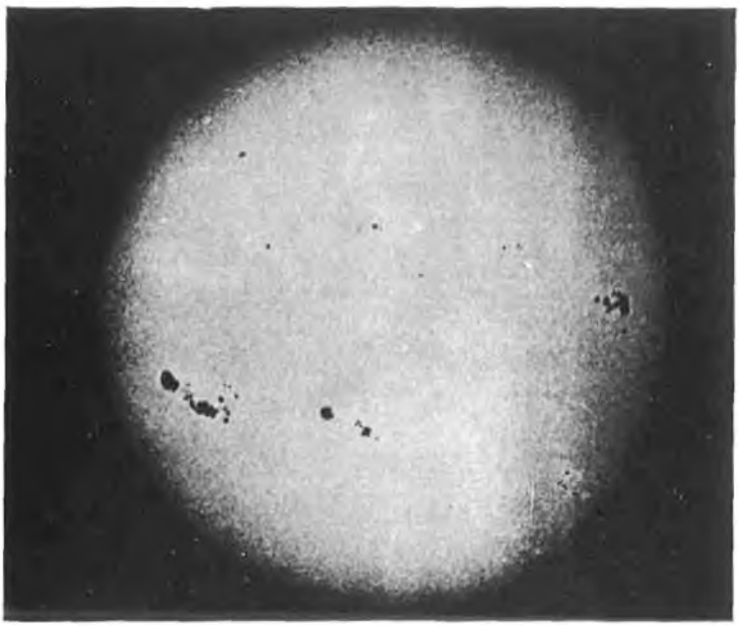


Fig. 3.3 A string of sunspots running across the Sun's southern hemisphere.

The existence of sunspots and a cyclic variation in the number of sunspots was firmly established in the mid-19th century by Heinrich Schwabe, a German druggist and amateur astronomer at Dessau. Schwabe was such a regular and consistent observer that it was said of him that 'the Sun never rose unclouded above

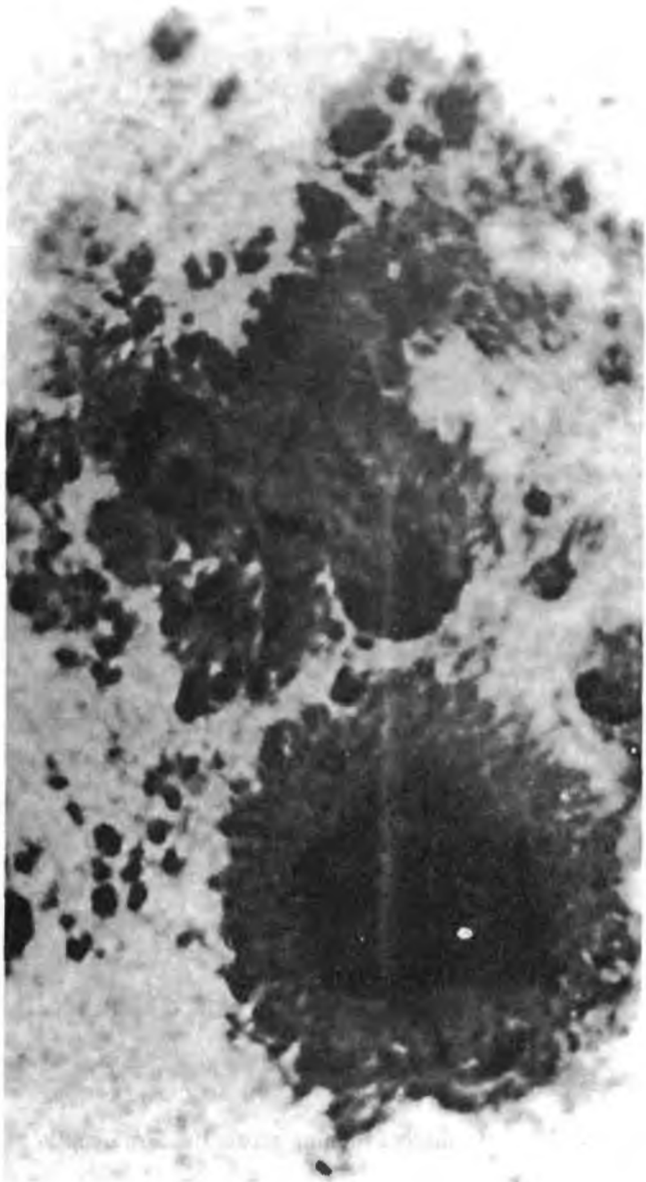


Fig. 3.4 A Modern photograph of Sunspots: The umbra and the filamentary penumbra grade into the finely structured solar granular surface. Only a small portion of the solar surface is shown in the photograph. The umbra of the sunspot is almost half the size of our Earth. (Sacramento Peak Observatory, New Mexico, U.S.A.)

Fig. 3.5 This remarkably detailed drawing of a single sunspot was made by the eminent American scientist Samuel Langley in 1873. The fascinating part is that photographs made in modern times confirm much of the details captured by Langley by visual observations through his telescope.

the horizon of Dessau without being encountered by Schwabe's imperturbable telescope'. After years of consistent observations, Schwabe calculated the sunspot cycle to be approximately 11 years. At the beginning of a new cycle, the *spottedness* begins first at latitudes of about 30° on both sides of the solar equator. As the cycle continues to develop and the number of spots increase, the spots migrate slowly towards the equator in both hemispheres until, near the end of the cycle, those nearest the equator begin to disappear. During and following the disappearance, spots again begin to appear at latitudes of 25° to 30°.

Sunspots are dark, as these are regions of cooler gases on the solar surface. The area covered by a sunspot may easily be of the size of Europe. Individual spots have a black centre, usually somewhat irregular in shape, known as the *umbra*. The grey *penumbra* outlines this area. Although sunspots are not yet fully understood, observations show that these are regions of very strong magnetic fields, of the intensity of several thousand gauss (in comparison, the magnetic field intensity at the surface of the Earth is approximately one-half gauss) [Fig. 3.4 and Fig. 3.5]. Sunspots occur in groups of two to several; opposite magnetic polarities north and south magnetic fields arch from one spot to the other. This pattern of magnetic polarities persists for a complete 11-year cycle, after which the field suddenly reverses for the subsequent cycle. Hence, a full cycle for magnetic polarities is 22 years [Fig. 3.6].

3.2 Sunspots and Solar Activity

Sunspots are very active regions of the Sun [Fig. 3.7]. In fact the Sun is said to be quiet when very few sunspots are seen. The most violent phenomenon that occurs in these centres of activity involves the transformation of a considerable amount of energy, of nearly 10^{32} to 10^{33} ergs, probably stored in the high magnetic fields of the sunspots in a relatively short period of 3×10^3 sec (about half-an-hour). This phenomenon is called a *Solar Storm*. Many complex solar processes are associated with the solar storm. The most spectacular of these is the *Solar Flare* [Fig. 3.8]. A solar flare is just like an outburst of flames. Intense brightening of a region of the solar surface that contains the sunspots occurs abruptly as the atomic ions and electrons in the solar atmosphere are suddenly energised due to the occurrence of a solar storm. Some of the energised particles impact against the solar atmosphere, producing optical and ultraviolet light as well as X-rays and γ-rays, the remainder are rapidly emitted

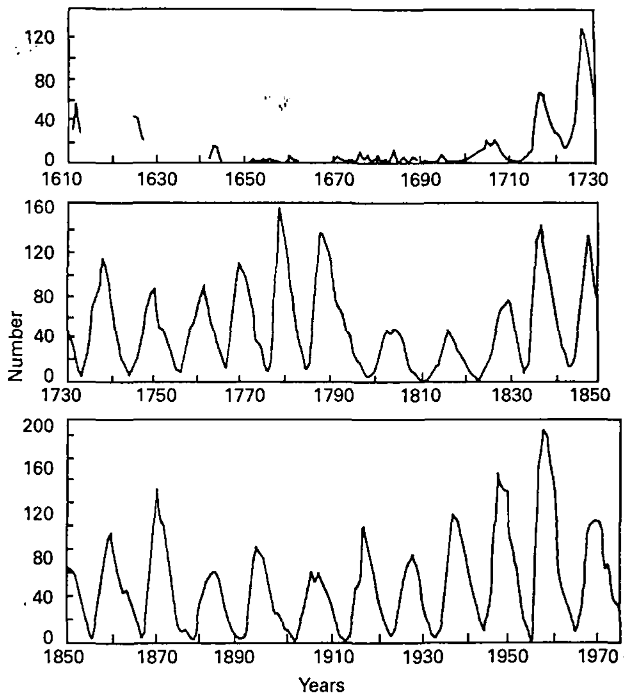


Fig. 3.6 The Sunspot Cycle, 1610–1976: Sunspots come and go on the Sun in an irregular cycle of about 11 years. Annual mean sunspot numbers (an average measure of spottedness of the Sun) are shown here for each year since the discovery of the telescope. The interval of about seven decades beginning in 1645 when sunspot numbers were unusually low, is known as the "Maunder Minimum", which coincided with a significant drop in global temperatures on Earth. The Thames river was frozen in the 17th century!

into interplanetary space and propagate to the orbit of the Earth. There is also an occasional blast of the solar plasma clouds ejected (coronal mass ejection) from the solar flares, travelling outwards into the solar system with a velocity of the order of 1000 km/sec. Both the energetic particles and solar plasma cloud can cause intense fluctuations of the Earth's magnetic field, a phenomenon which is called a *magnetic storm*. These magnetic storms (we shall discuss them later) are associated with the disturbances in the space environment of the Earth.

Fig. 3.7 An active sunspot area photographed in hydrogen light, showing the structure of the swirling hot gases. Some of the dark striations appear to be associated with the magnetic fields of the sunspot. (Sacramento Peak Observatory, Air Force Cambridge Research Laboratories.)

The other dynamic processes associated with the solar storms are 'flare surges', 'flare puffs', 'streamers' and 'active prominences'. Prominences are huge pinkish clouds at levels high above the solar surface but well within the corona. They arise during quiet period of the Sun also in the active regions. Surges are like giant geysers spouting to a height 16 00 000 km with velocities up to 1 000 km/sec. The ejection of plasma material implies that substantial magnetic fields may be carried along with the material.

3.3 Cosmic Rays of Solar Origin

Besides the solar flare plasma and the storm-time energetic particles, bursts of cosmic rays also come from the Sun. Cosmic

Fig. 3.8 Explosive solar flare on the Sun photograph in hydrogen alpha. A dark sunspot can be seen. The solar flare lasts for a few minutes to half-an-hour releasing a large amount of energy during this time (Big Bear Observatory, California, U.S.A.)

rays are not rays in the strict sense of the term; they consist initially of (primary) positively charged particles which interact with the nuclei of atmospheric oxygen and nitrogen to produce a highly complex (secondary) mixture of corpuscular and electromagnetic radiations. The primary particles in the cosmic rays originating from the Sun are mainly hydrogen nuclei (protons) of high energy, with a small proportion of helium nuclei (alpha particles), and considerably lesser amounts of some heavier nuclei. Considering only the protons, the energies of protons in solar cosmic rays range from about 10 million (10^7) to a few billion (10^9) electron volts, with an average of 100 million (10^8) electron volts. The intense activity of a flare, which itself is a very powerful electrical discharge, acts like an electric motor and drives particles up to energies where their speed approaches the velocity of light. Thus, they can appear on Earth at the same time as the light reaches us from the flare, and the cosmic ray counts increase.

3.4 The Solar Wind

Is the Sun–Earth plasma link limited to the active period of the Sun? Actually, scientists have come to know relatively recently that a very primary plasma link of the Sun with the Earth is through the solar wind, which blows continuously from the Sun in all directions through the solar system rushing past the planets into the interstellar space and is present all the time with or without sunspots or solar flares.

The realisation of the solar wind's existence came only gradually, over a period of several decades. Nearly a hundred years ago, astrophysicists and geophysicists, trying to understand phenomena such as Auroras, Comets, Earth's magnetic field fluctuations and cosmic rays, began to suspect that besides the visible radiation, the Sun emits some kind of invisible 'corpuscular rays' to the Earth all the time, with or without sunspots or flares. The first explicit assertion that something besides light was coming to the Earth, was made in 1896 by the Norwegian physicist Kristan Birkeland. He suggested that the aurora borealis might be caused by the electrically charged corpuscular rays shot from the Sun and sucked in by the Earth's magnetic field near the poles. He was led to this conclusion by the fact that the aurora looked very much like the electric discharge in the newly-invented discharge tubes. (See the Birkeland's Terrella experiment in Chapter 6.) However, the decisive evidence for the other kind of radiation from the Sun was made in 1951 by Ludwig Biermann, a German scientist in his study of comets.

Comets are visitors from the interstellar space to our solar system. Since they visit us after traversing the interplanetary space, comets have been studied extensively as useful probes for examining the properties of that space. It has been known that many comets have tails. The tail of the comet can be very long and is the most impressive part of a cometary display. The longest one on record, that of the great comet of 1843, was more than 2 AU. The tail of *Halley's comet* in 1910 grew at a rate of 8 00 000 km per day until it reached a length of about 14 40 00 000 km. For centuries it has been known that the tails of comets always point away from the Sun. No matter where a comet may be in its orbit through the solar system, its head is always towards the Sun and its gaseous tail streams away. In comets with straight tails, the tail points almost directly away from the Sun. Why is this so? In the 1950s, Biermann showed that the pressure of the Sun's light was not sufficient to violently push the comet's tail away as was then generally believed. He suggested instead that there have to be streams of charged particles which were coming from the Sun and which could account for the pushing away of the comet's tail [Fig. 3.9].

Biermann's theory also made it plain that the corpuscular radiation could not be coming merely in bursts during the solar flares, or from the sunspots in the form of cosmic rays, or bursts of energetic particles as discussed earlier; but the comets' tails showed that the radiation was blowing continuously in all directions and always away from the Sun. The comets' tails, in effect, behave like interplanetary 'wind socks' demonstrating the existence of a steadily blowing, space-filling radiation. The streaming of particles might intensify when the Sun became particularly active, but it was present all the time.

The existence of the 'invisible' radiation' has now been verified by the space vehicles. Now we know that besides the visible light, a primary link of the Sun with the Earth is through the solar wind plasma. A swift wind consisting of ions (mainly protons), electrons and magnetic fields from the Sun blows continuously through our solar system. Emanating from the Sun, it gets accelerated in about five days and a million kilometers' travel, and then it speeds past the Earth at 400 km/sec (about 90 00 000 m/hr) and rushes on past the planets into interstellar space. The transit time for the accelerated solar wind particles from the Sun to the Earth is about four days. From the Earth it takes another week to reach Jupiter's orbit, 645 million km away from the Earth.

Fig. 3.9 Head of Halley's Comet: The tail of a comet always points away from the Sun. The continuous flow of solar wind from the Sun is responsible for this phenomena.

To carry the calculations further, the solar wind starting from the Sun on a Sunday will be passing us about the Tuesday of the following week. Two weeks after this gas zooms by us, it will pass Jupiter, thus linking the solar plasma and the solar system.

Direct confirmation of the existence of the steady solar wind is not trivial because the wind cannot be observed near the Earth's surface. Since the solar wind is a plasma, it interacts with the Earth's magnetic field. Thus, a direct observation, planned to detect the solar wind, must be carried out at a location sufficiently removed from the Earth's magnetic field of influence. Just such measurements have been made by many spacecrafts which carry equipment for recording charged particles encountered in space and which have measured the density and wind velocity in space. Solar wind was detected and measured by the Soviet vehicles *Lunik I* and *Lunik II* in the year 1959 and by several U.S. vehicles, including the *Venus* craft *Mariner II* and the satellite *Explorer X* in the 1960s. These measurements have shown that the wind blows continuously throughout the space they have traversed and near the Earth it is expected to travel at a velocity of about 400 km/sec. It blows straight out from the Sun, sometimes at a steady pace and sometimes it is gusty. It tends to be turbulent and to move faster when the Sun is active.

The solar wind has now been extensively studied by instruments of ever-increasing sophistication on interplanetary spacecrafts, particularly in the *Pioneer* and *IMP* (Interplanetary Monitoring Platform) series. Spacecrafts have also detected the existence of solar wind near the other planets in the solar system. The *Voyager* spacecraft exploring the outer planets Jupiter, Saturn, Uranus and Neptune, is still detecting the solar wind far beyond the orbit of Neptune.

3.5 Solar Corona and the Origin of the Solar Wind

Theoretical studies, mainly by Sydney Chapman and Eugene N. Parker in the 1950s, have been able to unravel the mystery of the origin of the solar wind and have given us an understanding of its effects. We now know that the solar wind originates in the solar corona. The corona is the uppermost part of the solar atmosphere and has a temperature of nearly one million degrees [Fig. 3.10]. Now there is a puzzle! The visible surface of the Sun,

Fig. 3.10 Solar corona: An eclipse photograph of the Sun, taken from the Earth's surface, showing beautiful coronal streamers and coronal structures. The shapes of the coronal rays suggest magnetic lines of force and an expansion of the corona.

called the photosphere, has a temperature of 6 000°K, and is surrounded by the *chromosphere*, a region several thousands of miles thick, which is about 20 000°K. Now, the source for the solar energy is the gravitationally confined fusion reactor which lies at the centre of the Sun. The temperature at the centre is about ten million degrees and then it decreases to 6 000°K at the surface of the Sun. How can a cool surface transmit heat to the chromosphere and corona, which have much higher temperatures than the photosphere? How does the corona get so hot? This is still a major unsolved problem in solar physics. Possible causes include heating by acoustic waves generated by the convection of heat from the solar interior and/or heating by the damping *Alfvén waves* produced in the solar photosphere and which propagate outward, away from the Sun. The structure of the corona is a complicated plasma environment which often appears as radial streamers and arches in eclipse photographs. However, at such high temperatures the coronal gas is ionised and exists in the plasma state. The density of coronal plasma is very low. Even close to the Sun it contains only about hundred million to a billion hydrogen atoms per cc, a density only a hundred billionth that of the air we breathe.

Solar corona is a high temperature, low density plasma. Because it is so tenuous it is not self-luminous, inspite of its high temperature. It is visible, however, by virtue of the fact that atoms scatter the light from the Sun's luminous photosphere, just as grains of dust in the Earth's atmosphere become visible by scattering sunlight. We can see the corona in its full splendour during the total solar eclipse. Photographs of the corona show that it extends up to millions of miles from the Sun and, were it not for interfering haze and light in the sky, we could probably see its fainter reaches extending many times that great extension. At its very high temperatures, the corona emits X-rays. The X-ray images of the Sun from the satellite *Skylab* shows that the corona is highly non-homogeneous and finely structured. Large regions consist of loop-like structures, with the ends rooted in the solar surface, while there are also dark regions known as coronal holes [Fig. 3.11] which are somewhat cooler. The holes are main source of the solar wind. This is because the coronal holes are magnetically 'open' features, as opposed to 'closed' or arched-over field lines seen elsewhere on the Sun. Magnetic field lines diverge at the boundaries of the hole not arching the chasm. Therefore, electrically charged particles in the hot solar atmosphere are free to escape from the Sun through the coronal holes. Elsewhere, they are trapped in closed magnetic field lines and thereby give the structured corona its distinctive form.

The tenuous, high temperature solar coronal plasma has too much energy to be confined by the solar gravity and so it tends to expand and stream away from the Sun. As it moves on, it is replaced by more gas rising from below the photosphere. It was in 1958 that Parker concluded that the hot solar corona cannot be in static equilibrium but must expand as a wind into space.

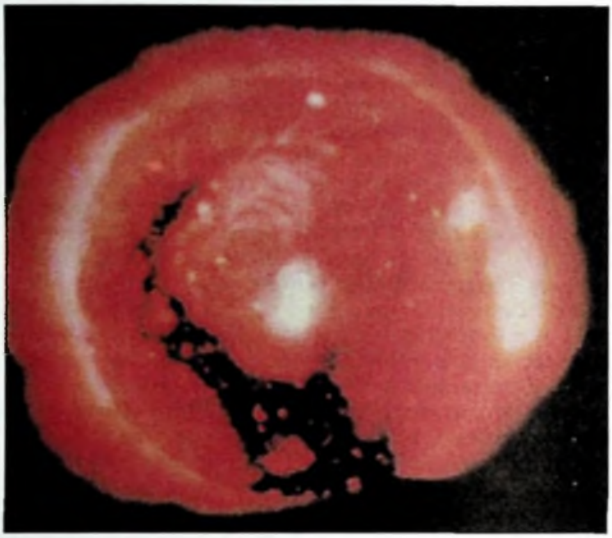


Fig. 3.11 Holes in the Corona were first noted in the X-ray pictures of the Sun. Bright emissions in this picture made with an X-ray telescope on the *Skylab* displays the corona at a temperature of about 2 to 3 million°K. The coronal hole seen begins at the north polar cap and extends down across the equator of the Sun, looking much like a shape of a boot. The temperature within the coronal hole is two to three times lower than the active regions, so X-rays are almost absent in the holes.

Further theoretical studies showed that at first the expansion is slow, but as the distance increases, the pressure within the corona gradually overcomes the weight of the overlying gas and rapid expansion takes place. At 10 million km from the Sun, the corona is expanding at a rate of several hundred kilometers per second — faster than the speed of sound. As that point, it must be considered as a supersonic wind rather than the Sun's atmosphere. It continues to accelerate and reaches velocities several times the speed of sound as it moves out of the Sun's gravitational field. Away from the Sun, the corona expands rapidly and becomes a high-velocity stream and then it is given the name 'solar wind'.

The solar wind carries a magnetic field along with it because the gas is ionised. The source is the general magnetic field of the Sun. The corona cannot carry away the Sun's concentrated local fields associated with sunspots and active regions, because they are strong enough to prevent the portions of the corona in their vicinity from streaming away at all.

If the Sun did not rotate (as it does once every 25 days), the solar wind would draw its general magnetic field straight out into space, so that the lines of force would stretch radially from the Sun and a compass in solar-system space would always point straight toward or away from the Sun. The Sun's rotation, however, imposes on this radial field a circular field; with the result that the field which now represents the interplanetary magnetic field (IMF) carried by the solar wind takes a spiral form [Fig. 3.12]. The strength of the IMF at the orbit to Earth is about 5 gammas during the quiet period of the Sun.

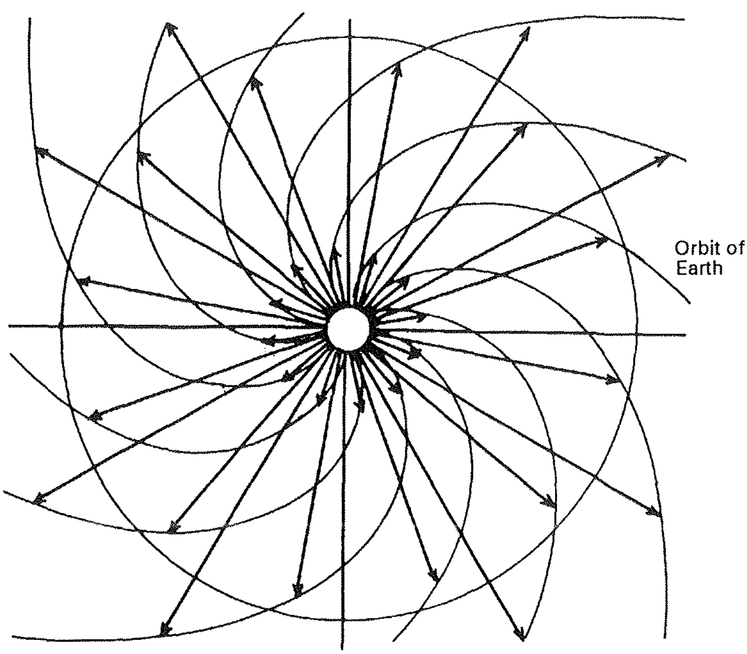


Fig. 3.12 Spiral structure of the interplanetary magnetic field (IMF) in the equatorial plane. The magnetic fields are carried by the radially expanding solar wind and a rotating Sun tracing out an Archimedes spiral. (An analogy is usually drawn to a rotating garden sprinkler.)

As the solar wind expands into the interplanetary space, the density drops off in proportion to the square of the increase in distance from the Sun. At a distance of 1 AU from the Earth, the highest measurement of the density has been given as 10 particles per cc. Even at this low density the solar wind has continuous properties, largely as result of the embedded solar magnetic field.

From the understanding of the nature of the solar wind some very interesting questions were explored by E.N. Parker. It was he who first named this coronal plasma reaching the Earth continuously as the solar wind, in his well known paper in 1958. For example, there is the problem of how much energy and mass the solar wind carries off into space. It can be calculated that it removes hydrogen from the Sun at the rate of about a million tons per second. Is this a drain on the Sun? In the estimated 15-million-year lifetime of the Sun, this amounts to only a little more than a hundredth of one percent of the solar mass, so it is not significant. Similarly, the energy consumed in expanding the corona to the solar wind velocity is only about a millionth of the total energy output of the Sun. The wind's energy per unit of volume is so slight that an object in space is not warmed significantly by it. The other question of interest is how far the solar wind goes into space. The upper estimate seems to be 160 AU from the Sun — nearly four times the distance of the farthest planet, Pluto. We shall read more about this question in the last part of the book.

Table 3.2 Summary of quiet solar wind plasma parameters at a distance of 1 AU

Velocity	:	400 km/s
Particle Density	:	$4 \sim 10$ part./cm^3
Magnetic field	:	~ 5 nT (nanotesla)

3.6 Disturbed Solar Wind

Solar wind properties, however, vary a great deal with the solar activities. For example, solar wind velocities and temperatures can become very much higher than the quiet time values as large-scale streams comprised of high speed, high-temperature plasma are observed in the solar wind over several days at a time. Solar wind is also disturbed by large fluctuations of the interplanetary magnetic field. The coronal mass ejection events (CMEs) [Fig. 3.13] related to solar flares and active prominences can be a cause of a very important class of disturbances in the solar wind. The CMEs are of huge proportions and were first observed in the 1970's by the *Skylab*. Large masses of plasma are expelled from the Sun by eruptions bigger than the disc of the Sun, disturbing the outer corona. Though truly immense and much larger than prominences, coronal transients contain very little solar matter and carry away only a negligible part of the Sun's total mass. The most important point is that these disruptions affect the solar wind which is thus propelled as far as the orbit of the Earth, establishing a definite link between the Sun and the Earth.

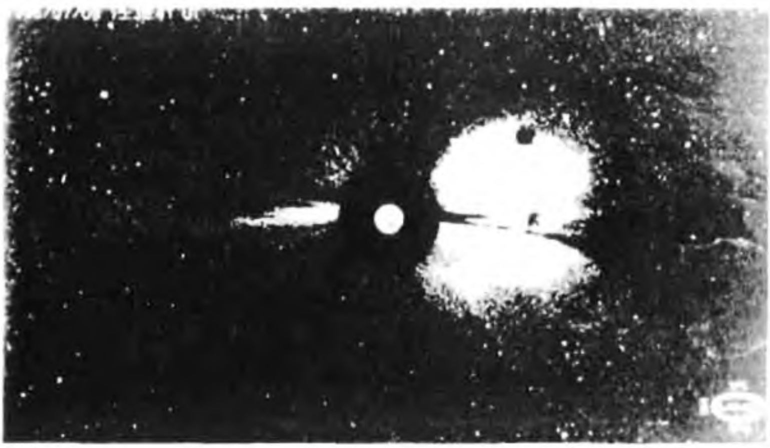


Fig. 3.13 A coronal mass ejection (CME) observed by the coronograph on the *SOHO* spacecraft on July 9, 1996. The large dark circle in the center is the occulting disk of the coronograph, it extends to 3 solar radii. The imbedded white circle (with grid) indicates the position of the Sun. The background white (and black) dots represent stars and cosmic ray hits. The dark occlusion at the top of CME is due to the planet Mercury. (EOS, 1997). [The coronograph is a simple device: a telescope in which the image of the photosphere is blacked out by a small metal occulting disk, which serves as a miniature Moon. Lenses behind the occulting disk focus the corona in an eyepiece, in a spectrograph, or on film.]

4.

The Magnetosphere: Earth's Magnetic Environment

...... this gift you have of speaking well on Homer is not an art; it is a divine power, impelling you like the power in the stone Euripides called the magnet ...... This stone does not simply attract the iron rings, just by themselves; it also imparts to the rings a force enabling them to do the same thing as the stone itself, that is, to attract another ring, so that sometimes a chain is formed, quite a long one, of iron rings suspended from one another. For all of them, however, their power depending on that lodestone.
— *Plato to Socrates.*
(Plato's *Dialogues Phaedo*, 407–399 B.C.)

The Earth, as we know, is a self-gravitating planet, the third planet from the Sun in our solar system. The important factor for us is that the Earth has a magnetic field. William Gilbert[1], physician to Queen Elizabeth and a contemporary of Shakespeare, was the initiator of the science of Geomagnetism in 1600, when he wrote:

"Magnus magnes ipse est globes terrestris"
("The Earth's globe itself is a great magnet".)

The oldest known consequence of the earth's magnetism is its

[1] As related by S. Chapman (1951), Gilbert "cut a spherical piece of the naturally magnetised mineral called lodestone, and examined the distribution of direction of the magnetic force over its surface by means of tiny magnetised needles freely pivoted. He saw that the distribution of dip agreed with what was known of the Earth's field. Hence, he concluded that the Earth itself is a great magnet, similar to his magnetised sphere except in size."

directive influence on the compass — still of great importance for navigation at sea and in the air. This effect was known and used for centuries before Gilbert showed that the cause lies within the Earth and not, as many had supposed earlier, in the heavens. This concept led Hanstein, in 1819, to write: "the Earth speaks of its internal movements through the silent voices of the magnetic needle". The origin of the magnetic field of the Earth is best understood to be caused by electric currents flowing in the Earth's core, below a depth of 2 900 km. Except for a small inner core, the material is in molten liquid form and in a state of slow convection. By dynamo action, such a flow across the magnetic lines of force can induce electromotive forces that can set up and maintain electric currents [see Chapter 2]. We observe the stray field of such currents on the Earth's surface.

4.1 The Magnetic Field of the Earth

Extensive studies of the Earth's magnetic field, due to its importance for navigation, led to the construction of magnetic maps from which it became evident that the magnetic poles of the Earth do not coincide with its geographic poles. The north magnetic pole (which is actually the south pole of the Earth's magnet) is located in northern Canada, 11.5° from the geographic pole, and the south magnetic pole lies at approximately the same distance from the geographic south pole in Antartica. The famous German mathematician, Karl Friedrich Gauss (1777–1855), showed that the magnetic field of the Earth can be described as being produced by a single bar magnet located in the Earth's interior [Fig. 4.1] and slightly inclined with respect to the rotation axis as commonly seen in textbooks. The field at the surface of the Earth is about 0.31 gauss near the equator and 0.7 gauss near the magnetic poles. The field falls roughly according to the inverse cube of the distance from the centre of the Earth's dipole. If there are no external influences, such a field would extend indefinitely into interplanetary space becoming gradually weaker with distance from the Earth, a picture scientists believed until forty years ago.

4.2 Earth's Variable Magnetic Field

Again, going backward in time, another very important step in the science of geomagnetism was a discovery, about 200 years

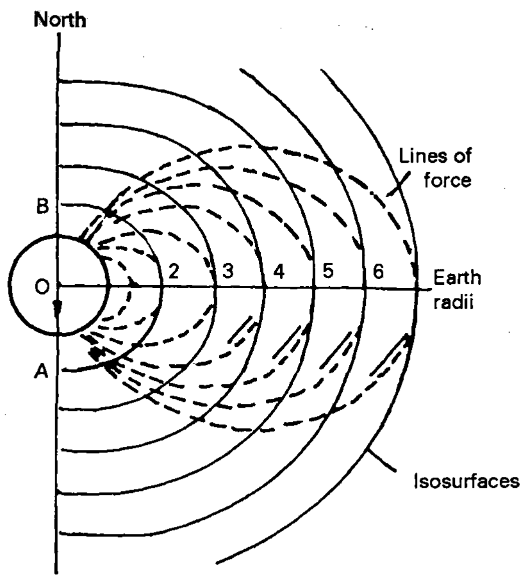


Fig. 4.1 Lines of force (- - -) and lines of equal field intensity form a dipole field on the external field of a uniformly magnetised sphere. The diameter BA in that direction is the magnetic axis, B and A are the magnetic poles. The plane through O, perpendicular to BA, is called the magnetic equatorial plane. The semicircles joining B and A are called the magnetic meridians.

ago, that the magnetic field of the Earth is not steady but shows variations with time (see Table 4.1). The variations are of two types, one which is secular (slowly varying) and the other, transient (temporal). The secular variations are relatively slow changes taking place gradually over time periods of millions of years, both in the locations of the magnetic poles and in the strength of the fields. These variations are irregular, varying both in direction and magnitude from year to year, so that it requires many years for the net effect to be significant. Such fluctuations are undoubtedly caused by changes within the Earth itself, and are not due to external factors associated with our space or solar-terrestrial relations. The transient variations on the other hand occur very rapidly, within periods of days or less, and are due to external sources probably of solar origin. Two major types of temporal changes in the magnetic field of the Earth are recognised: the first are disturbances of a more violent nature known as magnetic storms, and the second type are relatively small and regular daily variations. Both these temporal or transient variations are related to the solar and terrestrial phenomenon, and are of considerable interest to us for understanding the magnetic environment of the Earth.

Table 4.1 Periods of variations of the Earth's Magnetic Field (secular and transient).

Period/sec	Origin
10^{17}	
10^{16}	
10^{15}	internal and dipolar; dipole reversals
10^{14}	
10^{13}	
10^{12}	
10^{11}	
10^{10}	internal, non-dipolar; secular variation
10^{9}	
10^{8}	
10^{7}	
10^{6}	external; magnetic storms
10^{5}	external; diurnal variations
10^{4}	external; magnetic substorms
10^{3}	
10^{2}	external; micropulsations*
10^{1}	
10^{0}	
10^{-1}	external; sub-acoustic

* Discussed in Chapter 6.

It is interesting to note that the transient changes in the geomagnetic field were first announced in 1722 by George Graham, an eminent London clock-maker. It was based on his close and continued observations of the small movements of a compass needle. Now, these rapid changes in the Earth's field are measured with sensitive instruments, the magnetometers placed on the Earth's surface and in the last two decades, on Earth-orbiting and interplanetary spacecrafts. The worldwide transient geomagnetic activity is expressed by different geomagnetic indices. The most often used index is what is known as the K_p index. Magnetometers at a number of stations indicate a local 3-hourly (or K) index, ranging from 0 to 9. It is a measure of the variations in the field strength over a 3-hour period, thus $K = 0$ indicates a quiescent condition and $K = 9$ implies a very intense disturbance. The K indices from different places are then combined to give the planetary (or worldwide) index, K_p. The daily, quiet magnetic variations generally average about 0.1 percent of the quiet day value of the magnetic field strength. Taking the latter as approximately half gauss, on the average, the deviations are in the vicinity of 5×10^{-3} gauss of roughly 500 gammas or so. Gamma is the unit of magnetic field strength equal to a hundred thousandth of a gauss.

4.3 Solar Activity and Earth's Magnetic Weather

Schwabe's discovery of the sunspot cycle remained unnoticed for some years until it was highly publicised in a famous book *Cosmos* by Humboldt in 1851. Within a year Edward Sabine, a British scientist and the main architect of the worldwide network of magnetic observatories, and some others announced that the same cycle was shown in the transient magnetic variations. Thus, as Chapman said, for the first time it became clear that whereas ordinary weather depends on the changing geometrical relationships of the Earth and Sun [Fig. 4.2], the 'magnetic weather' is influenced by intrinsic changes on the Sun's surface. How did sunspots exert these influences? The first clue came in through the following reports. A very important report of scientific observation of few-minute time variations of the Earth's field was given by the Scottish physicist Balfour Stewart, who reported a great magnetic disturbance that was recorded at the Kew Observatory in England in the year 1859. During the same year and month, the British scientist Richard Carrington, while sketching sunspots in the course of his studies of solar phenomena, suddenly observed an intense brightening in the region of one of the spots. This occurrence so excited him that he quickly called his associates to the telescope to witness this event. Within a day of this event, violent fluctuations in the magnetic field were recorded at the Kew Observatory. It was noticed that during this large magnetic storm there were very large (several hundred gammas) and rapid (few minute) changes in the field magnitude and direction. We now know that Carrington had seen a solar flare. This connection between the solar flare and geomagnetic disturbances was, perhaps, the first observation giving a definite clue of the plasma link between the Sun and Earth. Not only this, the manifestations of this large magnetic storm were observed widely in the form of auroras over Europe, North America and as far south as Honolulu, Hawaii [Fig. 4.3].

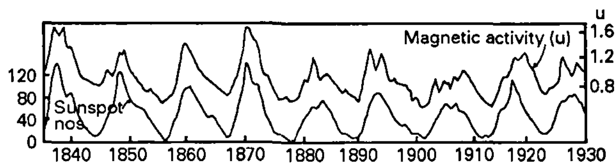


Fig. 4.2 Sunspot numbers and geomagnetic disturbance (as measured by u, the inter-diurnal variability) (after Bartels, 1932).

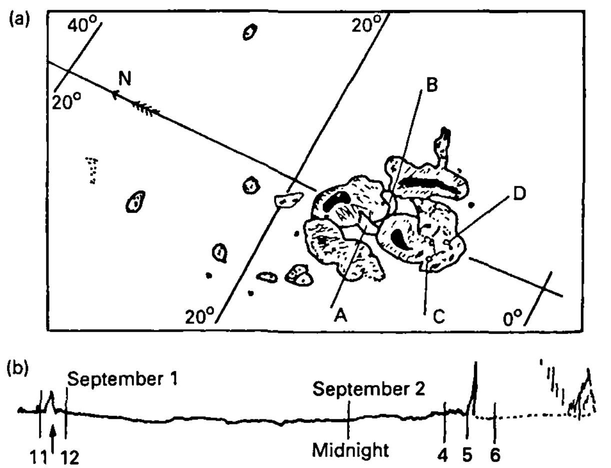


Fig. 4.3 (a) Carrington's 1860 drawing of the first reported flare (the light areas marked A, B, C, and D) observed in white light during his daily sunspot drawing on September 1, 1859. (b) The Kew record of the horizontal magnetic force showing the prompt (September 1) and delayed (September 2) effects of the eruptive flare observed by Carrington.

Subsequently, further observations showed that the large solar flares on the Sun were often followed a day or two later by severe magnetic storms on the Earth. As we shall read later, such storms generally begin with a sharp increase in the strength of the geomagnetic field over much of the Earth's surface. From this evidence, the well known British geophysicist Sydney Chapman and his colleague Vincent C.A. Ferraro, reasoned that the worldwide increase in field strength might be caused by the compression of the geomagnetic field. Interestingly, they proposed in 1931, that the agent of the compression was an electrically neutral cloud of protons and electrons (which we now know is plasma) ejected by the Sun in the course of a solar flare, which suggested for the first time that the geomagnetic field instead of extending to infinity (as does the gravitational field) was confined to a definite volume of space by a thin boundary layer. This suggestion came sixty years ago.

With our increased understanding of the solar-terrestrial relationships, we now know that it is not just during solar flares that the plasma from the Sun approaches the Earth, but that the Earth's magnetic field is continuously disturbed by the solar wind emitted by the Sun. Solar flare and sunspot activity apparently produces stronger gusts in the otherwise steady wind of the plasma.

The Chapman–Ferraro theory provided a very useful model, as a first approach to the actual situation. The general predictions made by this model have been in close agreement with the satellite measurements of the Earth's magnetic field across the boundary where the Earth's atmosphere ends and the solar coronal plasma environment begins. With the help of this model and satellite observations, we have the following basic concepts of solar wind interaction with the Earth's magnetic field.

4.4 Solar Wind Interaction

Though tenuous, the average solar wind possesses a high speed which, on average, can be taken as 400 km/sec. The sound speed in the interplanetary medium is about 50 km/sec. The solar wind flow then has a Mach Number equal to 8. The other significant speed in solar wind plasma flow is the Alfvén speed which can be calculated as 50 km/sec. So the calculations show that the Alfvén Mach number also turns out to be 8. Both these indicate that solar wind flow is supersonic. Now, imagine the solar wind blowing from the Sun approaching the Earth. It begins to sense an obstacle in its path: our planet with its magnetic field. If the solar wind plasma were moving slower than the speed of sound, it would have time to adjust its motion around the Earth — like the water flowing past a ship. However, since the wind speed is supersonic, it has no time to adjust to the 'Earth' obstacle and so it is 'shocked'. Taking another analogy, a shock-wave forms, just as one builds up around a supersonic aeroplane [Fig. 4.4].

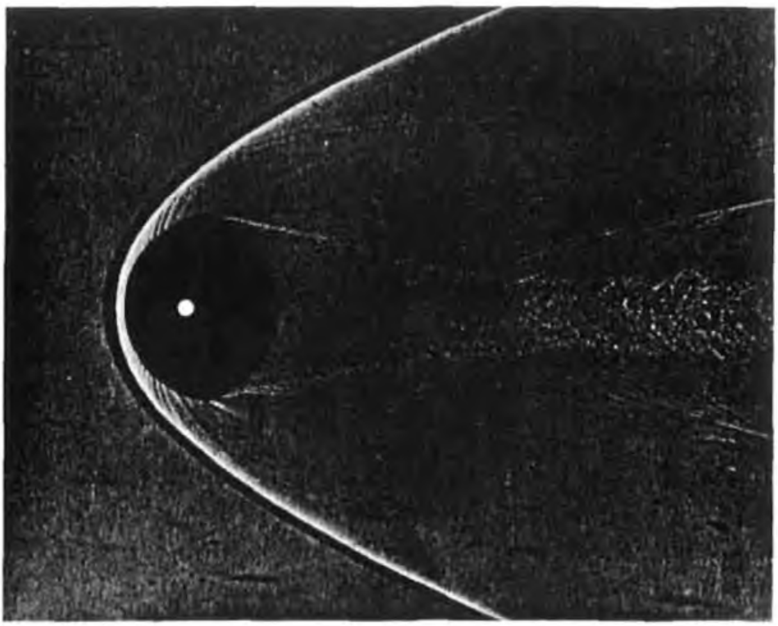


Fig. 4.4 Photograph of the bow-shock wave associated with a supersonic argon flow in a wind tunnel past a model magnetosphere in the form of a circular disc (after J.R. Spreeter, A.L. Summers and A.Y. Alksane, 1996).

The 'bow-shock' as determined by satellite measurements, forms some 14 to 16 R_E 'in front' of our planet towards the Sun. Its location is highly variable since it depends on the wind's speed, which changes with the level of solar activity. The plasma flows across the shock front into the transition region, the magnetosheath. The velocity of the plasma is reduced at the bow-shock and the plasma flow in the magnetosheath is subsonic and quite turbulent. The magnetic field also shows irregular variations in this region. Most of the solar wind particles are deflected around the magnetopause through this turbulent region.

The formation of the shock-wave in front of the magnetopause, however, is more complicated than the simple aeroplane analogy. The shock-wave upstream of an aeroplane is produced by close collisions between the neutral atoms. The solar wind plasma is collisionless as far as close collisions are concerned. So the solar wind plasma particles do not form the shock-wave by collisions. It is the imbedded magnetic field in the solar wind plasma which takes over the job and, by complicated plasma processes, produces the fluid-like conditions giving rise to the collisionless shock wave.

4.5 The Chapman–Ferraro Closed Magnetosphere

According to the original Chapman–Ferraro theory and other models derived from it, the pressure of the solar wind pushes the geomagnetic field closer to the Earth on the side of the Earth facing the Sun into a tear-drop shaped cavity with a tail pointing away from the Sun. The plasma is most effective in compressing the Earth's magnetic field where the direction of the plasma flow is perpendicular to the magnetic field direction. In the simplest situation, where the plasma is assumed to be streaming radially from the Sun in straight lines, the point of maximum compression is on the line that connects the center of the Earth to the center of the Sun. In the Sunward facing boundary, the magnetopause can be loosely identified as the place where the pressure of the solar wind is balanced by that exerted by the Earth's magnetic field. By estimating the density and velocity of particles in the solar wind, it is possible to predict that the magnetopause must be somewhere between 5 to 10 R_E from the Earth on the Earth–Sun line, with an increase of 30 to 40 percent near the dawn and dusk meridians.

Away from the central line, the plasma strikes the magnetopause at less than a right angle, and the pressure is correspondingly reduced. The pressure becomes almost zero as the solar wind becomes more and more tangential to the Earth's magnetic field as it flows around our planet. The pressure is zero where the flow of plasma is tangential to the magnetopause, just beyond the dawn and dusk meridians. As a result, solar wind plasma no longer compresses the field but instead drags, in particular the field lines that originate near the poles, to very great distances in the form of an elongated magnetotail [Fig. 4.5].

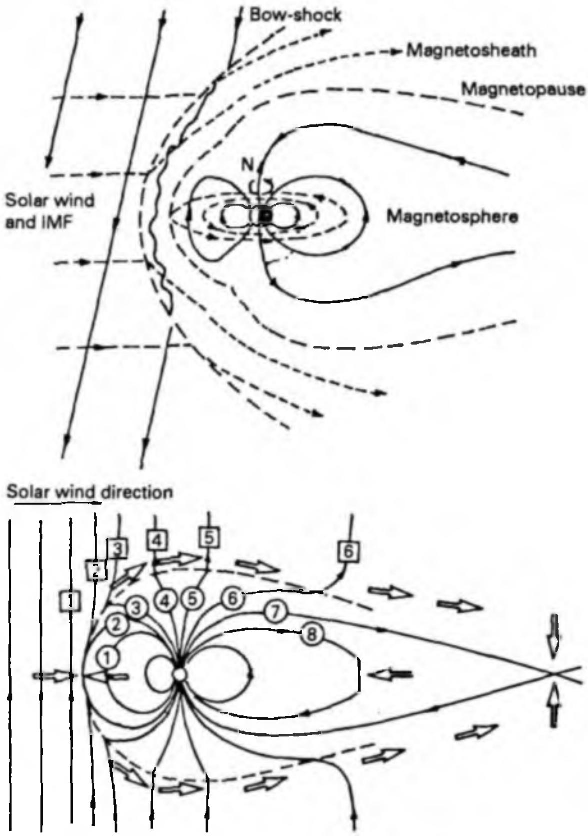


Fig. 4.5 Sketches of the structure of the Earth's magnetosphere in the noon-midnight meridian plane, showing: a) the Chapman–Ferraro closed magnetosphere based on strict application of frozen-in approximation, and b) the Dungey open magnetosphere, in which there is an essential breakdown of frozen-in-flow at the dayside magnetopause and in the tail leading to the occurrence of reconnection.

4.6 Dungey's Open Magnetosphere

The Chapman–Ferraro closed magnetosphere model offered a very accurate picture of the enclosed magnetic cavity around the Earth. This will be further evident when we look at the data from satellite measurements in subsequent sections. However, it became evident to space scientists that this model was based on the frozen-in-field concept, and so the interplanetary magnetic field and plasmas do not mix with the Earth's magnetic field and plasmas. Instead, the solar wind will confine the Earth's field to a cavity and then stretches the magnetic field lines in the solar wind direction to form the magnetic tail. The question that arose was: does the solar energy get transferred across the magnetopause to provide for the considerable energy to stretch the magnetic field lines? If the IMF and Earth's magnetic field do not mix, this question remains unanswered. J.W. Dungey, a British geophysicist, looking at this problem argued that the frozen-in-field concept as assumed by Chapman and Ferraro can break down under some circumstances. In that case, the IMF field lines can diffuse relative to the plasma in the magnetopause, allowing the interplanetary and terrestrial fields to merge through the boundary. This process of magnetic reconnection was proposed by Dungey in 1961.

In Dungey's open magnetospheric model [Fig. 4.5] the magnetotail is formed by the reconnection of the Earth's magnetic field lines to the IMF lines. Merged field lines have one end attached to the planet and the other in interplanetary space. Since the portion of the field line in interplanetary space is frozen in the solar wind, it will stretch into a magnetotail. The important point about the open magnetosphere is that the formation of a tail and the transfer of solar wind energy in the Earth's magnetosphere seems to depend on the IMF. It is seen that when the IMF has a direction opposite (southern) to the magnetospheric fields (northward), interconnection can take place, and the solar wind convects these fields back into the tail region where they reconnect once more. The magnetic tension on the freshly reconnected tail fields 'snaps' the reconnected fields and the plasma surges forward towards the nightside of the Earth and eventually flows to the dayside where the process can repeat. The cyclical flow is, therefore, excited in the interior by these reconnection processes — this is the key feature of the 'open' magnetosphere.

In a three-dimensional view of the magnetosphere, the inner magnetosphere appears to be doughnut shaped. The inner magnetosphere is the sunlit hemisphere of the tear-drop shaped cavity and a nearly symmetric column in the antisolar hemisphere. It consists of stable low-energy trapped particles in a region, where the energy density of the compressed magnetic field exceeds the energy density of these particles. The polar magnetic field lines both in the north and the south seem to thread the hole of the doughnut and remain inside the magnetotail [Fig. 4.6].

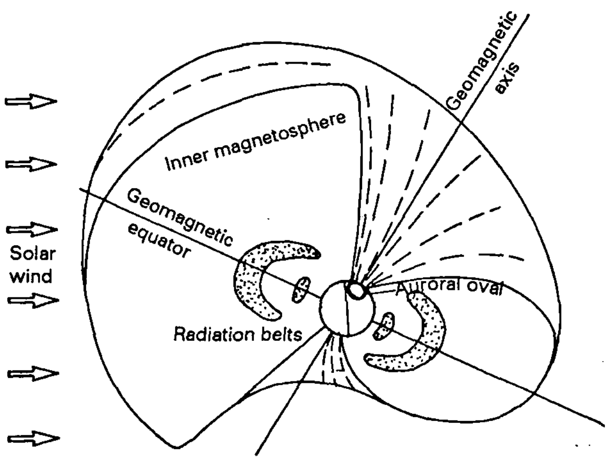


Fig. 4.6 Three-dimensional view of the magnetosphere. The inner magnetosphere is doughnut shaped and contains low-energy trapped charged particles. The magnetic field lines of force emanating from the north and south pole are seen to be contained within the magnetotail of the magnetosphere.(After S.I. Akasofu, *Scientific American*, December 1989.)

4.7 The Satellite Measurements

What did the satellite measurements show? Going back in time, the very first measurements of the magnetic field in the outer regions of the magnetosphere were made by the instruments carried in the space probe *Pioneer I* in 1958. The magnetometer in the space probe could measure only the magnetic field intensity. It was found that the measured field was reasonably close to an undistorted dipole field close to the Earth, but was much stronger and fluctuated widely between 12 to 14 R_E. Near 14 R_E, it was observed that the strength of the magnetic field decreased suddenly. Two years later, in 1960, *Pioneer V* carrying similar instruments, traversed the outer magnetosphere along the 3:00 p.m. (local meridian time) giving similar results to those obtained on the earlier flight: a gradually decreasing field out to 8 R_E, a strong fluctuating field beyond 10 R_E and a decrease to a weak, presumbly inter-planetary field somewhere between 15 and 20 R_E [Fig. 4.7].

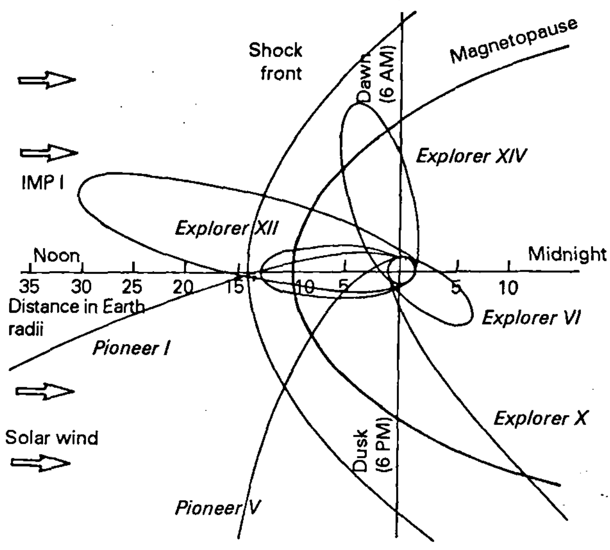


Fig. 4.7 Initial trajectories of the seven artificial Earth satellites and rocket probes, which were launched in the early days of Earth's proximal space research, are projected on the Earth's geographic equatorial plane in a view looking down on the North Pole. Positions in longitude with respect to the Sun are commonly indicated in terms of the local time meridian. (After Laurence J. Cahill, Jr., *Scientific American*, March 1965.)

The Earth's magnetic field, in turn, deflects the solar wind plasma flow around it. Hence, to locate the actual magnetospheric boundary it was necessary to have plasma velocity measurements also. However, both the above mentioned measurements could not locate the magnetospheric boundary as there were no instruments to carry out simultaneous plasma measurements. Even if the decrease in field strength observed beyond 14 R_E was interpreted speculatively as the magnetopause, these distances were found to be considerably greater than those predicted by the Chapman–Ferraro model.

The first observation of the magnetospheric boundary were made by the satellite *Explorer X*, carrying a magnetometer and a plasma detector, in March 1961. *Explorer X* measured high plasma velocities for the first time simultaneously when the magnetometer showed stronger and more erratic magnetic fields.

In the same Explorer series, the satellite *Explorer XII* was launched into a highly elliptical orbit with an apogee (the point in its orbit where a satellite or the Moon is farthest from the Earth) beyond 13 R_E and *Explorer XIV* was launched in 1962 with an apogee of 16 R_E. The measurements from *Explorer XII* and *XIV* showed that the confined geomagnetic field had a permanent existence. During the quiet sub-conditions, the magnetosphere extends approximately to 10 R_E from the Earth on the Earth's sunlit side and stretches back several Earth radii on the midnight side.

IMP I, the first of a series of IMP (Interplanetary Monitoring Platform) launched in 1963 and designed to carry instruments beyond the magnetopause to investigate cosmic rays, plasma and the magnetic field in interplanetary space, penetrated the magnetopause twice every four days. Again, the magnetopause was found to be 10 R_E from the Earth near the noon meridian but *IMP I* also mapped another shock front boundary of the magnetosphere at about 14 to 15 R_E from the magnetopause. These measurements obtained by *IMP I* experiments also explained the field transitions observed at 14 R_E by *Pioneer I* and between 15 and 20 R_E by *Pioneer V*. These were apparently the postulated shock front. *Explorer X* and *Explorer XII* did not travel far enough beyond the magnetopause to reach this second boundary.

Another interesting measurement made by *Explorer X* was the field just inside the boundary at 22 R_E. It was seen that the field at this distance was quiet and well-ordered, and quite clearly the geomagnetic field, but it pointed almost exactly away from the Sun and it had a strength of about 30 gammas. At this point the dipole field should be 38 gammas, so the measured field was larger than expected by a factor of 10. This pointed out that

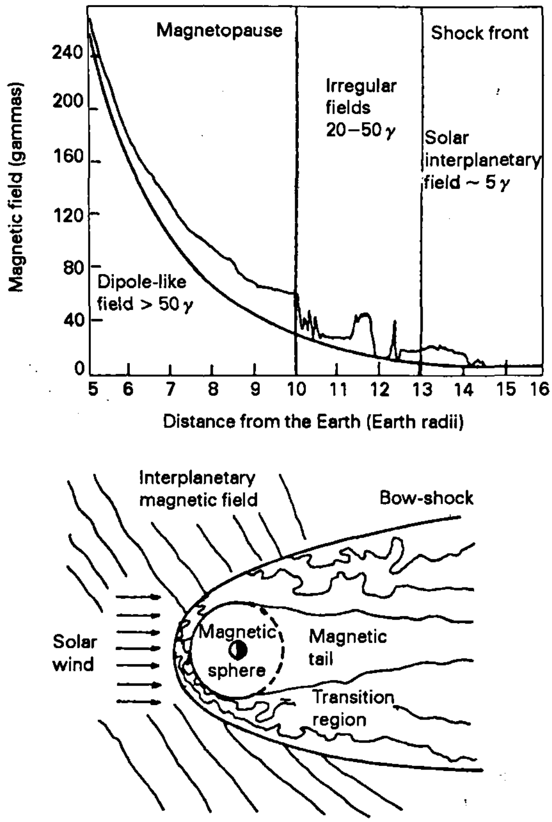


Fig. 4.8 Typical variation of the strength of the geomagnetic field with the distance from the Earth on the sunlit side as given by satellite measurements. The smooth curve represents the dipole field, strength and the field characteristics are shown by the jagged curve arising due to solar wind interaction. The important features are: a) The region near the Earth where the observed field is approximately the same as that for the unperturbed dipole magnetic field. b) Magnetopause across which the flow is turbulent. c) Shock front and across it is the interplanetary region with a low magnetic field. A schematic view of these features from above the magnetic pole is seen in the lower illustration.

the geomagnetic field behind the Earth was quite different from a dipole field. Other satellites in the *Explorer* series confirmed this fact but a reasonably detailed picture of the geomagnetic tail was obtained by *IMP I*.

The typical satellite measurements of the strength of the magnetic field on the sunlit side can be seen in Fig. 4.8. The stronger magnetic field at about $10R_E$ marks the compressed magnetic field boundary due to the solar wind, the magnetopause. The magnetopause is about 100 km thick, thus, compared to the size of the magnetosphere it is a thin boundary. Beyond the magnetopause, there is a fluctuating and irregular magnetic field which is the region where the plasma is also in a turbulent state and this is called the magnetosheath region. The boundary dividing the magnetosheath and the interplanetary medium, undisturbed by our planet's magnetic field, is the bow-shock. The shock front boundary is located at about $14R_E$ beyond which we see a very weak interplanetary magnetic field. Hence, looking through the eyes of a satellite outside of the Earth's environment, we will see the interplanetary medium, the magnetosheath and magnetosphere separated by the distinct boundary surfaces, the shock front and the magnetopause.

4.8 Structure of the Magnetosphere

The Earth's magnetosphere cavity is not empty. It consists of various regions of plasma with different characteristics. The results of a painstaking and, in many ways, a brilliant synthesis of over thirty years of in situ and ground-based magnetospheric observations has given us the picture of the plasma regions and boundaries. The main source of plasma is the solar wind and the ionosphere. We shall now discuss some distinct features of the plasma regions in the magnetosphere [Fig. 4.9].

4.8.1 Magnetotail and Plasma Sheet

A very interesting feature of the magnetotail is the change in direction of the magnetic field across it. The field pointing roughly towards the Sun in the northern half of the tail and away from the Sun in the southern half, gives rise to a well defined neutral sheet or a region of abrupt magnetic reversal. The measurements of the magnetic field direction at about 30 R_E above and below the ecliptic plane by the *IMP I* magnetometer experiment, prepared by Norman F. Ness of the Goddard Space Flight Centre, showed for the first time the presence of the neutral sheet. The field was consistently almost exactly antisolar below the ecliptic plane and, above this plane, generally pointed towards the Sun. As the satellite approached the neutral sheet region the field decreased to very small value and then changed direction abruptly. The neutral sheet was clearly observed on almost all of the *IMP I* orbits in the magnetic tail and is, therefore, a normal feature of the geomagnetic tail. The neutral sheet is 0.1 to 1 R_E thick and is frequently in motion. One consequence of the weakened field at the centre of the tail is that the plasma pressure on both sides of the neutral sheet has to increase to maintain the pressure balance for the system to be in equilibrium. Hence, a well formed plasma sheet with high plasma pressure develops around the neutral sheet region, bisecting the magnetotail into two lobes. *IMP I* data also showed the presence of a well developed plasma sheet. The typical particle energies of plasma in the plasma sheet are about 10,000 eV. The sheet is several Earth radii thick and usually has an identifiable inner edge, roughly seven to eight Earth radii from our planet on the midnight side.

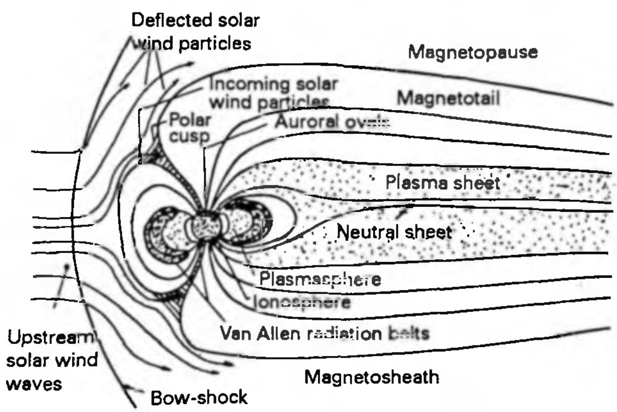


Fig. 4.9 The Overall Structure of the Earth's Magnetosphere.

The existence of the plasma sheet between the northern and southern lobes of the magnetotail presents a very interesting situation, for this configuration can store energy. If the magnetic fields in the two lobes come into contact, they can annihilate each other. When this happens, the energy stored in the fields will be transferred to the plasma particles, speeding up their random motions and thus heating them. Such energetic particles can be of considerable importance, for they are involved in auroras and magnetic storms, as we shall discuss later.

As it is now known, the geomagnetic tail structure extends to nearly 1 000 R_E. Since the Moon's orbit is only about 60 R_E away from the Earth, it spends about a week in the magnetotail each month. But, unlike the moons of outer planets, as we shall see in the last chapter, the Earth's Moon does not seem to play any role in magnetospheric dynamics.

4.8.2 Plasmasphere

Another distinct feature, beginning just beyond the ionosphere, is the plasmasphere. The plasmasphere extends between 20 000 to 30 000 km. This region which co-rotates with the Earth is composed primarily of ionised hydrogen atoms. These protons may have energies of a few electron volts, there may be 1 000 or more of them per cubic centimeter. Beginning with heights of 1 500 to 2 000 km (which are related to the ionosphere), one measures the electron or ion densities from a vertically ascending rocket; the instruments will not record any peculiarity in plasma density variation up to the region of an abrupt reduction of charged particle density called the 'knee' region. In other words, there is no boundary between the 'classical' ionosphere and the plasmasphere. This was perhaps the reason that in the earlier days of magnetospheric research, the plasmaspheric region was called the outermost ionosphere. The three-dimensionality of the knee phenomenon distinguishes the ionosphere and plasmasphere.

The plasmasphere is in approximate equilibrium with the ionosphere. The boundary of the plasmasphere, called the plasmapause, separates the magnetospheric plasma from the plasma co-rotating with the Earth.

4.8.3 Earth's Radiation Belts

We have already seen that the transient events on the Sun like solar flares can originate highly energetic particles, which are the solar cosmic rays. Besides this, it is now well known that interplanetary space is also prevaded by energetic particles originating in sources outside the solar system. These are called the Galactic Cosmic Rays.

The energetic particles interact with the magnetic field of the Earth and as these are charged particles, electrons and ions, they can get trapped in the magnetic field [Fig. 4.10] of the Earth, forming Radiation Belts. We shall first consider the most famous space age discovery by Van Allen, the radiation belts that bear his name and then a new radiation belt discovered nearly twenty years after Van Allen's discovery. It is interesting to recall that the *Time* Magazine, from U.S.A., featured the radiation belts in a 1959 issue with a picture of Van Allen, on the cover. The article remarked "No human name has ever been given to a more majestic feature of the planet Earth".

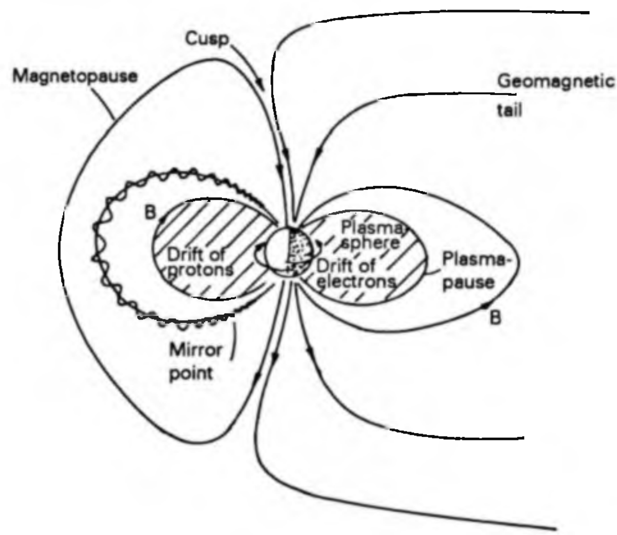


Fig. 4.10 Motion of Trapped Charged Particles and the Relevant Magnetospheric Plasma Regions.

The Van Allen Radiation Belts

"Instruments borne aloft by artificial satellites and lunar probes indicate that our planet is encircled by two zones of high-energy particles, against which space travellers will have to be shielded."

J. A. Van Allen

James A. Van Allen and his colleagues reported on May 1, 1958 a new major phenomenon in geophysics, namely the permanent existence of two belts of high energy particles consisting of electrons and protons. At the equator, these toroidal or doughnut-shaped belts encircle the Earth at distances of about 1.5 and 6 R_E from the planet's center. An important point is that these high energy particles are found at low and moderate, but not at high latitudes. The belts do not extend above geomagnetic latitudes of about 75° N or S.

The discovery of radiation belts was made during the studies of cosmic rays with instruments aboard the first U.S. satellite *Explorer I*. The instruments included a geiger counter for cosmic ray detection and a radio telemetry system for direct transmission of data to Earth. The fact that a sufficiently high level of radiation can jam the counter and send the apparent counting rate to zero, led Van Allen and his colleagues to discover an enormously high level of radiation at altitudes of 650 to 800 km. When the satellite went out to these altitudes the counting rates dropped to zero, the device became saturated and ceased to count at all.

The discovery of Van Allen belts is one of the most spectacular results of recent space studies. It started a new era in the understanding of our space environment. Though the presence of such belts came as a surprise to the scientific community, their presence was, in a sense, anticipated. Trapping of charged particles by a magnetic field had been known about for a long time and as far back as 1904, Carl Stormer, in Norway, had suggested that the geomagnetic field could act in this manner. Subsequently, many scientists including the Nobel Laureate Hannes Alfvén considered the trapping of charged particles by the terrestrial magnetic field. In an experimental simulation of the phenomenon, Willard H. Bennett allowed a stream of electrons to impinge on a sphere with a magnetic field resembling that of the Earth. Some of the patterns obtained bore a striking resemblance to that currently accepted for Earth's radiation belt (recall the artificially created radiation belt in Chapter 2).

Today, with the plasma physicists' interest in confining plasmas by magnetic fields in order to produce thermonuclear reactions, we understand the plasma and magnetic field interactions quite well.

As we have already discussed (Chapter 2), the spiral motion and mirror points of charged particles in the Earth's magnetic field are responsible for the formation of the Van Allen radiation belts. Because the charged particles are usually unable to move across, but only along the geomagnetic field lines, the belt is effectively attached to and rotates with the Earth. The Van Allen belt of electrically charged particles surrounding the Earth does not reach below about 650 km. This can be explained from the theory of reflection and loss of particles in the magnetic mirror system. Further, taking into account the drift of the charged particles around the globe, the theoreticians can explain the doughnut-like shape of the trapped particle region.

Explorer IV and *Pioneer III* gave us the first detailed picture of the radiation belts [Fig. 4.11]. The radiation belts lie well within

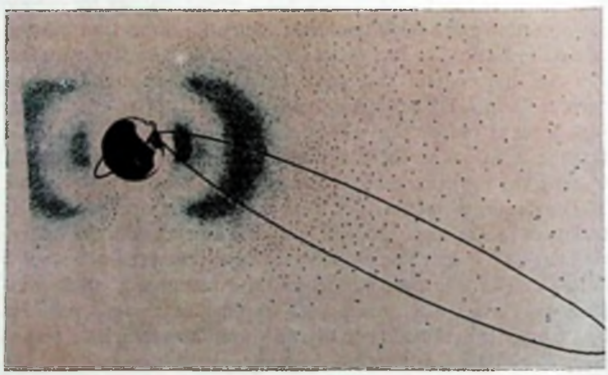


Fig. 4.11 *Explorer IV* and *Pioneer III* gave the first detailed picture of the radiation belts. The *Explorer IV* satellite (short ellipse) monitored radiation levels for nearly two months at altitudes up to 1 300 miles. The *Pioneer III* lunar probe (long ellipse) provided data up to 65 000 miles. Its orbit is shown distorted because of the Earth's rotation during flight. (After James A. Van Allen, *Scientific American*, March 1959)

the magnetopause. The inner radiation zone is embedded in the plasmasphere and contains electrons with energies as high as several million electron volts (MeV). Typical energies in the outer belt, which lies beyond the plasmasphere, appear to play a dominant role in producing the 'boundary' between the two belts.

Unlike the electrons, the trapped high energy protons decrease in number more or less continuously with increasing distance from the Earth. In the inner electron belt, the protons have energies of several hundred MeV, but on moving farther away the energies fall off steadily. During the active solar period the magnetic storms can cause large changes in the fluxes of the radiation belt particles.

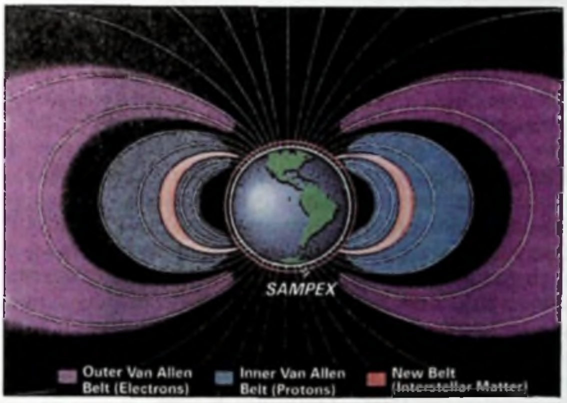


Fig. 4.12 Schematic cross-section of the trapped radiation belts surrounding the Earth. The Van Allen belts are shown in blue and purple. The inner belt is composed mainly of energetic protons, while the outer belt is mainly energetic electrons. A newly-identified radiation belt, shown as two bright yellow crescents, is composed of energetic heavy nuclei that originated in the local interstellar medium. All of those belts approach closest to the Earth in the south Atlantic region because of the offset of the Earth's magnetic dipole. The orbit of the polar-orbiting *SAMPEX* satellite, which has been studying the new belt, is indicated (after R.A. Mewaldt, A.C. Cummings and E.C. Stone, *EOS*, 1994).

Anomalous Cosmic Rays and A New Radiation Belt

Besides the galactic cosmic rays and solar cosmic rays, instruments of the *Pioneer X, IMP V, IMP VII* spacecrafts discovered a third component of energetic charged particles known as

Anomalous Cosmic Rays (ACR). It appears that these represent a sample of particles from the nearby interstellar space — the vast region between the stars. These cosmic rays originate in the process of complicated interaction between the interstellar medium and the heliosphere, the magnetic boundary or magnetospheric boundary of the Sun.

It has recently been shown that some of these ACRs have become trapped in the Earth's magnetic field, where they form a new radiation belt composed of interstellar material.

In July 1992, the satellite *SAMPEX* was launched into a polar orbit carrying instruments designed to study ACRs in the Earth's environment. During its first year, *SAMPEX* has confirmed that ACRs are singly charged particles and located a narrow belt of trapped ACRs within the inner radiation zone of the Van Allen radiation belts shown above [Fig. 4.12]. The data from *SAMPEX* also shows that this belt is closer to the Earth and is so narrow that the new radiation belt is analogous to a magnetic bottle that holds a sample of interstellar material. The *SAMPEX* observations have, therefore, provided an opportunity to examine the elemental and isotopic composition of a sample of interstellar matter which, if we talk on a galactic scale, is located right in our own backyard!

4.8.4 Auroral Ovals

The other very important feature of the magnetosphere is the Auroral Oval. Centered on each of the geomagnetic poles is a great luminous oval which is a permanent feature of our planet. The radius of the oval is about 2 500 km (the entire length of India!). Auroras occur virtually every night about auroral ovals around both magnetic poles. The northern auroral oval is centered roughly at the north geomagnetic pole, not the geographic north pole, and it stretches across Alaska and northern Canada, the southern tip of Greenland and Iceland, the northern coast of Norway and a little off the Siberian coast.

The southern auroral oval is centered on the geomagnetic pole in the Antarctic. *Aurora Australis* is rarely seen from inhabited areas, however, because this auroral oval passes partly over Antarctica and partly over the southern Indian Ocean. Because Africa, South America and Australia are too far from the southern magnetic pole to have frequent auroral displays, Aurora Australis was not discovered until 1773.

4.9 Solar Wind Interaction During the Disturbed Conditions

So far everything is perfect! Visible radiation from the Sun provides us heat and light to sustain life. The solar wind arranges the magnetic field of the Earth to form a closed cavity around the Earth, thus protecting us from various harmful radiations. Everything is peaceful and quiet in the interstellar medium and in the magnetosphere. This is all true during the quiet days of the Sun, but this peace is disturbed when the Sun is active. As seen in the earlier chapter, the most violent phenomenon that occurs on the Sun are solar storms. These storms cause several magnetospheric disturbances. A solar storm is associated with intense emission of X-rays, EUV (Extreme Ultraviolet) and UV radiations, and also with ejection of particles whose energies range from about 1 KeV to more than 10 GeV. The terrestrial ionosphere, just 500 km above the Earth, is affected within 10 minutes by these radiations. The sudden enhancement of soft X-rays during a solar storm produces extra ionisation in the ionosphere, particularly in the lower region (because of the penetrative power of X-rays). Most energetic solar particles spread quickly in the interplanetary space. The magnetosphere is temporarily embedded in the flow of such energetic particles for a few days. Some of the particles impinge on the polar upper atmosphere.

In addition to injecting high energy particles, solar flares also emit greatly enhanced solar plasma streams with speeds of the order of 500–1000 km/sec. Ninety percent of these high speed streams are associated with coronal mass ejections. These streams have a higher velocity and a greater particle number density than the normal solar wind. Shock-waves are, thus, formed in the interplanetary medium between the boundaries of the faster and slower moving winds. These shock-waves themselves can accelerate the interplanetary particles to higher energies and can greatly agitate the magnetosphere causing magnetospheric storms.

4.10 Magnetic Storms

A typical magnetospheric storm consists of three phases: the initial phase, the main phase and the recovery phase. The storm begins when the interplanetary shock-wave reaches the magnetosphere and compresses it. This compression occurs rather suddenly. Its effect is seen as a step function-like increase in the horizontal component of the geomagnetic field on the ground

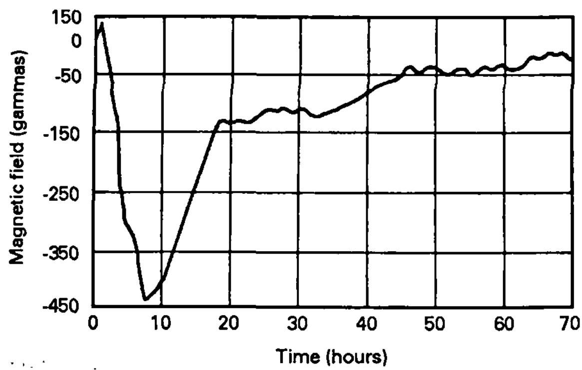


Fig. 4.13 A long geomagnetic storm, recorded at Honolulu on February 11 1958, exhibited the three distinct phases characteristic of the magnetic storm. During the initial phase of the storm, which lasted for two hours, the strength of the magnetic field at the surface of the Earth increased by about 50 gammas above the pre-storm level. During the main phase, the field strength dropped abruptly by more than 400 gammas. The rapid recovery phase was completed about 18 hours after the storm began. After several days, the field recovered its prestorm value.[2]

[Fig. 4.13]. The sudden increase in the magnetic field is due to the fact that the magnetopause is driven inward towards the Earth; sometimes it can reach almost 4 to 3 R_E. In the latter case, the changes in the surface magnetic field are almost 300 to 400 gammas. But after the sudden commencement, as it is called, the storm does not begin suddenly and there is a period

[2] As the K_p index as used to express the worldwide transient geomagnetic activity, the D_{st} index is used to provide information on magnetic storms and is constructed from worldwide mid-latitude and equatorial magnetograms. The number of stations that recorded the onset of a storm (generally determined by the Sudden Commencement) is noted, and then values of the magnetic field from all the stations are averaged. The averaged effect of a storm-time variation is a reduction of the horizontal component of the geomagnetic field. D_{st} is negative and a larger negative D_{st} means a more intense storm.

of a few hours of calmness (the calm before the storm!). This period is the initial phase. The duration of the calm period varies considerably, however, from one storm to another, from less than 10 minutes to more than 6 hours. After this the major phase of the storm begins, which is called the main phase. The field strength drops abruptly, nearly 50 to 100 gammas below normal. During this period there may be positive and negative fluctuations of short duration. Finally, in the recovery phase, the magnetic field strength of the Earth returns in a somewhat irregular manner to the quiescent value. The recovery phase requires one or two days, provided no other disturbances occur in the meantime.

The main phase of the magnetospheric storm begins when the shock-driving plasma, which is turbulent, reaches the magnetosphere. This phase is characterised by a succession of explosive processes, called magnetospheric substorms.

4.11 Magnetic Reconnection and Magnetic Storms

What causes magnetospheric substorms? How is the energy of the order of 10^{21}–10^{22} ergs generated? What are the processes which take place with the release of this energy? The following figure summarises the answers to this question as we understand it at present:

Solar Wind Energy → Stored Energy in the Magnetotail → Magnetospheric Substorm Energy → Polar Atmosphere Magnetotail Trapping Region

The solar wind energy gets converted into the kinetic energy of solar wind plasma particles. The flowing plasma, in the presence of magnetic energy, is stored in the magnetotail. The rate of energy input by the solar wind into the magnetotail is about 10^{12}W. The conversion of magnetic energy for the magnetospheric substorms takes place through the magnetic reconnection process in the magnetotail. The plasma sheet conditions change drastically during the substorms leading to reconnection. An extremely hot plasma of a temperature of the order of 10^7K or more is generated, a part of the plasma is precipitated into the polar upper atmosphere and a part fills the plasma sheet. The hot plasma injected into the polar region disturbs the polar ionosphere considerably, causing polar substorms. The auroral electrojet, an intense concentrated electric current around the auroral oval, is linked to the magnetotail current during the substorm. The auroral electrojet causes polar magnetic substorms.

A part of the hot plasma is also injected into the trapping region and forms the intense storm-time proton belt or what is called the *ring current*. The belt, made primarily of protons with energies of about 1 00 000 eV, forms just outside the plasmasphere. As protons are in motion due to grad-B drift (Chapter 2), they create a ring of electric current around the Earth. The ring current may exist at all times, but successive occurrences of magnetospheric substorms can build up a very intense current. Its magnetic effect on the ground is seen as a decrease of the horizontal component of the geomagnetic field in low and middle latitudes, during the main phase of the magnetic storm.

Both the polar upper neutral atmosphere and the middle latitude ionosphere are also greatly disturbed during the main phase. One of the major features of the disturbances is the considerable depression of the electron density in the higher regions, but its cause is not well understood. The most fascinating manifestation of the magnetospheric substorms, however, is the auroral displays during an auroral substorm (discussed in Chapter 6).

4.12 International Programmes

We save seen that the Explorer series of NASA Scientific Satellites have been especially important in delineating and investigating in detail many aspects of the magnetosphere and its interaction with the solar wind. The IMP series numbered in the Explorer sequence and primarily devoted to interplanetary investigations, also contributed importantly to studies of the magnetotail, the magnetopause and the bow-shock. The other observers of these series included several spacecrafts of the Orbiting Geophysical Observatory (OGO) type. These satellite observations revealed that the physical processes in the magnetosphere are of a very complicated nature. Hence, further efforts were necessary for examples to understand the energy, mass and momentum flow throughout the geospace; the interactive behaviour of different regions of the magnetosphere and the effect of geospace on human activities. Many research programmes have been planned by scientists all over the world. To mention a few of the international magnetospheric studies: a major programme since 1976–79 co-ordinating ground-based, rocket and spacecraft research on the Earth's magnetosphere; the three spacecraft ISEE (International Sun–Earth Explorer) mission which is a joint programme between NASA and the European Space Agency, designed for detailed studies of the solar wind interaction with the magnetosphere, using one spacecraft permanently located in the solar wind and two orbiting the Earth, in tandem, to give detailed spatial information about the magnetopause and the bow-shock.

The major objective of the ongoing Solar Terrestrial Energy Programme (STEP), the International Solar Terrestrial Physics (ISTP) programme and the Geospace Environment Modeling (GEM) programme is to understand the linkages between the Sun, the interplanetary medium, the magnetosphere and the atmosphere–ionosphere system.

The scientists hope that, in future, magnetospheric research projects such as ISTP, STEP and GEM, (satellite-based observations) should be co-ordinated by an advanced type of computer simulation study. This will allow us to obtain profound new insights into the complex three-dimensional world of magnetospheric plasma physics.

The Dynamic Explorer Programme with the launch of two *Dynamics Explorer* (DE) spacecraft into co-planar polar orbits has been successful in understanding the complex dynamic process that couple the magnetosphere and the ionosphere/atmosphere. This programme was developed to investigate, besides the above two, the strong interactive processes that couple the hot, tenuous convecting plasmas of the magnetosphere and the colder, denser plasmas and the gases co-rotating in the Earth's upper atmosphere, the ionosphere and plasmasphere.

5.

Current Systems: Earth's Electric Environment

"I have no need of that to believe in providence. A good thunderstorm is sufficient to make me recognise the existence of another world and a supreme judge. He who is not convinced by a lightning flash is not convinced by anything".
— *Lepoldo Alas in La Reagenta, 1885*
(Translated by John Rutherford, 1984)

The *entry of the solar wind plasma into* the Earth's magnetosphere, the large-scale motion of the plasma inside the magnetosphere known as magnetospheric convection and the coupling of magnetospheric and ionospheric plasma flow, is not well understood. However, we know (remember Chapter 2) that the motion of plasma in the presence of a magnetic field gives rise to various types of magnetospheric and ionospheric current systems.

Some of the principal magnetospheric current systems are: the magnetopause currents, which are responsible for the sharp confinement of the magnetospheric field, sustained by solar wind particles on, or drifting along, the boundary; the neutral sheet current dividing the magnetospheric tail into two lobes of oppositely directed fields, sustained by drifting plasma sheet particles; the ring current, an east–west flow around the Earth centered on the magnetic equator and sustained by low energy protons trapped in the geomagnetic field. Then, we have ionospheric currents flowing in the upper atmosphere caused by a variety of different mechanisms. Besides these, there are field-aligned currents which link the ionospheric current system of polar latitudes with that of the magnetosphere and play a very important role in the auroral dynamics. In order to get a comprehensive view of the Earth's Electric Environment, I shall list the currents in terms of the regions in which they exist. In the quiet state these currents determine the shape of the magnetosphere. However, magnetic disturbances, arising from solar disturbances, change this situation by the redistribution and dissipation of these currents.

5.1 Ionospheric Currents

Electricity and Magnetism were considered as quite independent, till a very important and exciting discovery in 1820 that there was a close connection between these two. The first discovery was that currents in wires make magnetic fields; then, in the same year, it was found that wires carrying current in a magnetic field have forces on them.

Electric currents can make magnetic fields. Then came the question: can magnets also make electric fields? Large magnets next to the wires produced no such effects. It was Faraday, in 1840, who discovered that only when a magnet is moved near an electric circuit, there is a current. These are called induced currents. Similarly, he noticed that if one of a pair of wires has a changing current, a current is induced in the other. Faraday's discoveries of induced currents was the beginning of modern electrical technology.

5.1.1 The Sq Electric Current System

Looking at Space Electrodynamics, it was in 1839 that Friedrech Gauss interpreted fluctuations in the magnetic compass to indicate the passage of electric currents at high altitude. Interestingly, in 1882, Balfour Stewart wrote an article for the *Encyclopedia Britannica* in which he envisioned a 'Great dynamo in the sky'. In essence, Stewart proposed that these currents were the result of the dynamo action of airflow across the geomagnetic field. With the discovery of the Ionosphere at the turn of this century, it became clear that the transient variations of the Earth's geomagnetic field were correctly interpreted in terms of ionospheric currents flowing mainly in the E-layer. They are generated by the tidal movement of ionised air above 100 km, driven by solar heating. The vertical movement is 2 or 3 km; sufficient to generate a horizontal current sheet of electricity.

The horizontal layer lies at an altitude between 100 and 150 km, concentric with the Earth's surface. Ionospheric currents are observed during both quiet and disturbed solar wind conditions. On quiet days, ionospheric currents are designated as Sq (solar, quiet days, daily) currents. A daily pattern of variation of the geomagnetic field is observed by a magnetic station at a fixed point on the Earth and rotating through this current system.

Figure 5.1 illustrates the Sq ionospheric currents in a sunspot minimum year (quiet Sun). At the equinox, the current-lines show the direction of flow: over the day hemisphere (as viewed from the Sun) on the left and over the night hemisphere on the right. The lines are spaced so that 10 000 amperes flow between adjacent lines. About 65 000 amperes flow in each of the two daytime circuits north and south of the equator, anti-clockwise and clockwise, respectively.

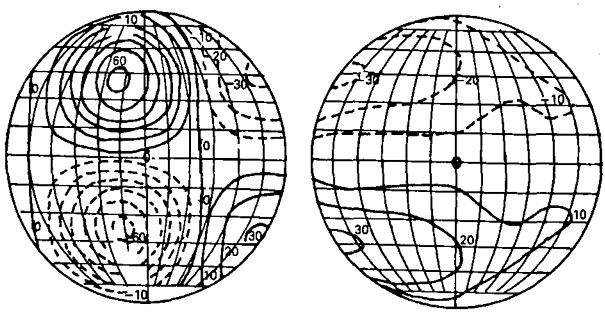


Fig. 5.1 The overhead electric current system at the equinox during the sunspot minimum corresponding to Sq (the solar daily magnetic variation on quiet days), over the daytime hemisphere (left) and the night hemisphere (right). (From Chapman & Bartles, *Geomagnetism.)*

At sunspot maximum (active Sun) the currents have a similar pattern, but are more intense, by 50 percent or more. The currents are of less intensity by night than by day, corresponding to the reduced electron density at that time.

5.1.2 The Equatorial Electrojet

The continuous observations of the magnetometer recordings of the daily variation of the Earth's magnetic field at Hunacayo, Peru, began in 1922. It soon revealed that the range of daily variation of the horizontal component at this station, close to the geomagnetic equator, was larger by a factor of about 2.5, compared to that at other equatorial stations several degrees beyond the geomagnetic equator. This indicated a circulating system of electric currents of opposite symmetry in the northern and southern hemispheres. These currents join at the equator to form a strong flow from west to east at 1100 LT. An enhanced eastward current in a narrow belt, centered on the magnetic equator, was first correctly identified by J. Egedal, and the name *Equatorial Electrojet* was given to this phenomenon by S. Chapman in 1951. The equatorial electrojet (EEJ) turned out to be a multifaceted phenomenon and it has been the subject of a variety of scientific studies in the last four decades. Driven by the global E-layer dynamo effect, the EEJ constitutes a current sheet of about 15 km half-thickness near to and below the E-layer electron density peak. This normally flows eastward with the dayside hemisphere in a narrow belt of about 600 km centered at the magnetic equator. Later years brought increasing interest in EEJ studies with the installations of new magnetic observatories at equatorial and vicinity locations at different longitude sectors of the Earth. The electrojet was discovered to reverse its direction westward during certain hours of the day, a phenomenon known as the *counter electrojet* [Fig. 5.2].

The EEJ's intensity is not just what is expected from the confluence at the equator of the north and south Sq current systems, i.e., it was not accounted for by the spherical harmonic analysis of global magnetic data. The International Association of Geomagnetism and Aeronomy designated September 1990–March 1993 as the International Equatorial Electrojet Year. The following figure shows the locations where intensive and co-ordinated campaigns on the EEJ were conducted.

5.1.3 Field-Aligned (Birkeland) Currents

These have a very interesting history. The Norwegian physicist, K. Birkeland, studied the dynamics of the Earth's aurora [See the famous *Terella* experiment in Chapter 6]. His extensive studies of geomagnetic data, recorded during magnetic storms in polar regions, suggested that in 1908 the geomagnetic disturbances recorded on the Earth's surface below the auroral region were due to intense currents flowing horizontally in the ionosphere above. We refer to these now as *auroral electrojets*.

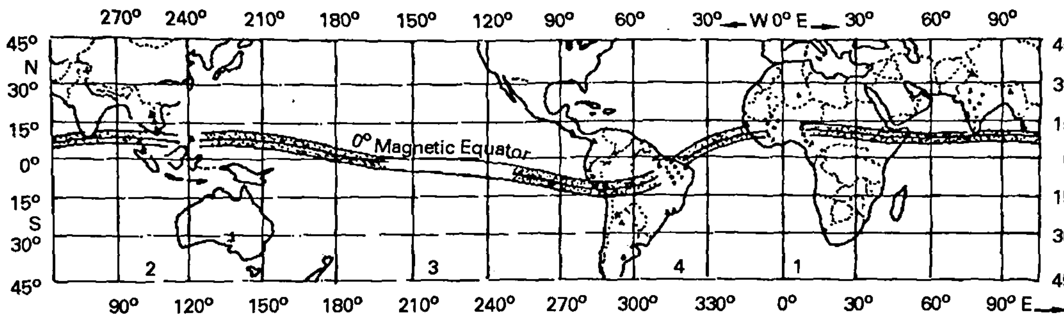


Fig. 5.2 The magnetic equator, with the approximate latitude width (shaded region) of the equatorial electrojet current; also shown are the existing magnetometer locations (Δ) in the equatorial electrojet and its vicinity, as well as those definitely planned (•) and tentatively planned (○) for the International Electrojet Year: September 1991–March 1993. (From M.A. Abdu, *EOS*.)

In Birkeland's words: "We consider it to be beyond doubt that the powerful storms in the northern regions, both those of long duration, and the short, well-defined storms that we have called elementary, are due to the action of electric currents above the surface of the Earth near the auroral zone. These currents, as far as the elementary storms are concerned at any rate, act, in the districts in which the perturbation is most powerful, as almost linear currents, that for a considerable distance are approximately horizontal". [K. Birkeland, 1908] He went on to compute the current strength to vary between 5 00 000 and a million amperes and he determined that the altitude of these currents was located above 100 km. Presently, it is found that Birkeland's values are close to the intensities and altitudes determined from modern-day experiments. Birkeland further made an interesting hypothesis that the horizontal currents were connected to outer space by a system of currents flowing up and down along the geomagnetic field lines [Fig. 5.3].

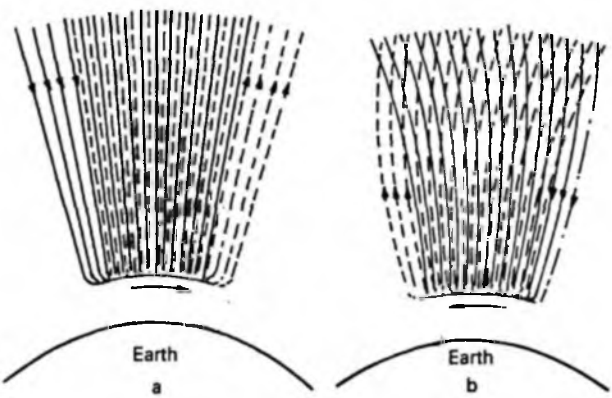


Fig. 5.3 The system of field-aligned currents originally suggested by Birkeland in 1908. Figure (a) represents those in which the current-directions at the storm-center are directed westwards, and (b) those in which the currents move eastwards.(From *The Norwegian Polaris Expedition 1902–1903*, by K. Birkeland, 1908.)

Birkeland's curiosity about the horizontal currents being connected ultimately to the Sun is reflected in his writing: "With regard to the further course of the current, there are two possibilities that may be considered. (1) The entire current system belongs to the Earth. The current-lines are really lines where the current flows upon the Earth's surface, or rather at some height above it. (2) The current is maintained by a constant supply of electricity from without. The current will consist principally of vertical portions. At some distance from the Earth's surface, the current from above will turn off and continue for some time in an almost horizontal direction, and then either once more leave the Earth, or become partially absorbed by its atmosphere."

Birkeland already had his *terrella* experiment results and, stimulated by his beautiful and striking experiments on the movement of cathode rays in magnetic fields. Carl Stormer, a mathematician, made very extensive theoretical studies of the propagation of charged particles in a magnetic dipole field. These experimental and theoretical results led Birkeland to favour his second suggestion. His suggestions, however, evolved into a controversy concerning the current system which was to continue for a quarter of a century. This controversy continued through the 1960s, till satellite data was provided to confirm their existence. The first evidence for the existence of field-aligned currents came in 1966. A magnetometer on board the polar orbiting US Navy navigation satellite launched in 1963, in a 1 100 altitude polar orbit, recorded magnetic field disturbances on nearly every pass of the high latitude region of the Earth. These were carefully interpreted as field-aligned currents, though initially these were thought to be Alfvén waves along the field lines.

Chapman and his colleagues opposed Birkeland's ideas. It appears that this was inspired by Lord Kelvin's remark. He was the President of Royal Society and proclaimed in 1893 that, "the supposed connection between magnetic storms and sunspots is unreal".

Hannes Alfvén was a great supporter of the field-aligned current concept. In 1939, he published an article that incorporated the Birkeland field-aligned current system in the aurora. The ideas put forward by Alfvén in this paper still influence modern space plasma physics.

Now, we understand the Global Current Systems in the Earth's near-space environment, which transfer forces, energy and information into and through the magnetosphere. Electric currents stretch like power lines from the solar wind to the ionosphere, through the body of the magnetosphere, linking every component to a generator. Thus, field-aligned currents play an important role in the dynamic coupling of the magnetosphere and the ionosphere.

5.1.4 Auroral Electrojet: Nightside Auroral Currents

Intense nightside auroral currents of the order of a million amperes, or more, flow in the ionosphere in the auroral oval regions (Chapter 4). These are the auroral electrojets. The ionospheric auroral currents are connected, through magnetic field-aligned currents, to the earthward edge of the magnetotail current sheet. The auroral electrojet appears as an essentially continuous oval band of illumination in the ionosphere encircling each geomagnetic pole; the size of the oval expands very much, nearly up to the equator during geomagnetic disturbances.

The dayside portions of the auroral currents are connected, again via field-aligned currents, to the currents flowing on the dayside magnetopause [Fig. 5.4].

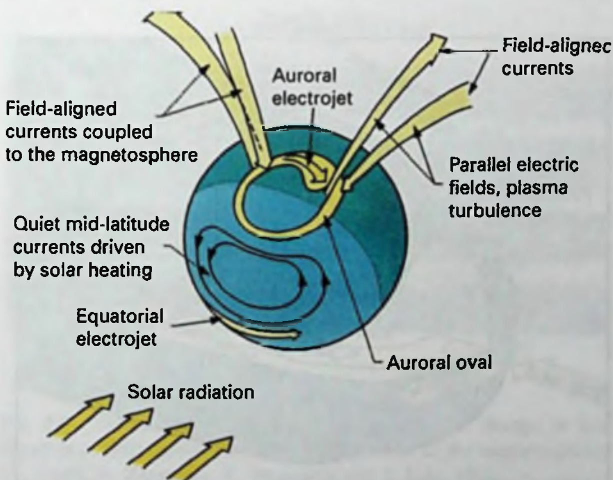


Fig. 5.4 Dominant current systems associated with the Earth's ionosphere.

5.2 Magnetospheric Currents

Magnetospheric currents are produced by the solar wind interaction with planetary magnetic fields, the motion of trapped particles in radiation belts and convection of plasma sheet particles in the tail and ionospheric particles. The dominant current systems in the magnetospheres are illustrated in the figure below [Fig. 5.5]. We shall discuss these in some detail.

5.2.1 Chapman–Ferraro Currents or Magnetopause Currents

Currents with densities approximately of the order of 25–150 mA/m^2 flow along the Earth's dayside magnetopause, and provide for the separation of the Earth magnetic field-dominated regime from that of the interplanetary medium. These arise due to solar wind flow and to the magnetic field undergoing sharp changes across the magnetosphere boundary.

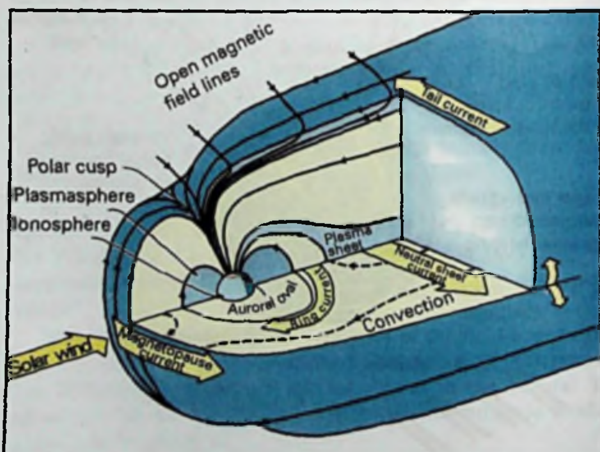


Fig. 5.5 The dominant current systems in the overall magnetosphere.

5.2.2 The Magnetic Tail Currents

As we have already seen (Chapter 2), magnetic tails are a very important region of the magnetic structures as they include neutral sheets and, thus, the merging or reconnection process can take place. The magnetic reconnection and the large-scale circulation of magnetospheric plasma establishes a potential difference across the tail of the magnetosphere. The resulting magnetospheric convection electric field is oriented from dawn to dusk. The currents flow through the center of the magnetotail and close around its boundary. The intensity of the magnetic tail current can be of the order of a hundred million amperes ($\sim 10^8$ A).

The magnetic reconnection and, as a consequence, the variability in the intensity of the cross-tail current depends on the changes in the direction of the interplanetary magnetic field (IMF) (Chapter 4). The eventful variability of tail currents has been shown very vividly in a computer simulation of the magnetosphere with a long tail interacting with southward and northward directed IMF [Fig. 5.6].

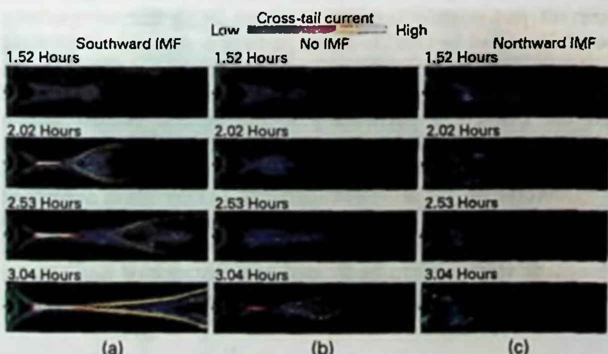


Fig. 5.6 Eventful variability of a tail current with change in the direction of IMF, shown in a computer simulation of the magnetosphere (A. Usadi, A. Kageyama, K. Watanable and T. Sato, 1991)

The shape of the magnetosphere was produced by the flow of solar wind for about 1.5 hours. Once the magnetosphere was formed, the three cases of IMF with different directions were simulated. As seen in the Fig. (a), southward IMF gives the explosive reconnection and plasmoid ('pinched off' plasma sheet) formation and expansion. The cross-tail current becomes very high. In Fig. (b), no IMF is present, the reconnection is a weak process. In Fig. (c), the northward IMF reconnection process is inhibited. The tail current decreases and a long tail is not formed.

The important aspect of the variability of the tail current is that it represents a key feature of magnetospheric substorms.

5.2.3 The Ring Currents

Ring currents are closely associated with magnetic storms (Chapter 4). This current system may exist at all times, but during geomagnetic disturbances it is highly intensified and a global ring current completely encircles the planet above the equatorial ionosphere, flowing in the westward direction. The drift motion of the charged trapped particles is charge-dependent, so the electrons and ions drifting in the opposite direction create a large-scale current just outside the plasmasphere. Ring current particles were identified by satellite-borne particle detectors in 1967. Ring currents can carry several million amperes of current during a moderate sized magnetic storm. These currents can be connected to the ionosphere particularly to the auroral current system through magnetic field-aligned currents; thus, dissipating most of their energy into the polar ionosphere during auroral events.

Interestingly, the inner boundary of ring currents in our planet is found at 4 to 5 R_E equatorial distance, but with increased geomagnetic activity it moves closer, such that during intense magnetic storms it can be located at a distance of just $1R_E$ or roughly 6 400 km above the Earth's surface where we live!

5.3 Electric Currents at the Earth's Surface

Time-varying electric currents in the magnetosphere and ionosphere induce secondary currents in the surface of the solid Earth. These geomagnetically induced currents are commonly known as GICs and can be as high as 100 A. We shall look into details of GIC's affecting the technical systems in Chapter 7.

The other principal sources for induced currents is the lightning in the Earth's atmosphere and atmospheric clear weather electric fields. Statistical studies show that some 2 000 thunderstorms, on an average, are in progress around the world at any given time. Cloud-to-ground lightning discharges typically transfer some 25 coulombs of negative charge from the clouds to the Earth's surface. Locally at the Earth's surface, the peak current in a lightning discharge flowing upward can be a few hundred amperes for tenths of a second. These currents, therefore, as we are aware, can cause destruction to lives, trees or man-made structures in the area in close proximity to a lightning discharge channel.

5.4 Summary of the Dominant Magnetosphere–Ionosphere Current Systems

Chapman–Ferraro Currents or Magnetopause currents generate magnetic fields that push on the geomagnetic dipole, thereby transferring to the Earth the force of the solar wind's impact on the magnetosphere.

Tail Currents magnetically store the energy received directly from the solar wind.

Ring Currents store thermal energy.

Field-aligned Currents transfer energy to and from the ionosphere.

Currents flowing only in the ionosphere trace the path of convection on the ionospheric surface.

6.

Some Interesting Manifestations of Magnetospheric Plasma Dynamics

Nothing is rich but the inexhaustible wealth of nature. She shows us only surfaces, but she is a million fathoms deep.
— *Ralph Waldo Emerson, 1802–1882*

The Sun is a source of energy; especially during the active period of the Sun when the solar energy dissipated into the magnetic storm may be as much as a billion kilowatt-hours (approximately equal to India's energy consumption in a day). Interactions between the plasma and the energetic particles in the presence of magnetic and electric fields, make our space environment a dynamic system. We, living on the Earth, are quite oblivious of the fact that in our vast space plasma laboratory, various kinds of plasma processes are going on every moment of our lives, thus protecting the Earth from all the harmful radiations. However, some of the interesting manifestations of this dynamic activity of the magnetospheric plasma which we can observe on the surface of the Earth, either with or without simple instruments, make us aware of the electricity and magnetism of our space environment. Not long ago these electromagnetic phenomena were associated with supernatural powers but today, as we shall see, we can understand these with reference to our space plasma and magnetic environment.

The geomagnetic storms, a phenomena identified as an intense worldwide decrease (Chapter 4) of the Earth's surface magnetic field intensity, is the most dramatic manifestation of the large-scale magnetospheric plasma dynamics which involves the sudden inward motion of the entire magnetosphere. The transient process related to this dramatic event is the magnetospheric substorm. Amidst all the controversies, there seems to be good physical reasons for scientists to believe that a magnetic storms consists of intense substorms. A magnificent clue to the occurrence of substorms is the Aurora. The association of auroral phenomena to magnetospheric substorms is well established. Interestingly, it was as early as 1745 that Celsius, of Upsala, Sweden, found that auroras are correlated with magnetic disturbances. The appearance of an aurora was so striking and fantastic that it often inspired awe and fear among its beholders and consequently it was explained as a supernatural happening.

Another dynamic plasma process in the magnetosphere which was attributed to some supernatural events is the phenomenon of Whistlers. Whistlers are whistling radio emissions, deriving energy from natural lightning, occurring during thunderstorms and rains. In the following sections, we shall find out what type of electrodynamic processes in our space gives rise to this audiovisual show in nature.

Finally, we will look into the mystery of very small shakings of the huge magnetic system of our planet Earth. The understanding of micropulsations, as these are called, can tell us almost everything important about the system.

6.1 Aurora: The Moving Lights in the Sky

The word *Aurora* means Goddess of Dawn. In Sanskrit, Aurora is appropriately known as Usha, the bright morning. As the name suggests, auroras are spectacular displays of luminous radiation in the arctic sky. The light is so bright that it appears as if the morning has arrived. The auroras occur simultaneously in both the polar regions, with their symmetry defined by the Earth's magnetic field. The northern aurora is known as Aurora Borealis (Northern Dawn). This name was given by Gassendi (1592–1655), a French astronomer and mathematician, after seeing an outstanding display of the aurora in Southern France on September 12, 1621. The southern aurora is called the Aurora Australis (Southern Dawn). The first record of Aurora Australis was by Captain Cook (1728–1779), who saw it on February 19, 1773, when he was in the latitude $57°6'S$ on the Indian Ocean, and he gave it this name. Together, the Aurora Australis [Fig. 6.1] and Aurora Borealis [Fig. 6.2] are named the Aurora Polaris or polar aurora.

Fig. 6.1 Aurora Australis over Antarctica taken by astronauts aboard the space shuttle *Discovery*.

Fig. 6.2 Aurora Borealis (the University of Alaska Geophysical Institute)

From the ground, the aurora appears to be a curtain of light, streaked with rays. The curtain begins at an altitude of several hundred kilometers above the ground, almost ten times the height at which an aeroplane flies. The sheet is less than a kilometer thick, although it extends laterally for thousands of kilometers.

The auroral curtain is streaked with rayed bands and it always displays shimmering undulations. It seems to ebb and flow across the polar sky. This movement led the ancient observers to name it *Moving Lights in the Sky*, perhaps for an Indian reader the best title will be *Flying Sarees in the Sky*!

Why do we not see the aurora in India or, in general, in the tropics? The aurora usually occurs in the high latitudes' sky, mainly between 65° to 80° geographic latitudes (See Auroral Ovals). The visibility of auroral light at low latitudes, as in India, is a very rare phenomenon. There is, however, an interesting historical record that an unusual aurora was observed in the tropics at Bombay, as well as in many other parts of India on February 4, 1872. It was also seen in Egypt and elsewhere and was associated with an equally outstanding magnetic storm.

Historically, auroras have been recorded at least from the time of Aristotle. There are interesting write-ups by the medieval and ancient writers describing auroras in fanciful, superstitious ways. In one write-up it is mentioned as a 'blood-coloured spectacle' and then as a 'terrible potent','a conflagration falling Earthward'. Aristotle himself refers to them as *Chasms* (Chasmata). This may imply that he thought of them as cracks in the dark sky, through which the flames beyond could be seen. Perhaps this was the reason that auroral displays were often seen as portents of disaster or of some great events taking place on the world's stage.

Seeing the flashing lights of the aurora, superstitious people also often explained them as sparks from the clashing of swords. Especially since auroras seen in unusual latitudes are commonly red. This red colour was invariably interpreted as be due to some fire in the north. Fire brigades have actually gone out in search of it! This happened in ancient Rome during the time of Tiberius and even as recently as 1938 in England, when it was thought that Windsor Castle was on fire.

The glorious sight of the aurora has inspired various poetic descriptions also. One of these written by the Russian scientist, Lomonosov, in 1743, gives a very vivid picture of the aurora, as can be noted from a verse in his poem:

"But, where, O Nature, is thy law?
From the midnight lands comes up the dawn!
Is it not the Sun setting his throne?
Is it not the icy seas that are flashing fire?
Lo, a cold flame has covered us!
Lo, in the night-time day has come upon the Earth".

What causes an aurora? From the Greek times, almost up to the very early part of this century, a great variety of auroral causes and associations have been proposed. In early times, associations with shooting stars, earthquakes and then weather were suggested and the causes suggested were vapours, ether, exhalations and electric discharges. It was later imagined that these spectacular displays in the Arctic sky resulted from sunlight refracted rainbow-like, in the atmosphere. The shimmering undulations, they speculated, were caused by the movement of air. Auroral physicists today know that auroras are lights emitted when atoms and molecules in the ionosphere are struck by electrons blowing in from the Sun. These ideas were first proposed by the Norwegian scientists, Birkeland and Stromer, in the early part of this century. The apparent motion of the auroral curtain is caused not by atmospheric turbulence, but by changes in the electromagnetic conditions that propel the electrons; just as a motion on a television screen is a picture created by changes in electric and magnetic fields, that direct electrons from a cathode ray tube onto the screen.

In the case of the aurora, however, we should know what serves as the cathode tube. Where does it get its power supply from? Why does that power seem to fluctuate from time to time, causing the aurora to ebb and flow across the polar sky like colourful flying sarees spread out by a dyer? The connection of the aurora with geomagnetic storms tells us that the aurora occurs due to complicated interactions between the solar wind magnetic field and the magnetosphere. In fact, the solar wind magnetic field on reaching the boundary of the magnetosphere, reconnects with the Earth's magnetic field [Fig. 6.3]. The wind then flowing across the reconnected field lines constitutes a solar-wind-magnetosphere generator, which can generate more than one million megawatts of electric power, the induced voltage being about 20–150 KV. It was indeed reported in 1859, in the early days of telecommunication, that it was possible to operate a telephone system without it being connected to its battery power supplies during the period of intense auroral activity.

Can we not use this huge electrical power supply? It appears to be a very lucrative proposal indeed, but in reality there are many difficulties arising mainly from the huge scale sizes of the geophysical current systems, the violent and varying nature of the power supply and the varied conductivity structure of the Earth's crust. In actual situations, as we shall read later, this geophysical power system instead can wreak havoc on man-made technical systems, creating many problems for communication engineers.

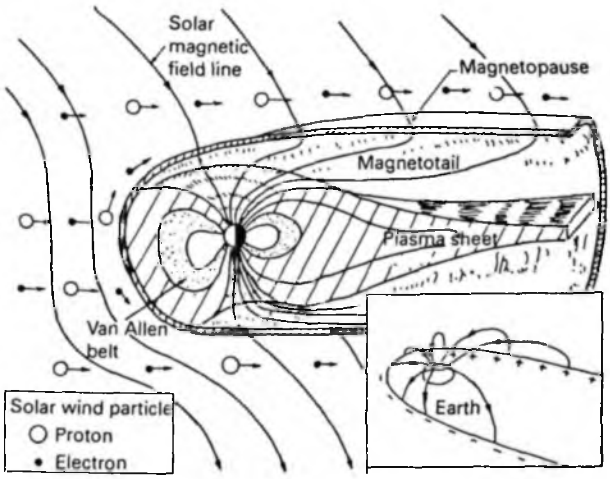


Fig. 6.3 The schematic diagram of the noon–midnight cross-section of the magnetosphere shows some of the solar wind magnetic field lines (IMF), the Earth's magnetic field lines and reconnected field lines. Note that the solar wind particles flow across the reconnected field lines. We see here that the observed interplanetary magnetic field normal to the ecliptic plane is about 2 gammas and the direction has a preference towards the south. This component plays a very important role in the magnetospheric processes. The inset shows the primary discharge circuit powered by the solar wind-magnetosphere generator (after S. I. Akasofu, 1993).

The aurora is associated with a global electrical discharge process powered by the solar wind-magnetosphere generator. So Birkeland (Chapter 3) was not far from the truth! In 1908, Birkeland conducted the historical experiment now known as the *Birkeland Terrella Experiment*. Birkeland simulated the planet Earth by a large spherical magnet suspended in an evacuated box [Fig. 6.4]. The spherical electromagnet was surrounded by a thin crust of brass covered with a coat of barium platinocynamide. He then exposed the terrella to a stream of nearly parallel

Fig. 6.4 Precipitation of cathode rays on a magnetised sphere. From Birkeland's experiments. (*The Polar Aurora*, C. Stormer, 1955)

cathode rays. Birkeland noted that the electron beam directed towards the terrella was guided towards the magnetic poles and produced rings of light around the poles [Fig. 6.5]. He writes, "With the exception of some oscillations, these luminous rings remain stationary in space during the rotation of the spherical electromagnet round its axis but their position greatly depends on the magnetic condition of the sphere." Birkeland also identified the auroral zones [Fig. 6.6]. The ionospheric current system in the auroral region is connected to the magnetospheric current system by field-aligned or Birkeland currents (See Chapter 5). The field-aligned currents control the dynamics of the aurora and are responsible for the curtain-shape of the aurora.

The electric currents flow to and from the northern and southern polar regions, producing basically identical auroral forms. Most of the time, northern and southern auroras are exactly alike and move around in the same way at the same time. This conjugacy was verified in 1967, when scientists found out that the electrons causing both auroras come from the same source, creating simultaneous and often mirror-image auroras in the north and south polar regions. This was shown by using two specially equipped aircrafts which flew in coordinated round trips across the northern and southern auroral ovals. The aircrafts reached conjugate points simultaneously, to record the state of both the northern and southern auroras.

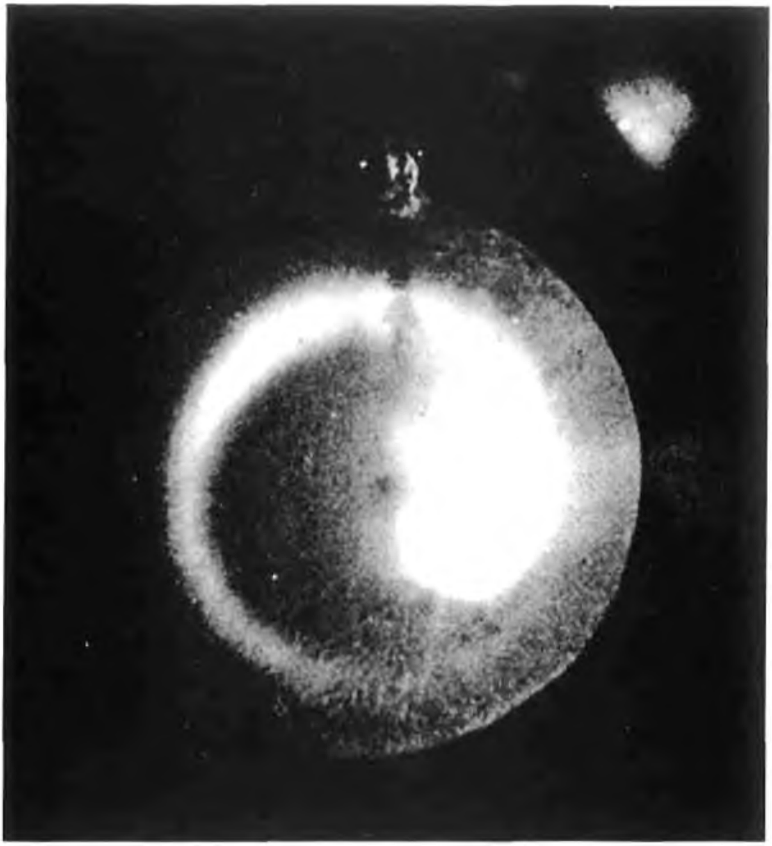


Fig. 6.5 The northern aurora belt. From Birkeland's experiment. The cathode is to the right (*The Polar Aurora*, C. Stormer, 1955).

The next question is, what causes the spectacular colours of the aurora? The potential difference between the aurora and the field-aligned currents accelerate the electrons along the magnetic field lines. This 'rain' of electrons reaches the ionosphere. When atoms and molecules in the lower ionosphere are hit by electrons, radiation is emitted [Fig. 6.7]. Different types of collisions with different types of molecules or atoms give rise to different coloured emissions. The important atoms and molecules are oxygen and nitrogen. When oxygen and nitrogen atoms are hit by energetic particles, they are excited and ionised. They then give off light at characteristic wavelengths as they return to their ground states. A greenish-white emission is emitted by oxygen atoms between 110 and 250 km upwards. A rather steady, red glow is produced when oxygen atoms are hit by less energetic particles some 300 to 400 km in altitude. Nitrogen atoms also give off a green coloured emission, but with a much wider distribution. Ionised nitrogen molecules produce blue light; neutral nitrogen molecules create purplish-red lower borders and ripple edges.

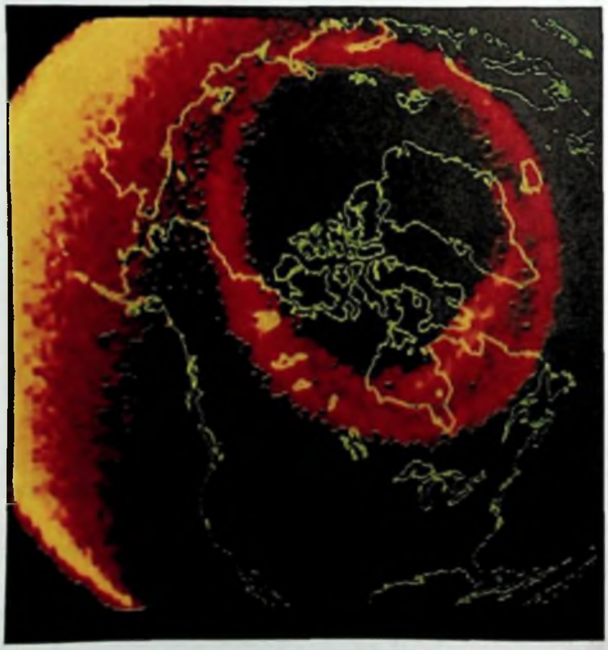


Fig. 6.6 Auroral oval from space: The false-colour image shows the complete auroral oval in the northern hemisphere. The image was made in ultraviolet light by University of Iowa Instrumentation on the *Dynamic explorer* satellite in November, 1981. The sunlit face of the Earth is on the left (after L.A. Frank, J.D. Craven and R.L. Rairden, 1985). Compare this with Birkeland's Terrella Experiments.

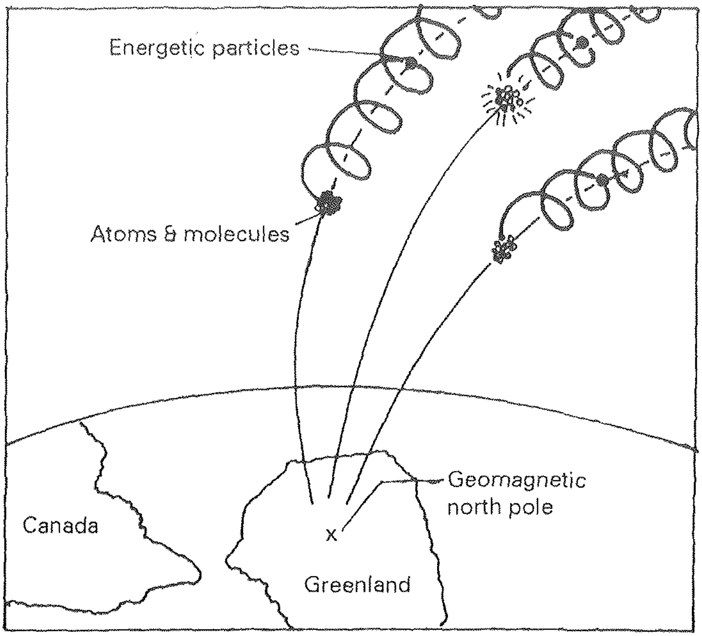


Fig. 6.7 The spectacular colours of the aurora are caused when energetic particles, particularly electrons, rain down along the Earth's magnetic field lines and produce the different auroral emissions on interacting with the molecules of atmospheric gases.

There is intense flux of KeV electrons in the magnetosphere during substorms which produce a brilliant auroral display on collision with the atmospheric atoms. Now, we can understand the association of geomagnetic storms and auroral displays.

Throughout a single night, the auroral display varies in intensity and form due to occurrence of auroral substorms, a consequence of substorms (Chapter 4). The auroral substorm is an intermittent surge of auroral activity, arising due to electromagnetic disturbances in the magnetosphere. The lifetime of such an intermittent activity is about 2 to 3 hours. Several substorms occur in a day during a fairly active period. The first sign of a typical auroral substorm is the sudden brightening of the auroral curtain in the midnight sector. The brightening rapidly spreads westwards and eastwards until, after about ten minutes, an auroral curtain in the entire dark hemisphere brightens. A westward travelling surge then propagates westward and the auroral curtain develops a large-scale fold, making it by far the most spectacular display that can be observed from the ground. At the same time, auroras in the morning sector appear to disintegrate into many rays. This activity lasts for about 2–3 hours, and the aurora all along the oval becomes quiet till an auroral substorm occurs again.

After a major solar flare on the Sun, the associated solar wind is intensified and also carries a stronger solar wind magnetic field. The auroral substorm is caused by a ten-fold increase of power of the solar wind–magnetosphere generator, from about 0.1 million MW during a quiet period to a speed of 1 million MW for a few hours. Such an increase in power will cause stronger global discharge currents and brighter auroras. Actually, an average of about one to ten percent of the solar wind energy flowing past the Earth gets injected into the magnetosphere.

Let us look into an aurora watcher's day during a period of solar activity. From late evening to the early morning hours, an aurora watcher will observe successive auroral substorms. Between seven and ten o'clock, in the early evening the aurora appears as an *arc*, an uniform strip of light stretching from one horizon to the other. Later in the evening, if a substorm happens to occur, the auroral form becomes more active and it develops line-folds and is called a *rayed arc*. With more intense activation, larger scale folds are superimposed on the rayed arc form, and such an active form is called a *rayed band*. In the most activated form, a fold of scale of the order of a few hundred kilometers develops. After midnight, the aurora often becomes quite different. From being active and filling the entire sky, it seems to almost disappear, except for a white or pale green colour throughout the sky. Then, patches of light slowly start to appear. They often look like puffs of smoke or fluffy clouds. These patches usually blink on and off in a regular pattern ranging from one or two seconds up to half a minute. They are called the *pulsating aurora*. Sometimes, toward morning the patches disappear and long auroral rays will appear. Later, as the Sun rises, the aurora can no longer be seen because it is dimmer than the daylight. During the day, the aurora also moves so far to the north, that even if it were visible, it would only be in uninhabited areas.

For thousands of years, and even today, there have been reports from people about hearing the aurora. Several different sounds have been reported, but most are described as a very quiet swish or a faint crackling. These sounds have usually been heard during the time when the rayed bands move rapidly overhead.

The scientists are puzzled by these reports, because the air ninety kilometers above the Earth is much thin to carry sound. Yet, reports describing these sounds continue to come. But all attempts to record them have failed till now.

Why do we study the auroral phenomena? Is it only to satisfy our intellectual curiosity to understand the spectacular and beautiful patterns in the polar sky? No doubt the understanding of the auroral physical process has enriched the subject of space physics, but these studies have practical applications also. In this space age, there are many man-made satellites orbiting around the Earth. During the high auroral activity, radio and radar waves are frequently distorted or absorbed (they cannot propagate because radiowaves propagate over long distances by bouncing off the ionosphere). The auroral discharge can give false commands to a satellite orbiting in the area of the aurora. At least one satellite has been known to be lost due to such an event. The current storms can also produce surges of electric current in power lines that leads to power failures. The auroral study, therefore, plays an important role in understanding the effect of natural phenomena on the man-made technical systems on Earth. We shall read more about this later.

The geomagnetic nature of the aurora is now well verified by the observations of auroras from outer space. It is now understood that the presence of three elements, the solar wind, the magnetic field and the atmosphere of a planet or its satellites, are needed to create the aurora. We have the following cases to test this fact. All the planets are exposed to the solar wind. Mercury has an Earth-like magnetic field, but no atmosphere. Thus, there is no aurora. Both Venus and Mars do not have a detectable magnetic field, and there is no aurora on either planet. The Moon has no magnetic field, no atmosphere to speak of and thus no aurora. Jupiter has a very strong magnetic field and an atmosphere consisting mainly of hydrogen. Since Jupiter is much larger than the Earth, the Jovian Auroral Oval is much larger than Earth's. The Jovian Aurora is visually pinkish or magenta, resulting from hydrogen atom emission. Saturn also has an intense magnetic field and an atmosphere. Although there has been no opportunity to image the aurora on Saturn, there are some indications of auroral activity there. Both Uranus and Neptune have a magnetic field and an atmosphere. The aurora on Uranus was imaged by the *Voyager* spacecraft.

6.2 Whistlers: Whistling Radio Signals from Space

Let us go back into the history of communication. In the first half of the nineteenth century, long-range conductors were coming into use for telegraphic poles with a long wire attached to the receivers forming a part of the equipment at various government and post offices. At mid-latitudes, especially during thunderstorms and at night-time, it was not uncommon for the operators to hear queer whistling tones. Historically, the first such signal was heard in 1859, by George B. Prescott, a telegraph operator at Boston, U.S.A. It was a puzzle. The tone was very distinctive and was not due to any local effects or disturbances in the equipment, as these tones had a very distinctive and repetitive character. An interesting observation was reported by the physicist, Heinrich Barkhausen, in 1919, during World War I. He was supposed to listen to and report the enemy conversation on the other side of the line. With his equipment, which could pick up weak electric currents leaking into the ground from the Allied telephone wires, he occasionally heard curious whistling sounds which completely swamped the military chatter. He first thought that these whistles probably originated in his apparatus, but when all his attempts to eliminate these failed, he was very impressed with this phenomena. He wrote "A very remarkable whistling note 'pious' is heard in the telephone." At the front, soldiers say that one hears the 'grenades fly'. These queer repetitive sounds and their association with thunderstorms especially on stormy nights made people imagine that these sounds came from beings on Mars or with 'Flying saucers'. The *Los Angeles Times* had a regular column reporting experiences of people about these voices. A clearer scientific understanding of the phenomenon has come with the dawn of the satellite age. These unusual sounds are now understood to be induced in the receiving apparatus by radio signals in the audio or VLF (Very Low Frequency, 300–30 000 Hz) range originating due to strong lightning discharges in the atmosphere.

The radio signals in the audible frequency range which 'whistle' are now known as *whistlers*. The whistlers are closely associated with lightning as these derive their energy of propagation from the lightning source. There are some VLF noises similar to whistlers called VLF emissions. These sounds which are also heard by telephone operators are very unusual: some sound like a multitude of birds waking up in the morning and is called the 'dawn chorus', others include hissing sounds called the 'hiss', roaring sounds called 'roars', sounds of rising tones called 'risers'. These VLF emissions are less understood and, though related to whistler phenomena, have different energy sources and properties.

Though whistlers have been studied since 1894, serious interest in this field started only from 1951, due to the development of precision equipment for spectrum analysis — the sound spectrograph developed for the study of speech and noise, and the magnetic tape recorder which was brought to a high level of performance after World War II. Whistling radio sounds are heard on a telephone receiver, since the telephone line or cable acts as an antenna, and the telephone receiver converts the weak electrical currents into sound waves. Though whistlers can be heard by the human ear, the frequency of these waves is very low and falls below the lowest broadcasting frequencies so one cannot hear these on our ordinary radio sets.

The modern equipment used for observing whistlers is basically the same as that used originally. It consists of a single-turn loop antenna connected to a high-gain, low-noise, wide-band audio amplifier. The output is recorded on magnetic tape, the spectrograms being produced by standard techniques. Some markers are added from a local clock or from a radio station. Networks of whistler stations of this general design are scattered all over the Earth to provide data on the geographic variation of whistlers and other related phenomena.

The phenomenon of whistlers is now fairly well understood. When lightning strikes at a point A on the Earth's surface, a part of the radiated electromagnetic energy is refracted upwards into space. There is a tendency for ionisation in the magnetosphere to form columns along the magnetic lines of force. The upward directed wave energy of the whistler mode is guided along these columns or 'ducts' [Fig. 6.8]. The wave propagating along this duct reaches the point B which lies along the same magnetic field line as the point A, but in the opposite hemisphere (the magnetic conjugate point). A ground-based whistler station situated at or near this point receives and detects the energy propagated through such ducts. The wave, however, suffers dispersion; that is, different frequency components of the wave travel with different velocities as it propagates through the magnetospheric plasma. This dispersion is caused by interaction with free electrons: higher frequencies travel faster than the lower ones. Since the impulse from the lightning discharge excites all frequencies simultaneously, the characteristic whistler signal at the end of the path consists of a gliding tone in which the higher frequencies arrive first at the detector [Fig. 6.9].

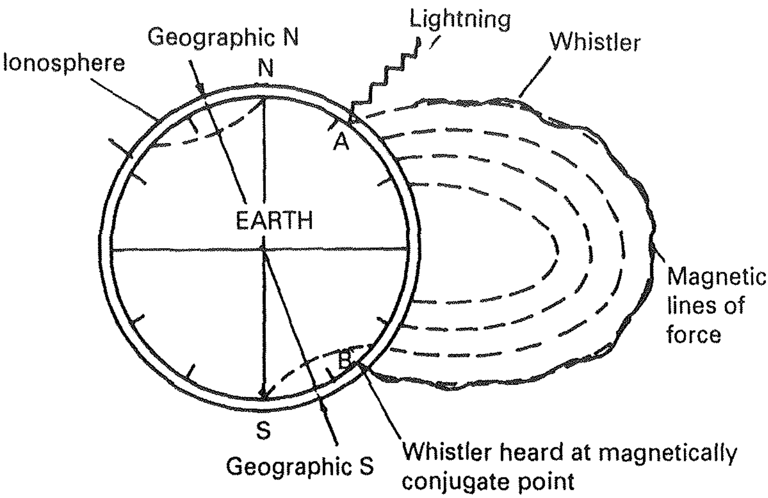


Fig. 6.8 Field line path followed by a ducted whistler.

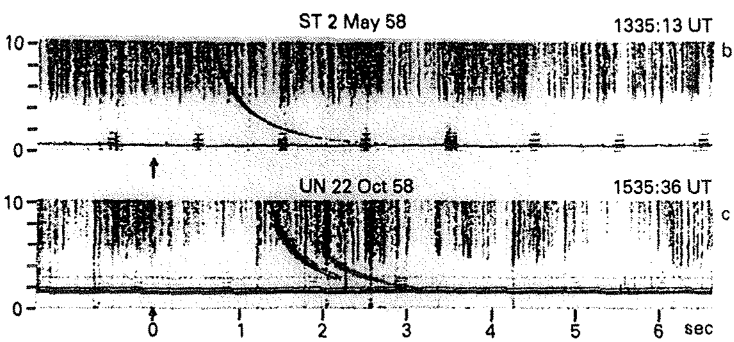


Fig. 6.9 A ground-based recording of the frequency-time spectrum of whistlers.

In recent years, in order to avoid interference with air-traffic and other noises, a quiet site which has become very important for measurements and study of whistlers is the Siple (named in honour of American Geophysicist Paul A. Siple, in recognition of his great contributions to science in Antartica) station at Antartica, located at the base of the Antartic peninsular. It has a powerful (100 KW) transmitter [Fig. 6.10]. Besides being a very quiet electromagnetic site, the choice of this continent of ice-sheet is very important as it is situated at the average position of the plasmapause, a critically important boundary in the magnetosphere. It affords the opportunity to make ground measurements at the magnetic foot-point of the field lines that probe from inside the plasmasphere to the geomagnetic pole. Another important reason for the choice of this place is that the magnetic conjugate point to the transmitter is readily accessible. The location of the Siple station has important conjugate locations at Roberval, Girardville, La Tuque, Lake Mistassini, Quebec, Canada and Pittsburg, Durham, Newhampshire, U.S.A.

Being dependent on lightning, whistlers are more frequent at locations and times where electrical storms are common,

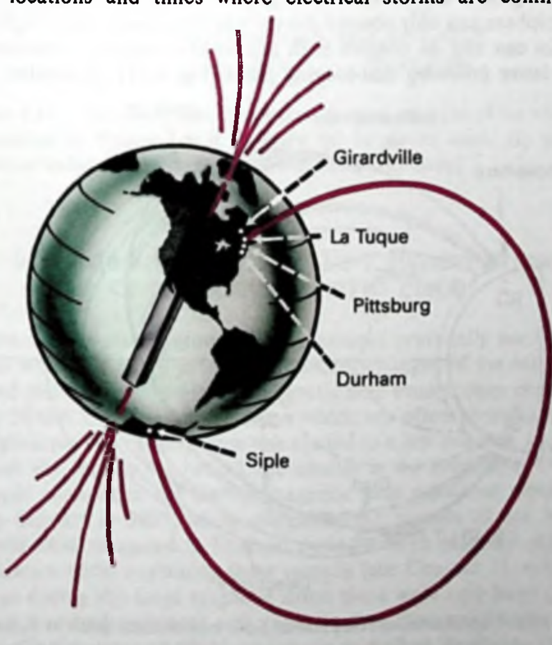


Fig. 6.10 Siple Station, Antarctica, and the conjugate locations.

or at points magnetically conjugate to the regions of lightning activity. They also tend to be more common during the night, mainly because of their relatively high absorption in the daytime ionosphere. Studies of ducted whistlers indicate that whistler activity is mainly confined to the middle latitudes, reaching a maximum in the vicinity of fifty degrees geomagnetic latitude. In the polar regions, their rate is significantly lower, and at the geomagnetic equator, where there are no ducts, whistlers are virtually unknown. However, some low latitude whistlers have been observed in India at the Gulmarg and Nainital stations. The propagation mechanism of these non-ducted whistlers is now under investigation.

With the recent advances in space technology, it has become possible to observe whistlers within the ionosphere. The first such observation was made with the satellite *Vanguard III* in 1962. While ground-based stations in general, and satellites near the ionosphere can only observe ducted whistlers, satellites in higher orbits can and do observe both ducted and unducted whistlers, the latter following non-looping paths [Fig. 6.11]. A satellite is

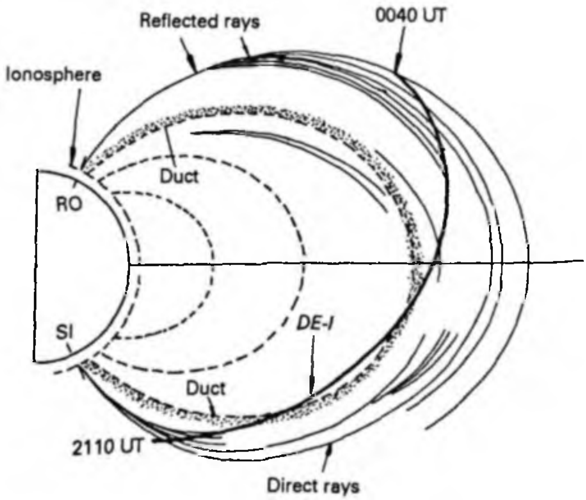


Fig. 6.11 Simultaneous reception of Siple transmitter signals at Roberval (conjugate to Siple station) and on the *DE I* satellite (after D.A. Gurnentt and U.S. Inan, 1988).

also capable of detecting a whistler twice between its traverses of the equator, once as it crosses the equator on its journey to the reflection point and once as it returns to the equator from its reflection point.

Are there whistlers on the other planets of our solar system? The data obtained by the spacecrafts *Voyager I* and *II* showed that there is a great deal of whistler activity in the Jupiter, Saturn, Uranus and Neptune magnetospheres [Fig. 6.12].

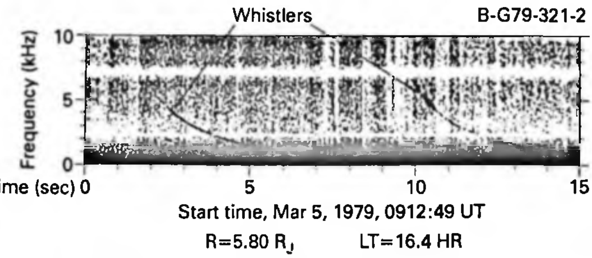


Fig. 6.12 Frequency-time spectrogram showing examples of the whistlers detected by *Voyager I* as it traversed the Io plasma tours. R_J is the Jovian radius (courtesy: D.A. Gurnett, Iowa University).

6.3 Micropulsations: Tiny Fluctuations of the Geomagnetic Field

Instruments on the ground have measured practically every day, for well over a 100 years, the transient changes in the intensity and direction of our planet's magnetic field smaller than one part in 50 000. Such tiny fluctuations, which are often periodic, have typical periods ranging from one second to a few minutes. In general, the shorter the period, the smaller is the amplitude. These rapid changes in the Earth's magnetic field were first reported by Stewart in 1859, while examining the records of the magnetic field measured in England during a large magnetic storm. Stewart, while examining these records (see Chapter 3), noticed that during this large magnetic storm there were very large (several hundred gammas) and rapid (a few minutes) changes in the Earth's magnetic field magnitude as well as direction. These fluctuations are called *micropulsations*.

In 1942, when Prof. Hannes Alfvén discovered the Alfvén Waves (Chapter 2) in conducting fluids in the presence of the magnetic field, little did he realise that these waves are an ubiquitous phenomenon in the space environment of our planet Earth, just 10–14 R_E distance away. Micropulsations are hydromagnetic waves in the frequency range from just above 1mHz or 0.001 Hz to the local proton gyrofrequency, about 1Hz. In this range, the ULF (ultra-low-frequency) band magnetic signals are commonly called geomagnetic pulsations as these arise due to the sinusoidal (periodic) low frequency oscillations of the Earth's magnetic field. Micropulsations were first observed with magnetometers on the Earth's surface and, in the last twenty years or so, placed on Earth-orbiting and interplanetary spacecrafts. They are observed during both quiet and disturbed geomagnetic conditions. The amplitudes of geomagnetic pulsations are of the order of a fraction of a gamma to several tens of gammas. Some pulsations are very periodic (called continuous pulsations P_c), while others are irregular (called irregular pulsations P_i). The geomagnetic pulsations are classified by periodic and characteristic features (continuous or irregular) as P_c 1-5 and P_i 1-2.

We can say that micropulsations are persistent, very small shakings of the whole magnetic field system of our planet. Looking at the magnetometer recordings (see the figure below), we see that they are neither spectacular like geomagnetic storms nor exciting like Whistlers or VLF (very low frequency) waves. Then why are these interesting to study? On realising that it takes a tremendous amount of energy to keep the huge dipole magnetic field system vibrating this way day after day, we are immediately curious to know about the source of energy required to vibrate these huge systems and the mechanisms required to excite the periodic vibrations. The basic scientific philosophy being that if you understand how a system shakes, you can know almost everything important about the system. The pulsations are, therefore, diagnostic tools to understand the complex magnetospheric plasma dynamics.

In 1957, to explain the long-period ULF waves, James W. Dungey proposed that micropulsations are generated by the Alfvén waves in the magnetospheric plasmas. By the 1960s, some ground experiments at each end of a magnetospheric field line had established that many micropulsation signals appeared to have a standing Alfvén wave structure along the dipole field lines of the Earth [Fig. 6.13]. Spacecraft measurements further verified the existence of standing Alfvén waves along field lines, thus confirming Dungey's idea and also providing an indirect experimental evidence of the existence of Alfvén waves in the magnetosphere. How are these waves excited? The flow of the solar wind plasma along the magnetospheric boundary gives rise to surface waves along the magnetopause, just as the wind blowing across the sea ruffles the ocean surface, These surface waves in turn propagating into the magnetosphere interact with the Earth's dipole magnetic field, exciting the standing Alfvén waves along the field lines. The micropulsations are thus manifestations of the interaction of the magnetospheric surface disturbances with the Alfvén waves, along the Earth's magnetic field.

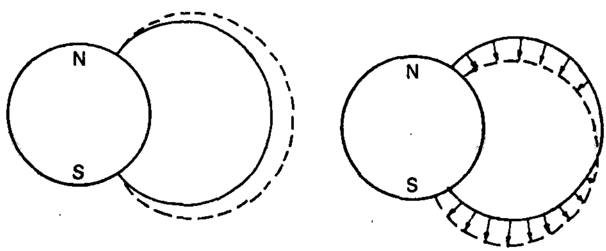


Fig. 6.13 Standing waves in the dipole magnetic field.

Micropulsations are now widely used to diagnose the condition of the magnetosphere and even, to some extent, the solar wind. The latter application is possible because wind conditions strongly influence the surface waves that are excited along the magnetopause and propagated in the magnetosphere. The transmitter at Siple station used for whistler study is also used to study the micropulsation signals.

7.

Impact of the Earth's Near Space on Technological Systems

"There are some who question the relevance of space activities in a developing nation. To us, there is no ambiguity of purpose. We do not have the fantasy of competing with the economically advanced nations on the explorations of the Moon or the planets or manned spaceflight. But, we are convinced that if we are to play a meaningful role nationally, and in the community of nations, we must be second to none in the application of advanced technologies to the real problems of man and society, which we find in our country".
— *Vikram A. Sarabhai, 1919–1971.*
(Progenitor of Indian Space Endeavour)

Let us go back in time to the year 1859 and take a look at the events (Chapter 4) occurring in our space environment. In that year, precisely in the month of September, Carrington saw and recorded the first solar flare on 1 September. Stewart observed violent magnetic storms a day or two later, intense auroral displays were seen from the tropics (a rare display) during this period, and at the same time telegraph operators commented that it was possible to operate the telegraph system without the battery supply. In the latter case, the potential drops generated by the (observed) aurora provided sufficient power (Chapter 6). It was also in this year that for the first time, a whistler signal was reported to be interfering with radio communications. The influence of geomagnetic disturbances on long, man-made, Earth-based conductors such as telegraphic lines, have thus been observed for well over a hundred years. With the introduction of the new types of long conductors such as transoceanic and transcontinental cables, oil pipelines and long-haul power transmission lines, it has become necessary to understand the detrimental effects of the induced currents in these conductors. These currents are produced by the now fairly well understood, wave and current systems of the ionosphere and the magnetosphere.

In the earlier part of this century, we began to realise that it is the existence of ionospheric plasma (Chapter 2) which made wireless transmissions over large distances successful. The whistler signals propagating in the magnetosphere and causing the disturbances on communication systems had become obvious since the experiences during the First World War. Scientists today know that drastic changes in the ionospheric conductivity and electron densities can occur during the disturbed conditions in the magnetosphere, which subsequently affects the radio communication systems over large portions of the globe.

With the dawn of the space age, man has begun to realise the need to utilise larger portions of space around the planet Earth. The progress in space technology has made it feasible to place various sophisticated space systems with applications for the benefit of mankind and society. There are communications and navigational satellites which have revolutionised the world in which we live. As the balloonists use to speak about their 'bird's eye view' of the Earth, the astronauts get what is termed as 'God's eye view'. The remote sensing satellites give us this view of the Earth from above which means that we get a better idea of how to manage the Earth's land resources like agricultural crops, forest products, water resources, minerals, wildlife, as well as its recreational and environmental resources. Better monitoring will enable us to manage all these resources more wisely in the future. The design, development and operations of all these space systems depend on up-to-date knowledge of the impact of physical processes in space on these systems. Considerable research is going on to understand the effect of the Earth's magnetic environment, both from ground-based and space-based technologies. To give a flavour of these problems, we shall provide some interesting examples which are found in scientific literature, regarding the effect of natural electric and magnetic processes in man-made technical systems.

7.1 Long Conductors

The earliest, widely reported examples were communicated by various telegraph operators working in north-eastern U.S.A. and in Europe during the large solar disturbances of August–September, 1859. Mr. Prescott, the now-familiar operator in Boston who had heard the first whistler signal (Chapter 5), reported that the telegraphic lines running out of Boston were rendered inoperative for long periods of time. During other intervals, it was possible to operate the telegraph system without it being connected to its battery power supply; the potential drops generated by the (observed) aurora were sufficient. The geomagnetic storm was of such severity that even during local daytime (when the optical aurora was not visible), the telegraph operator commented that the increase and decrease in auroral surges appeared to coincide with the increase and decrease in the induced currents on the telegraphic line. The periodicity of these variations was estimated to range from 30 sec to several minutes.

The problem of electromagnetic induction on long-range conducting systems by geomagnetic disturbances persists to this day. Research on how to ameliorate the worst effects of geomagnetic disturbances on long conductors, and on the relays, amplifiers, repeaters and other components connected to them, continues to be a major area of study. The basic cause of the disturbances on conductors arises from the scale sizes of geophysical current systems (Chapter 5), and the varied conductivity structure of the Earth's crust. Large voltage differences induced on the Earth can exist across the length of a conductor. The association between geomagnetic storms and disturbance of cable communications systems has been observed for many years. The highly variable (in both amplitude and tone) geomagnetic field during magnetic storm conditions induces Earth currents and, thus, the Earth surface potentials across the length of a cable. These induced voltage drops in a conductor grounded at large separations can produce disruptions of the cable relay powering system. The 'great' geomagnetic storm of March 24, 1940 was reported to have rendered inoperative 80 percent of all long-distance telephones out of Minneapolis, Minnesota, in the U.S.A. During another 'great' geomagnetic storm on 10 February, 1958 (nearly a 100 years after Carrington's discovery) the Bell system transatlantic cable from Clarenville, Newfoundland to Oban, Scotland, had induced voltages estimated to be about

2650 V [Fig. 7.1]. Although the cable system was never totally inoperative, the effect of time-varying Earth potentials was to have voices transmitted in the eastward direction as alternatively loud squawks and faint whispers, while the west-bound signal strengths remained near normal. A geomagnetic latitude effect was clearly evident in that no major voltage swings were observed on the San Fransisco-Hawaii cable, the route of which is at a lower geomagnetic latitude than the route of the Atlantic cable.

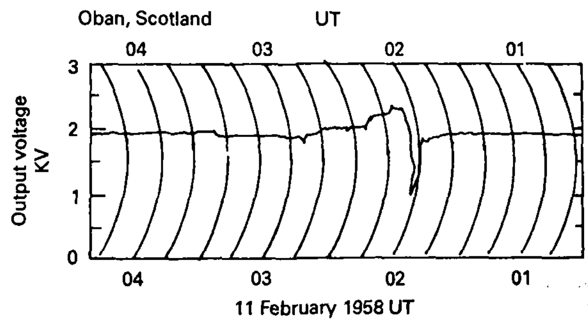


Fig. 7.1 Geomagnetic storm induces cable voltage: Output of power-feed equipment of the Oban, Scotland–Newfoundland cable. The voltage variation in North America was somewhat larger, leading to a total variation of about 2 700 V.

A detailed analysis of an outage of a transcontinental cable during the 4 August 1972, magnetic storm showed that potentials as high as 7 V/m were induced along a cable route from near Chicago to northern Iowa. The analysis of ground-based and satellite data indicated that an ordinary auroral current system was not the principal cause of the induced ground potentials in the U.S.A. Rather, the large magnetopause currents associated with the significant compression of the magnetosphere at the time of the cable disruption seems to have been the external cause.

The magnetic field changes observed in the area of the cable disruption were employed in a model calculation, to estimate the potential difference along the route between relay power stations. It was found that the surface potential drop exceeded by at least 10 percent the Earth-potential design limit for the system. Though such disruptions have been infrequent in the past few years, due to increased system design margins and the phasing out of ground return cable systems, the uncertainties in the knowledge of the scale sizes of large geometric disturbances does not allow the scientists to be as yet absolutely confident of having eliminated the geomagnetic induction problem from potential cable communication disruptions.

One magnetic-induction problem that has received relatively little attention is the general question of the generation of low levels of 'noises' on communication cables by geomagnetic activity. Much attention has been directed to the effects of total outages, as discussed above. However, fluctuations in the geomagnetic field can generate fluctuating currents that produce noise in cable systems. For audio transmissions, such low levels of noise may not be objectionable. For digital transmissions concerned with data communications, however, such noise may at times produce an unwanted error rate. It appears that further research is needed in this direction.

A pipeline represents another form of a long conductor that can be affected by induced currents from natural geomagnetic activity. There does not seem to be a severe corrosion problem on present-day pipelines from induced currents. Rather, the induced currents are more of a nuisance, as they interfere with normal pipeline corrosion surveys.

The effect of auroral currents on the Alaskan pipeline, which extends for 1 300 km in an essentially geomagnetic north–south direction, is under study. These currents probably severely affect pipeline monitoring and control electronics. Large transient currents can greatly disrupt, or even prevent, corrosion surveys of the pipeline.

7.2 Power Systems

The August 1972 geomagnetic storms also produced disturbances in power distribution systems. For example, the failure of a 230 KV power transformer at the British Columbia Hydro and Power Authority was attributed to the storm. Such power system disruptions have been well-documented in the past. For example, during a magnetic storm in 1958, Toronto, Canada, was plunged into a temporary blackout because of the tripping of circuit-breakers in the Ontario transformer station.

In March 1989, a severe geomagnetic storm affected power systems in North America and Scandinavia. Quebec, a city of six million people, went without power for nine hours.

Why are the power systems affected during geomagnetic disturbances? One serious problem is that of the current induced in the winding of power transformers. This can be understood by looking at the recordings in Fig. 7.2. The variations in the magnetic field that constitute a geomagnetic disturbance, induce

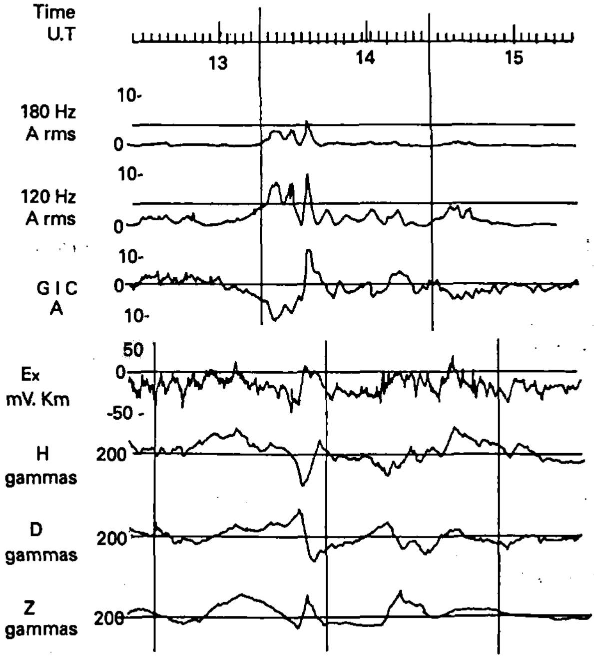


Fig. 7.2 Illustration of the effect of the geomagnetic storm on the power systems. Variations in the magnetic field (shown by components H,D and Z) induce electric fields, E_x, in the ground, these drive GICs into a power system. The GICs flowing through power transformers produce currents at 120 Hz and 180 Hz and higher harmonics of the power system frequency which, in extreme cases, can lead to power blackouts. (The recordings were made on the B.C. Hydro Power System in 1979, by the B.C. Hydro and Power Company and scientists from the University of British Columbia.)

electric fields in the Earth and in the power system. These geomagnetically induced currents (commonly known as GICs), which can be as high as 100 A, flow into the ground through the power system transformers, where they produce their own magnetic field inside the transformer core. This shifts the magnetic field variation produced by the alternating current and the combined magnetic field, produced every half-cycle, when the fields add together and can saturate the transformer core. This saturation can produce fluctuations in the distribution system voltages and intense localised heating of a transformer itself. This local heating can greatly shorten the lifetime of a transformer and may eventually lead to the collapse of the system. Or shall we say, the system is "gone with the solar wind"!

7.3 Radio Waves

The distress calls for a small plane crash in West Virginia in February 1979, heard thousands of miles away in Orange County, California, caused considerable confusion in the local civil emergency procedures of West Virginia. This incident was reported as 'sunspots playing tricks with radios' in the *Los Angeles Times* on 13 February 1979. It was indeed a trick played by the Sun. The increasing solar activity and the disturbed conditions of the magnetosphere substantially alter the ionisation levels in the ionosphere, which in unpredictable ways and for various lengths of time, produce anomalous long-path propagation of signals which are intended to be only local. A very interesting study correlating the strength of the transatlantic transmission signal and the number of sunspots was made for the years 1915–1932 [Fig. 7.3]. The yearly average intensities in the daylight signal curve were derived by averaging the observed values from some ten European stations, broadcasting in the frequency range between 15 and 23 KHz, after reducing them to a common base (a signal from Nauen, Germany was used as the base). The yearly sunspot numbers for the same year were plotted and a relationship between the two quantities is clearly seen, so the sunspots do play tricks with radio communication systems.

7.4 Space Systems

We have already noted in the introductory chapter that historically the first artificial satellite *Sputnik I* was launched in October

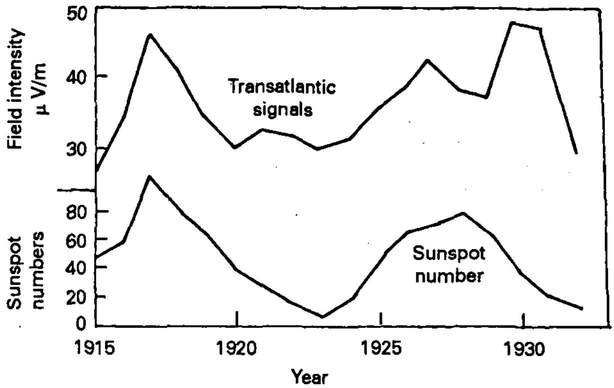


Fig. 7.3 Yearly average daylight transatlantic transmission signal strengths and monthly average sunspot numbers per year for the period 1915–1932.

1957 by Soviet Russia. However, the first active satellite in geosynchronous orbit was launched by the U.S.A. in February 1963 and was called *Syncom I*. The first geostationary satellite to be successfully tested for communication capabilities was *Syncom III*, in 1964. Excellent television pictures of the opening ceremonies of the Olympic Games held in Japan in October 1964 were received in United States via *Symcon III*, and several successful transmissions of short duration were made on subsequent days.

What is a synchronous satellite? A satellite moving from West to East with a twenty-four hour circular orbital period is said to have a synchronous orbit or is a *synchronous satellite*. In the special case where the orbital plane of the synchronous satellite is the same as the Earth's equatorial plane, the satellite is referred to as *geostationary*, i.e., stationary with respect to the Earth [Fig. 7.4]. If the synchronous orbit is inclined to the equator, the satellite will appear to move back and forth following a figure-eight path in a north–south direction. The range of apparent motion increases with the angle of inclination. Synchronous and particularly geostationary satellites have important applications in intercontinental communications, and possibly also in meteorology. Interestingly, the original suggestion that an Earth satellite might be used for radio broadcasting was made in 1945, nearly fifty years ago, by Arthur C. Clarke, a pioneer of the British Interplanetary Society. He proposed placing three manned space stations, carrying the required equipment, in synchronous equatorial, i.e., geostationary, orbits, so that the broadcasts could cover all the Earth except for small regions near the poles. Now, we know such communication satellites do not require the presence of man. With progress in space technology, more than fifty satellites spread over various longitudes are flying in the geosynchronous orbit. The future plans of various nations to utilise the Earth's space environment predicts an even heavier population of satellites in orbit.

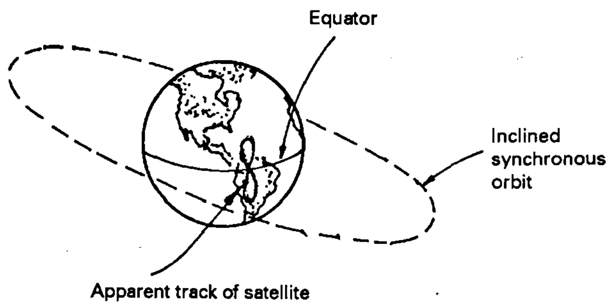


Fig. 7.4 Apparent path of synchronous satellite with its orbit inclined to the equator.

To understand how the space environment affects the satellite placed in it, let us look at the most utilitarian synchronous orbital location which is at an altitude of approximately 6 R_E above the surface of the Earth. This location as it appears, forms a fascinating space plasma physics laboratory. The plasmapause, the extraterrestrial ring current, the boundary of the zone of trapped energetic particles and the earthward terminus of the magnetotail plasma all meet and interact near this location. There cannot be a better laboratory for the study of dynamics and interactions of plasma with vastly different temperatures and densities. This variability, which provides interesting problems to scientists, causes significant headaches to space system designers. The synchronous satellite encounters charged particles with vastly different energies as it can be orbiting in the plasmasphere, or in the trapped particle regions, or in the plasma sheet environment.

The trapped energetic electrons are the major cause of radiation damage to solar cell arrays as well as to semiconductor devices contained deep in the interior of a spacecraft. For example, a typical solar cell array of a spacecraft loses a few percent of the original power output per year of exposure [Fig. 7.5]. The low

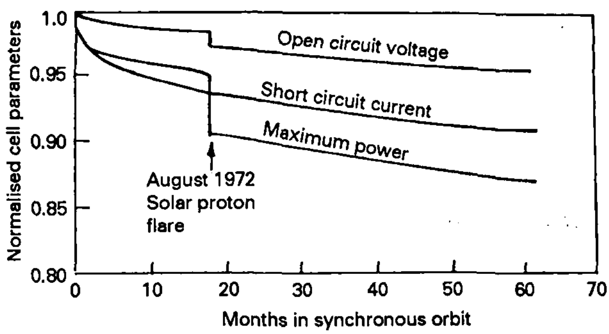


Fig. 7.5 Synchronous orbit performance of the Hughes Aircraft Company; solar arrays as a function of time after launch. The long-term decrease in performance is attributable to damage by energetic electrons. The step function decrease is the effect of one large solar proton event (after L.J. Goldhammer and S.W. Gelb).

energy particles though do not cause radiation damage, but affect the space system by differential electrical charging. The satellites have surface materials of widely varying conductivities and solar illumination conditions on the surface are also different, and this gives rise to different potential at different parts of the spacecraft surface, which consequently gives rise to differential charging. During magnetospheric substorms, potentials of the order of several KV can develop. The electrostatic charging subsequently gives rise to effects like electrical breakdowns and discharges on satellite surfaces. Satellite logic and control systems can be drastically altered by such discharges, which lead to many operating anomalies. A frequent occurrence is false commands being given by noise on the spacecraft command lines. In at least one case, an Air Force spacecraft was totally lost, most probably because of extreme differential charging prolonged by an intense geomagnetic substorm (see Auroras). The investment in space systems is enormous — it runs into tens of billions of rupees. Therefore, even the saving of a fraction as a result of better information from the space scientists regarding the energetic radiation of the space environment which can, for example, extend the life and efficiency of a spacecraft will directly lead to the saving of tens of millions of rupees.

A space shuttle, flying at about 200–300 km above the Earth's surface has been found to have a visible glow around it constantly. It appears that this glow is produced by the interaction of the shuttle with the oxygen ions at these altitudes, though the precise physical and chemical processes involved are not understood yet. The main concern of the scientists is that it is possible that such a glow could also exist around the orbiting telescopes, which could then seriously effect the sensitivity and operational conditions of these instruments.

The communication satellite system designers had another concern imposed by the effect of the ionosphere on radio waves. It was believed that by going to higher frequencies at several GHz (10^9 Hz) in addition to increased communication band width, the ionosphere would no longer be a problem because it is essentially non-absorbing at such frequencies (Chapter 2). But nature is not so easily understood! It was soon found by scientists and engineers that the radio frequency signals propagating through the ionosphere showed rapid fluctuations (scintillations). The scintillation radio signals occur at all frequencies from the HF (3–30 MHz) on, upwards. However, one of the earliest discoveries made when the propagation frequency was increased to 4–6 GHz, was that fluctuations of these signals was observed to be quite severe at times in the equatorial regions of the Earth. These scintillations of the signal amplitudes were reported from Hong Kong in 1973, the Earth station located at low latitudes. Studies of the characteristics show that these are apparently produced by irregularities in the plasmasphere, upper ionosphere (200–300 km) or the inner ionosphere. Extensive experimental and theoretical investigations are being conducted to test, understand and explain the phenomenon of scintillations of communication satellite signals.

7.5 SPACE WEATHER FORECASTS

The next solar maximum is expected around the year 2001. The increase in solar activity can increase the particle and electromagnetic disturbances resulting from solar storms, coronal mass ejections and fast solar wind streams, leading to geomagnetic storms and ionospheric disturbances. This can impair hardware in space and disrupt power and communications grids on Earth and communications with satellites.

A famous recent example of the 1989 disruption of the Hydro-Quebec power system for nine hours brought about a loss of 500 million dollars, counting only losses from unserved demand. In January 1994, a prolonged energetic-electron storm knocked out a Canadian communication satellite for nearly six months. Full services were restored after this time, but the lost revenue and the rescue operation cost the company about 200 million dollars. During and after these events, many other failures and impairment of hardware caused by space storms added to the losses.

Calculations in the U.S.A. show annual losses attributable to space storms as probably approaching a 100 million dollars. In future, as the power systems and space systems become more complex and grow in numbers, such expensive hazards will pose many problems.

Can the industry save itself from such losses? Yes, if we know the space weather conditions in advance. Space Weather Forecasts, just like ordinary weather forecasts, can allow the customers, who receive such services, to take evasive actions and reduce these hazards.

U.S.A. space weather services are trying to improve these services, before the solar maximum. Other countries, including India, are also launching programs to give Space Weather Forecasts. These forecasts will be based on gathering data pertaining to the solar wind conditions, IMF conditions, the energetic charge particles in space and other space plasma data supplied by several agencies, and finally interpreted by a central agency. Let us hope we will achieve Space Weather forecasting as successfully as weather forecasting! By the way, Space Weather Forecast by satellite, communicated on T.V. will be known to us only if Space Weather conditions are friendly!

Summary of the Impacts of Solar-terrestrial Plasma processes on technical systems [Fig. 7.6]

- Ionosphere effects

  1. Radio propagation

2. Communication satellite signal interferences
3. Induction of electrical currents in the Earth
   (a) Power distribution systems
   (b) Long haul cables
   (c) Pipelines

- Radiation effects

1. Solar cell damage
2. Semiconductor damage and failure
3. Spacecraft charging
4. Astronaut safety
5. Airline passenger safety

- Magnetosphere currents

1. Attitude control of communication spacecraft

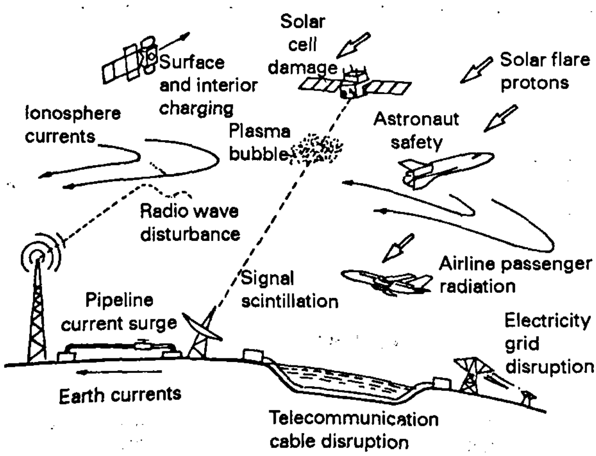


Fig. 7.6 Schematic illustration of present-day technical systems that can be influenced by the solar-terrestrial environment.

8.

Solar System Magnetospheres

"Our voyager knew marvellously the laws of gravitation and all attractive and repulsive forces. He used them in such a timely way that, once with the help of a ray of sunshine, another time thanks to a cooperative comet, he went from globe to globe, he and his kin, as a bird flutters from branch to branch".
— **Voltaire**–*Micromegas,*
Histoire Philosophique (1752)

In 1977, U.S.A. launched two unmanned *Voyager I and II* spacecrafts on an extensive tour of the four outer planets; Jupiter, Saturn, Uranus and Neptune. Why choose 1977? Because, this was the year of the rare heavenly alignment of planets, which occurs once in every 176 years. The alignment enabled the use of a gravity-assisted trajectory, in which the gravity field of a planet may be used to hurl the spacecraft on to the next planet. Unaided by gravity, the trip to Neptune would have taken eighteen years longer than it did. Both *Voyager I and II* [Fig. 8.1], completed successful fly-by encounters of Jupiter and its moons and rings on March 5 and July 9, 1979, respectively. The two voyagers went on to rendezvous with Saturn on November 12, 1980 and August 25, 1981 [Fig. 8.2]. *Voyager II*, encountered Uranus on January 24, 1986 and Neptune on August 24,1989. Pluto's eccentric orbit will keep it inside Neptune's until 1999. Still relaying data, both voyagers are now looking for a heliopause, where the Sun's magnetic field gives way to interstellar space.

The *Voyager's* tour to the outer planets of our solar system (Tables 8.1 and 8.2) was the most spectacular and successful mission which confirmed that, like the Earth (though an inner

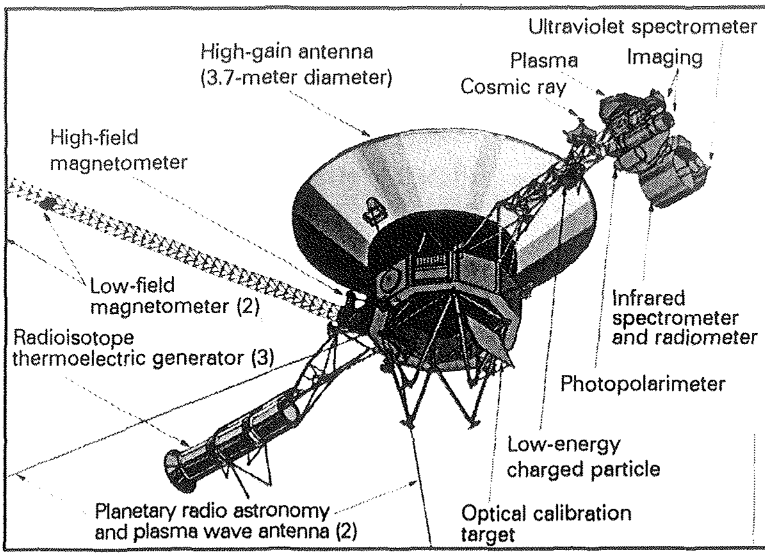


Fig. 8.1 *Voyager* Spacecraft and scientific instruments.

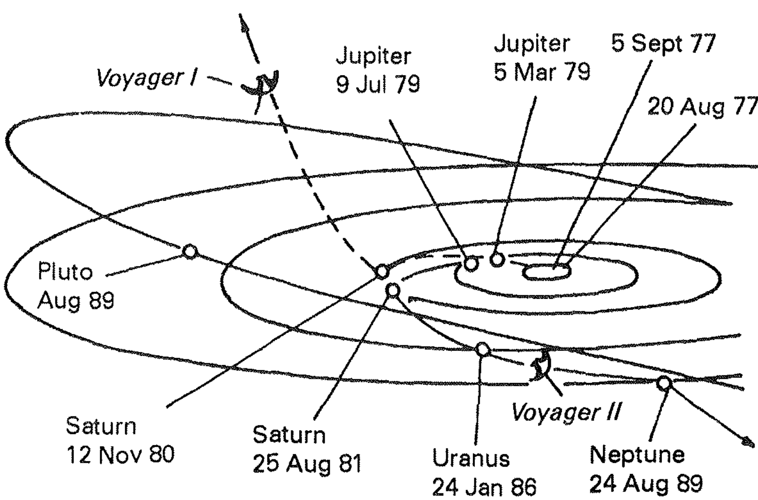


Fig. 8.2 Trajectories of Voyager Spacecrafts: Launched second, but sent on a faster trajectory, *Voyager I* was ahead leading the way. *Voyager II* backed it up to analyse and record features at close range and from a variety of angles. It also explored areas which *Voyager I* could not. After its grand tour to Saturn, *Voyager I* soared towards the stars above the plane of the solar system. *Voyager II*, after travelling to Uranus and Neptune, is still within Neptune's orbit.

planet), all the four giant, gaseous planets have vast extensive and active magnetospheres [Fig. 8.3].

Fig. 8.3 'Gas Giants' visited by the *Voyager* spacecraft, shown to scale with the Earth. From left to right: Jupiter, Saturn, Uranus and Neptune. Methane gas in the atmospheres of Uranus and Neptune absorbs the colour red from the sunlight, and is responsible for the blue colour of those planets.

Table 8.1 Planetary magnetic properties

Planet	Dipole Moment ($G\ cm^2$)	Equatorial surface field (Gauss)	Polarity with respect to the Earth	Angle of magnetic axis from rotational axis	Typical magnetopause position (planetary radii)	Plasma sources	Planet's spin period (days)
Mercury	-3×10^{22}	0.0035	same	~ 10°	1.1	W	58.6
Venus	$< 10^{21}$	0.0003	-	-	1.1	A	243
Earth	8×10^{25}	0.31	same	11.5°	10	W, A	1
Mars	2.5×10^{29}	0.00065	opposite	-	?	?	1.02
Jupiter	1.5×10^{30}	4.1	opposite	~ 10°	60–100	W, A, S	0.41
Saturn	1.5×10^{29}	0.4	opposite	1°	20–25	W, A, S	0.44
Uranus	3.9×10^{27}	0.23	opposite	~ 60°	18–25	W, A	0.72
Neptune	1.6×10^{27}	0.14	opposite	46.8°	23–26	W, A	0.74

The known properties of planetary magnetospheres are listed here for comparison. The dipole moment is a measure of the total strength of a planet's magnetic field; note how weak Venus is compared to the other planets. The polarity of the Earth's field is that of a bar magnet with a south magnetic pole in the Northern Hemisphere; Mercury has the same configuration. The plasma sources listed in this table are the solar wind, W, the planet's own atmosphere, A, and satellites, S.

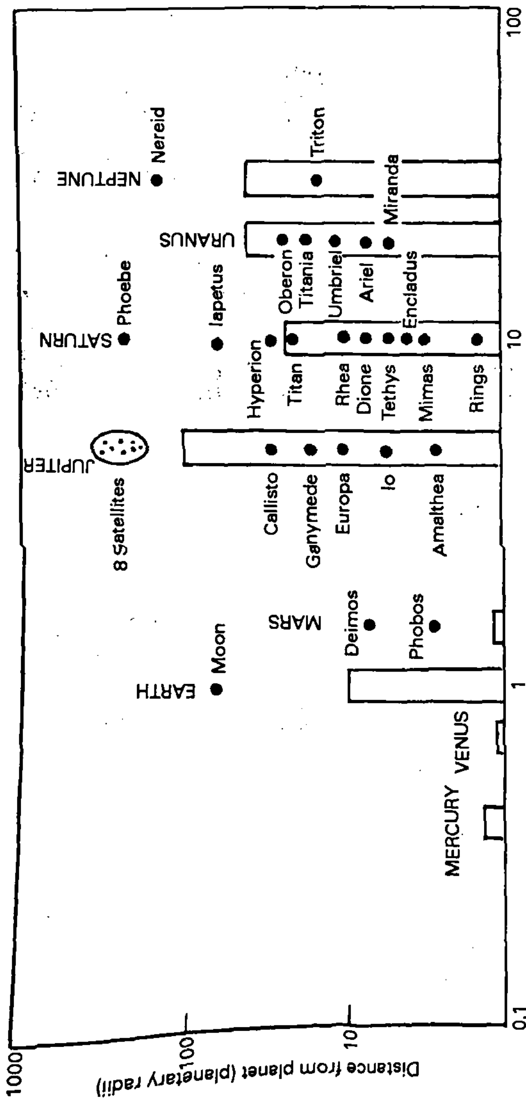


Fig. 8.4 Bars indicate the sunward extent of solar system magnetospheres in terms of the radii of the planets that they enshroud. The location of some satellites are shown in the same units (adapted from G. L. Siscoe, 1979).

The solar wind, continuously flowing away from the Sun, engulfs the planets in the solar system. Like the Earth, many planets are magnetic objects interacting with the solar wind plasma. This interaction gives rise to the magnetically organised structures, the magnetospheres, or the regions of space influenced by the planet's magnetic field. Such structures are now confirmed to be common in the universe. Here, we will survey the other planets, especially the outer gaseous planets, in our solar system which provide important additional examples of magnetospheres, along with the Sun itself. Magnetospheres can also form due to the interaction of the solar wind with the celestial object's associated atmosphere [Fig. 8.4]. Important examples are the magnetospheres of Venus and comets.

Much of our knowledge about the magnetospheres of the planets in the solar system comes from spacecraft observations. All the six planets Mercury, Venus, Earth, Mars, Jupiter and Saturn have been visited both by Soviet and United States spacecrafts. The most distant planets of the solar system, Uranus and Neptune, were visited during the *Voyager's* epic journey to the outer gaseous planets. From all these space explorations, we have learned that all the planets investigated have magnetospheres. Most are associated with the magnetism generated in the planet's interior. In the case of Venus, however, a field is produced by electrical currents in the planet's upper atmosphere.

The characteristic dimensions, the morphology and dynamics of a planet's magnetosphere, are controlled by the planetary magnetic properties. While the size of a planetary magnetosphere depends on the strength of a planet's magnetic field, the configuration and internal dynamics depend on the field orientation, which is described by the tilt angle of the magnetic field with respect to the planet's rotation axis, and the angle between the solar wind direction and the rotation axis, the obliquity.

The table shows that all the inner planets, Earth, Jupiter and Saturn have both small dipole tilts, but Uranus and Neptune each have magnetic fields which are highly tilted with their rotation axes and offset from their centres by large fractions of the planetary radii [Fig. 8.5].

The principal plasma and energy source powering most planetary magnetospheres is the plasma flow from the Sun, or solar wind. However, the plasma in the magnetosphere may also come from a variety of other sources. On Earth, the ionosphere provides most of this material while, on Jupiter and Saturn, satellites play an important role. These different sources, combined with the peculiar properties of each planet, produce the observed variety of dynamic plasma processes in the solar system which we shall discuss with respect to each planet.

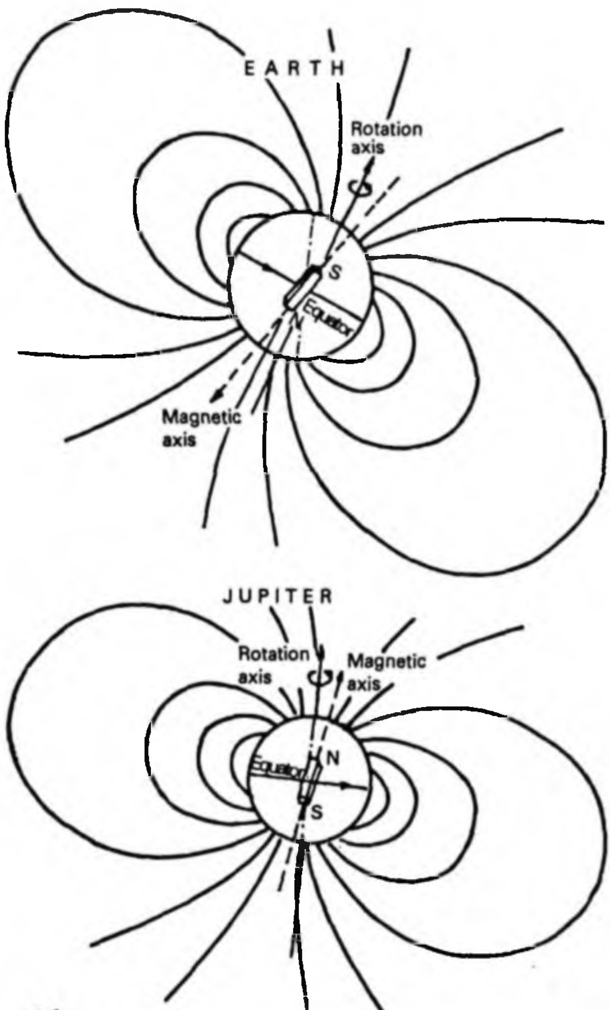
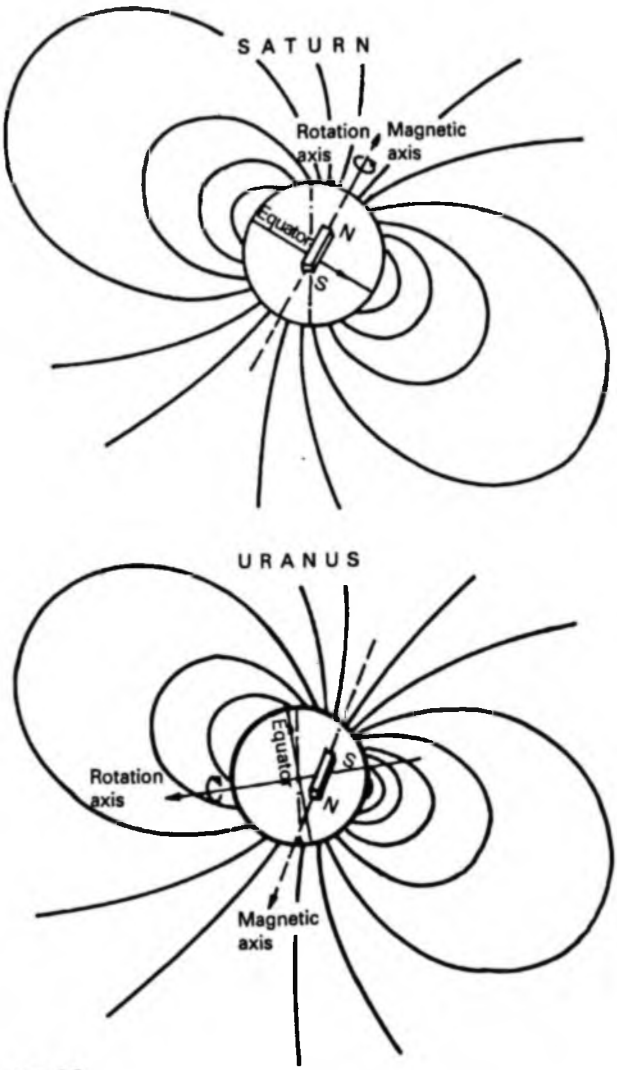


Fig. 8.5


SATURN
Rotation axis
Magnetic axis
Equator
N
S
URANUS
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Rotation axis
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Fig. 8.5

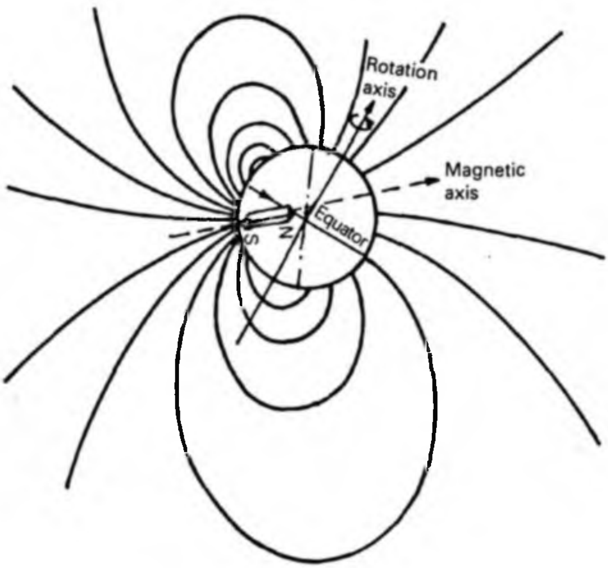

Fig. 8.5 Relative orientations of the four giant planets and the Earth's spin axis and magnetic axis. In Uranus and Neptune, the magnetic axes are grossly misaligned with the rotation axes. Also, note the offsets of the magnetic fields from the centres of the planets.

8.1 The Inner Planets

The magnetospheres of Mercury, Venus and Mars are each characterised by the dominating presence of the planet itself.

I Mercury

Mercury's small size implies a quick response to changes in the solar wind. The magnetospheric processes of this planet appears to occur over minutes, compared to the hours this takes on Earth. For example, particle accelerations with time-scales of minutes were observed by *Mariner 10*.

Mercury has no radiation belts, and its lunar-like surface and lack of an appreciable ionosphere suggest that any interactions between the planet and its magnetosphere are small. This situation is very different from the Earth, where electric currents lying along the magnetic field lines can form closed loops in the conducting ionosphere and, thereby, provide strong magnetosphere–ionosphere coupling.

II Venus

In the case of Venus, the dominant coupling is between the solar wind and the ionosphere. This is due to the fact, as already mentioned above, that Venus' magnetic field arises from currents in the planet's upper atmosphere. Venus has a massive atmosphere and it seems to exert a strong control over the plasma and magnetic structures alike. The internal structure of Venus' magnetosphere is not well known. Also uncertain is the length of the magnetotail that streams away from the planet's night side.

III Mars

Not much is known about Mars' magnetosphere. The US *Mariner* and *Viking* probes concentrated on other investigations. The Soviet *Orbiters* studied the planet's magnetic sheath in the 1970s, but their orbits and instrumentation were not well suited to the task, so the results were inconclusive. Based on a few measurements, we think that Mars has a field about 15° from the planet's rotation axis. The recent *Phobos* mission has updated this information and it is seen that these numbers remain pretty much the same. The *Phobos* mission, though, has given further information regarding the typical magnetopause position which seems to be 4 277 km or 1.4 R_m (R_m: the Martian radius).

8.2 The Outer Planets

I Jupiter

The region of interplanetary space affected by Jupiter's magnetic field and plasma environment is enormous. The magnetopause on the sunward side varies in distance between 50 and 100 Jovian radii (R_J = 71 492 km, this makes the dimensions of the magnetosphere nearly 7 million km = 7×10^6 km). The magnetotail is even bigger as it measures out to a distance of 5 AU behind the planet, long enough to engulf Saturn periodically! This is reminiscent of the similar situation arising with our Moon which, once a month, passes through Earth's magnetic tail. However, there is a major difference between the two cases because Saturn, unlike our satellite, has a strong intrinsic magnetic field.

Jupiter's magnetosphere is so big that the Sun would easily fit into it. If this magnetic structure was illuminated like a comet, it would appear to be the largest object in the sky to an observer on Earth.

Table 8.2 Planetary properties

Planets	Solar Distance (AU)	Radius (10^3 km)	Spin period (days)	Synchronous orbital radius (Planetary radii)	Average density (gm/cc)	Surface gravity (N/kg)	Escape velocity (km/sec)
Mercury	0.4	2.42	58.6	100	5.4	3.6	4.2
Venus	0.7	6.10	243	254	5.1	8.7	10.3
Earth	1.0	6.37	1	6.6	5.5	9.8	11.2
Mars	1.5	3.38	1.02	6.0	4.0	3.7	5
Jupiter	5.2	71.4	0.41	2.3	1.3	26.0	61
Saturn	9.5	60.4	0.44	1.9	0.7	11.2	37
Uranus	19.2	26.2	15.57(?)	4.5	1.18	9.4	22
Neptune	30.0	25.3	17.83(?)	4.5	1.56	15.0	25

The study of Jupiter's magnetospheric plasma has an interesting history. In the 1950s, radio waves were discovered from Jupiter. It was soon realised by the scientists that this radio emission must come from energetic, charged particles in a strong magnetic field. This trapping of charged particles in Jupiter's magnetic field came before Van Allen's detection of the Earth's radiation belts and the understanding of the solar wind interaction with the planetary systems. A more puzzling discovery came a few years later, when it was revealed that these radio emissions were controlled by the orbital position of the innermost Galilean satellite, Io. With the *Pioneer* and *Voyager* probes, it is now confirmed that Jupiter has a strong magnetic field, trapping a large energetic particle population. It is also revealed that, farther from the planet, the magnetic field is considerably stretched out so that the Jovian magnetosphere [Fig. 8.6] is shaped more like a disc than a sphere.

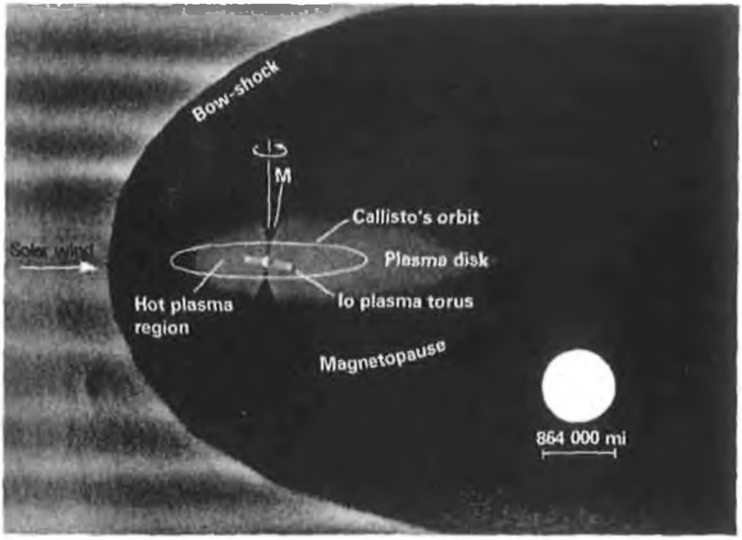

Fig. 8.6 *Schematic illustration of Jupiter's magnetosphere.* The plasma is concentrated in a disc-like region near the planet's equator. The Sun is shown on the same scale for comparison, but Jupiter itself has been enlarged to make it visible.

The mystery surrounding Io's influence was resolved by the *Voyager I* spacecraft as it confirmed that Io is the major source of plasma in the magnetosphere. It is now believed that the Moon Io with its volcanic activity [Fig. 8.7] provides perhaps the most prodigious plasma source in the solar system, short of the Sun. Before the *Voyager's* visit to Jupiter, it was found by the scientists that Io is accompanied in its orbital path by a glowing cloud of sodium atoms. Sulfur and calcium atoms and ions are also present. Interestingly, the *Voyager* images revealed vigorous volcanic activity on the satellite. These eruptions, which are produced by gravitational interactions between Io, Jupiter and Europa, constantly resurface on Io with sulphur and sulphur dioxide, and ice, along with other materials from the interior.

Sputtering, due to the direct impact of the energetic Jovian magnetospheric particles, can remove solid volcanic ejects from Io's surface. In addition, uncondensed gases from the volcanoes can be removed directly from the satellite's ionosphere and atmosphere. Freed atoms and molecules, ionised by sunlight and by collisions with magnetospheric plasma, then become trapped in Jupiter's magnetic field. These particles immediately acquire a share of the magnetic field's rotational energy and can be accelerated to much higher energies. This plasma tends to be confined to the magnetic equator, forming a disc as already noted. The very high-energy charged particles, especially the electrons, produce the Jovian radio emissions observed on Earth.

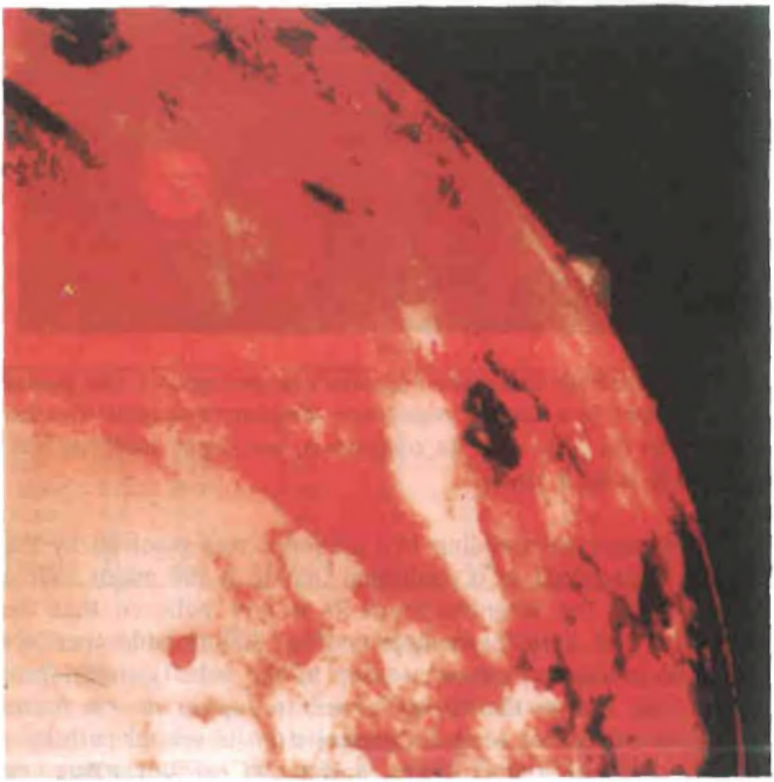

Fig. 8.7 Volcano on Io : The first active volcanic eruptions other than those on Earth were discovered on Io. These volcanoes are extremely explosive with ejection velocities of more than 1 km/sec. Io is a major source of plasma in Jupiter's magnetosphere. It displays three types of plumes due to the interaction between its molten silicate interior (red), sulfurous mantle (magenta) and hard sulphur crust (brown). This picture was taken by *Voyager I*.

Accelerated particles that originated on Io can reimpact their satellite's surface, producing even more plasma. In fact, Io, Europa, Ganymede and Callisto, all the Galilean satellites, play an *important role in the Jovian magnetospheric processes.* These satellites together produce so much ionised material that Jupiter's magnetic field cannot contain it all. Where the plasma pressure is as great as that exerted by Jupiter's confining magnetic field, ionised material can escape into the interplanetary medium. It can do so on the sunward side of the magnetosphere or down the planet's magnetotail as a very fast and very hot planetary wind, substantially faster than the solar wind.

Spacecraft observations show that large plasma waves are launched by Io as it traverses Jupiter's magnetosphere. These disturbances connect the satellite to the planet's ionosphere by a process not yet completely understood. They also modulate some of the gaseous giant's radio emission and are probably involved in accelerating some of the plasma to very high energies. The auroral phenomena also seem to be due to the plasma processes that connect Jupiter's magnetic field and Io. The Jovian aurora, the largest aurora ever observed: nearly 29 000 km long, was photographed by *Voyager I* on the dark side of the Jupiter six hours after a close encounter (the closest approach was 2 80 000 km from Jupiter). These auroral lights are brighter than any northern lights seen on Earth.

The energy derived from Jupiter's rapid rotation drives the planet's magnetospheric engine. However, Jupiter's rotational energy is so enormous that magnetospheric phenomena do not significantly contribute to slowing down the planet's rotation.

II Saturn

It was a big surprise when scientists learned that Saturn's magnetic field was much smaller than Jupiter's (Table 8.1) and, further, that the axis of the magnetic field is aligned nearly perfectly with the planet's rotational axis. Our lack of understanding about such differences between two similar planets emphasizes how much we have to learn about planetary magnetism.

Overall, Saturn's magnetosphere is found to be similar to the Jovian magnetosphere. Satellites are the major source of magnetospheric plasma and the plasma dynamics are dominated by the planet's rotation. Nevertheless, Saturn's magnetosphere is considerably smaller than Jupiter's and does not appear to be as dynamic. Saturn's small magnetic moment limits the size of its magnetosphere under normal conditions of the solar wind. As noted earlier, Saturn and its magnetic shroud are periodically engulfed by Jupiter's magnetotail, an experience probably unique among the major planets.

The rings of Saturn [Fig. 8.8] play important roles in the planet's magnetospheric phenomena. For example, the approach of the plasma towards Saturn is limited, because rings A and B absorb particles that reach them. Saturn's plasma is composed of ionised hydrogen, oxygen and nitrogen. The oxygen comes from the icy surfaces of satellites, probably primarily by sputtering. Indeed, a feedback process similar to that operating around Io, seems to be at work. The sputtered particles can be accelerated and reimpact satellite surfaces, producing even more plasma.

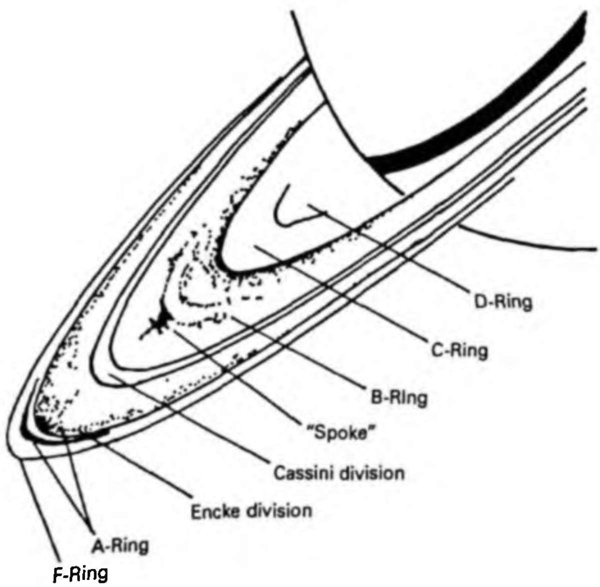

Fig. 8.8 The classic features of Saturn rings: The rings are named in order of their discovery, so the labels do not indicate their relative positions. From the planet outwards, they are known as D, C, B, A, F and E. (The tenuous E-ring is not seen here)

The predominantly nitrogenous atmosphere of Titan can also contribute to the magnetospheric plasma. On the dayside of Saturn, this satellite can be either inside or outside the planet's magnetopause, depending on the variable intensity of the solar wind. On the nightside, Titan always passes through the planet's magnetotail.

Saturn's aurora was first detected by an ultraviolet instrument on *Voyager I*. The emission intensities suggest that the auroral power is similar to that of the Earth.

III Uranus

Sometime in its history, a cataclysm almost certainly befell Uranus and caused the planet's rotational axis to lie in the ecliptic plane rather than almost perpendicular to it. Models for the development of the solar system cannot produce such an orientation without invoking a collision with another object.

By analogy with the other major planets, whose rotation and magnetic axes are more or less aligned, scientists expected Uranus' magnetic axis to lie approximately in the ecliptic plane. With such a configuration, the solar wind could impinge directly on one of the magnetic poles, and some fairly exotic magnetospheric conditions were expected.

However, one of the major discoveries by *Voyager II* was that the planet's magnetic axis is tilted approximately 60° to the spin axis. This situation is unlike that of any planet yet studied, but the result is that the magnetosphere is not as anomalous as expected. For example, the solar wind is not funneled into a polar cap, but interacts with the planet's magnetic field much as it does around the Earth. However, Uranus's magnetotail does undergo considerable 'flopping' in the ecliptic plane as the planet rotates.

Uranus' magnetosphere [Fig. 8.9] was found to be filled with protons and electrons. The plasma densities are not very high and the planet's magnetic field dominates it's plasma physics. There are, however, tantalising hints of much more intense radiation closer to Uranus. Unfortunately, *Voyager II* only came to within 4 planetary radii of the cloud-tops, so confirmation of the hints was not possible.

There are enough energetic particles near Uranus to produce darkening effects in any organic materials on the icy surfaces of the planet's moons. All of the satellites and rings pass through the magnetosphere as it is routed past them with the planet's spin period. Freshly-exposed, organic ice surfaces could be significantly altered in just 1 000 to 10 000 years.

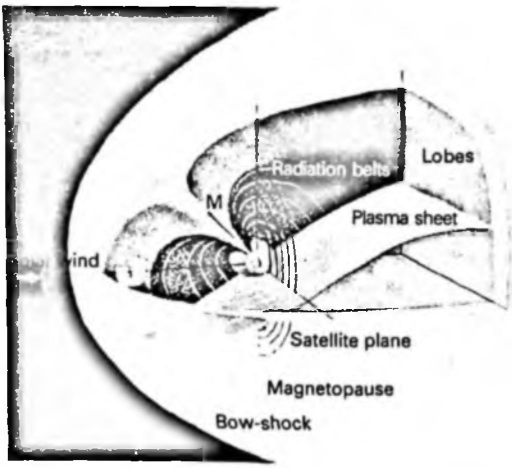

Fig. 8.9 Schematic illustration of Uranus' magnetosphere, showing the radiation belts and the satellite's orbit plane.

Voyager II detected ultraviolet emissions from the planet, that appear to indicate auroral processes with intensities somewhat lower than those of the Earth and Saturn. However, it is important to remember that terrestrial auroras vary widely with time, and that auroral observations at Uranus were limited to only a few hours.

IV Neptune

For Neptune, interestingly, the planetary rotation axis is not approximately aligned with either the magnetic dipole axis or the solar wind flow direction. It can be calculated that the angle between the solar wind and the dipole axis changes between 20° and 114° over the 16.1 hour planetary rotation. When the angle is near 90°, the configuration is momentarily symmetrical like the Earth, Saturn and Jupiter. When the angle is small, we have a unique configuration with the magnetic axis pointed 'pole-on' into the solar wind, a configuration that was expected for Uranus before *Voyager II* found a large dipole tilt. This leads to a complete reconfiguring of the magnetosphere. Every planetary rotation shows an extreme configuration of the Neptune magnetosphere [Fig. 8.10]. The dramatic changes in the magnetotail, occurring every planetary rotation, complicates the dynamics of Neptune's magnetosphere.

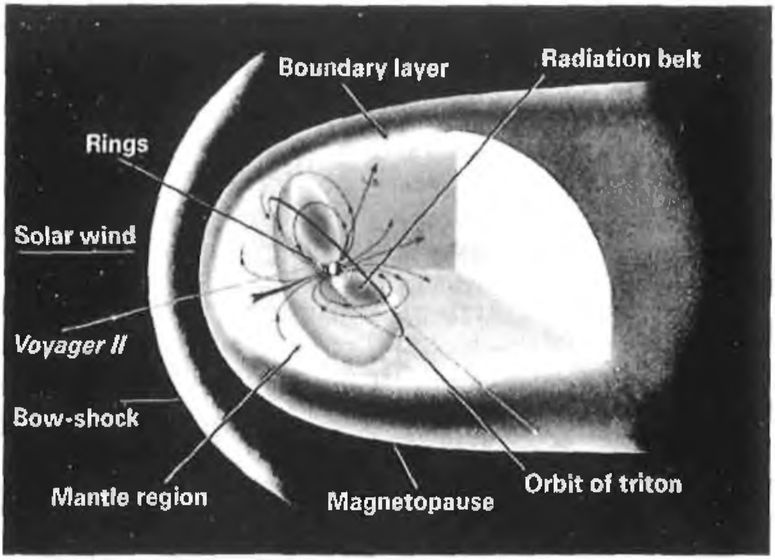

Fig. 8.10 A conceptual model of Neptune's magnetosphere as it might appear at the time of the *Voyager's* entry through the cusp region.

Although Neptune's large satellite, Triton, orbits at $14.6R_N$, well inside the magnetosphere, unlike Jupiter and Saturn this does not act like a source of plasma, as plasma densities in Neptune's magnetosphere are low. Clearly, to understand this situation, a further study of Neptune's magnetospheric dynamics is required.

While Uranus and Neptune have significant radiation belts, the energy density remains small compared with the magnetic field, and the ring current is very weak. The ultraviolet emissions detected by the *Voyager* are reported to be very weak with no clear auroral signature. The role of Triton in the origin of Neptune's weak aurora is still not understood.

8.3 Comets

In September 1985, NASA's *International Cometary Explorer* (*ICE*) spacecraft passed through the tail of the comet, Giacobini–Zinner. Then, in March 1986, a flotilla of American, Japanese,

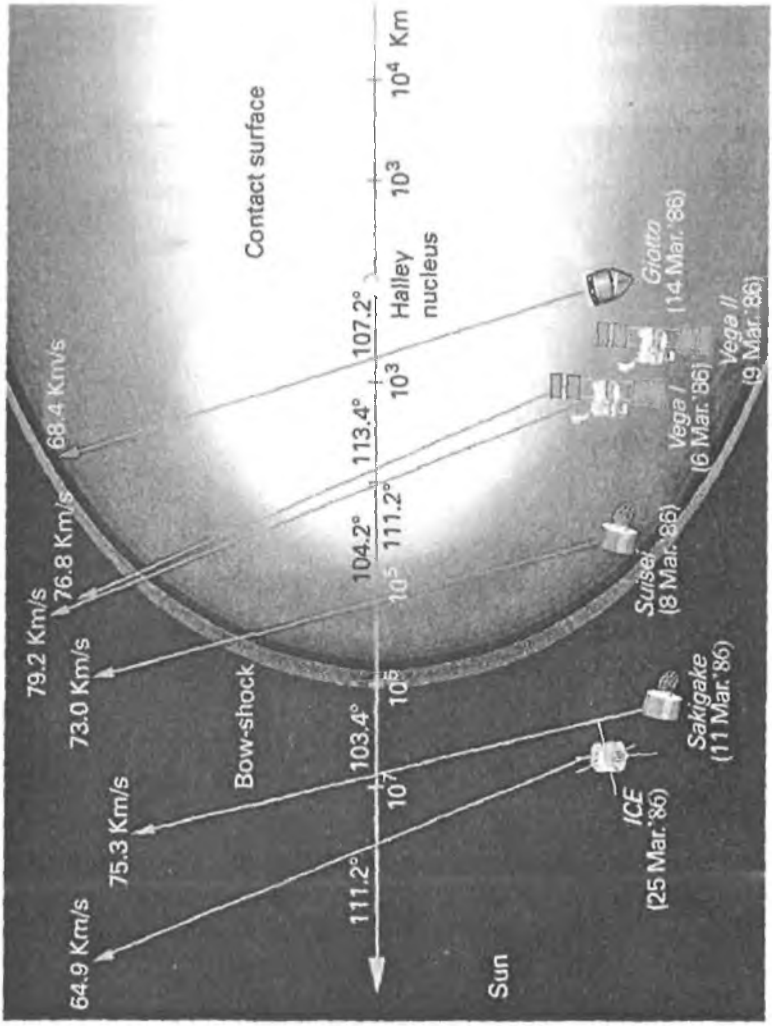

Fig. 8.11 Space Mission to Halley's Comet. This picture gives a summary of comet fly-by trajectories of the spacecrafts: *Giotto* (European Space Agency), *ICE* (NASA), *Vega I and II* (Intercosmos Soviet Union) and *Suisei* and *Sakigake* (ISAS, Japan) (note the logarithmic scale). (from Reinhard, 1986).

Soviet and European probes encountered Halley's comet, returning with detailed information on the magnetosphere of that body [Fig. 8.11].

The interaction between the solar-wind plasma and the comet's ionosphere produces two distinct boundaries: the bow-shock and the so-called contact surface. Far from the nucleus, outside the bow-shock, the solar wind is undisturbed. Closer to the comet, inside the bow-shock but outside the contact surface, there is a mixture of cometary and solar wind interactions. Strong magnetic fields are also present in this region due to the solar wind's interaction with cometary ions. Inside the contact surface (only the European *Giotto* spacecraft passed close enough to Halley to penetrate this region), there are only cometary ions in a field-free cavity. Even though a comet's nucleus has no magnetic field of its own, the fact that its 'magnetosphere' is visible provides us with the opportunity to draw analogies with the planets. In fact, the turbulent behaviour seen occasionally in comet tails has been linked to the plasma variations observed in the Earth's magnetotail at times of magnetic disturbance and auroral activity.

8.4 THE HELIOMAGNETOSPHERE

The largest magnetic organisation of matter in the solar system is the Sun's magnetosphere, called the **heliomagnetosphere** or **heliosphere**. As the solar wind expands through interplanetary space, its pressure falls until it becomes too weak to push aside the interstellar medium [Fig. 8.12]. We are now sure that the interstellar medium, at least in our galaxy, is not empty but filled with interstellar gas, the interstellar magnetic field and cosmic rays. These entities exert force on the solar wind. At the boundary, where the pressures of the local interstellar medium and the solar wind balance out, the supersonic solar flow is expected to undergo a shock transition to subsonic flow.

The distance of this shock transition from the Sun is unknown. Roughly 100 AU is something of a consensus view, but estimates vary (see Chapter 3). The working *Voyager* and *Pioneer* spacecrafts presently moving out of the solar system may eventually detect the boundary.

Another very unique mission, the *Ulysses* mission was launched on 6 October 1990, by the Shuttle Discovery. The *Ulysses* will explore the heliosphere and, for the first time, provide a detailed picture of the three-dimensional structure of the Sun, studying the unexplored regions far above the north and south poles of the Sun. This mission is unique as *Ulysses* was first launched towards Jupiter and in February 1992, with the gravity assisted manoeuver during the Jupiter swing-by, it has been injected in an high inclination orbit which placed the spacecraft over the southern Solar pole in May–September 1994.

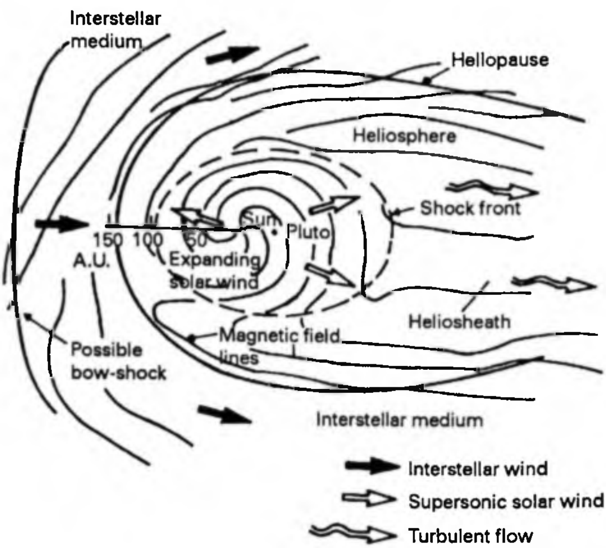

Fig. 8.12 Heliosphere or Heliomagnetosphere, the Sun's magnetosphere is the largest magnetic organisation of matter in the solar system.

8.5 Concluding Remarks

There is still much to understand about the magnetospheric objects in our Solar System. Now, it is known that magnetosphere-like systems are not only found in our Solar System but, in all probability, throughout the universe. One example is of the spectacular magnetised neutron stars called pulsars, where the only information on their physical conditions comes from the various magnetospheric radiations they emit. Pulsars differ from planets in that their plasma does not originate from an external source like the Sun, but flows from the pulsars themselves.

On an even larger scale, observations have revealed that magnetically organised matter can exist around normal stars and even entire galaxies. The size of the presently-known magnetospheres range from a few thousand kilometers in the case of the planet Mercury, to more than ten million light-years for a large radio galaxy like NGC 1265 in Perseus.

In fact, present observations indicate that the large-scale magnetic organisation of matter in the plasma state may be as common as the more familiar gravitational organisation. Since the different magnetic systems will have certain physical processes in common, any new data and understanding of our solar system brings us closer to unveiling the mystery of similar magnetically organised systems throughout the universe.

Appendix

Anthropomorphism in Magnetospheric Nomenclature

We have noticed while reading the story of our neighbouring space that, interestingly, various nomenclatures for physical features and plasma processes in the Earth's magnetosphere are anthropomorphic.

The thin extended part of the magnetosphere is called the geomagnetic 'tail'. A reasonably complete picture of the magnetospheric tail was given by satellite measurements of the geomagnetic field made by N.F. Ness in 1965. The doughnut-shaped regions of trapped electrons girdling the Earth at distances of about 1.5 and 6 Earth radii from the planet's centre, as we know, are called the Van Allen Belts as these were discovered by James A. Van Allen and his colleagues in 1958. The sharp drop in density at about 4 R_E in the plasmasphere gives the appearance of a 'knee'. This term was first used by D.L. Carpenter in 1963, as this region shows slow movements; moving radially inward during the night and a slow outward movement during the day. The plasmasphere also has a region of 'new' high density plasma which is supposed to have moved inward from the tail of the magnetosphere. This enormous new plasma region measures 1 to 5 R_E across and is called the 'bulge'. Another term which reminds one of the ear is the 'lobe' region which defines the plasma region across the geomagnetic tail. The boundary layer plasma, termed thus due to the solar wind flowing past the magnetospheric boundary, is called the plasma 'mantle'. We have seen that whistlers, the whistling radio waves, propagate along the column of plasma or the 'duct' formed along the lines of force. The whistlers which are guided along these ducts are called 'ducted whistlers'. There are non-ducted whistlers also. Some whistlers contain both rising and falling whistles. These are called 'nose' whistlers. The phenomenon of nose whistlers was first studied by R.A. Helliwell and his colleagues in 1956.

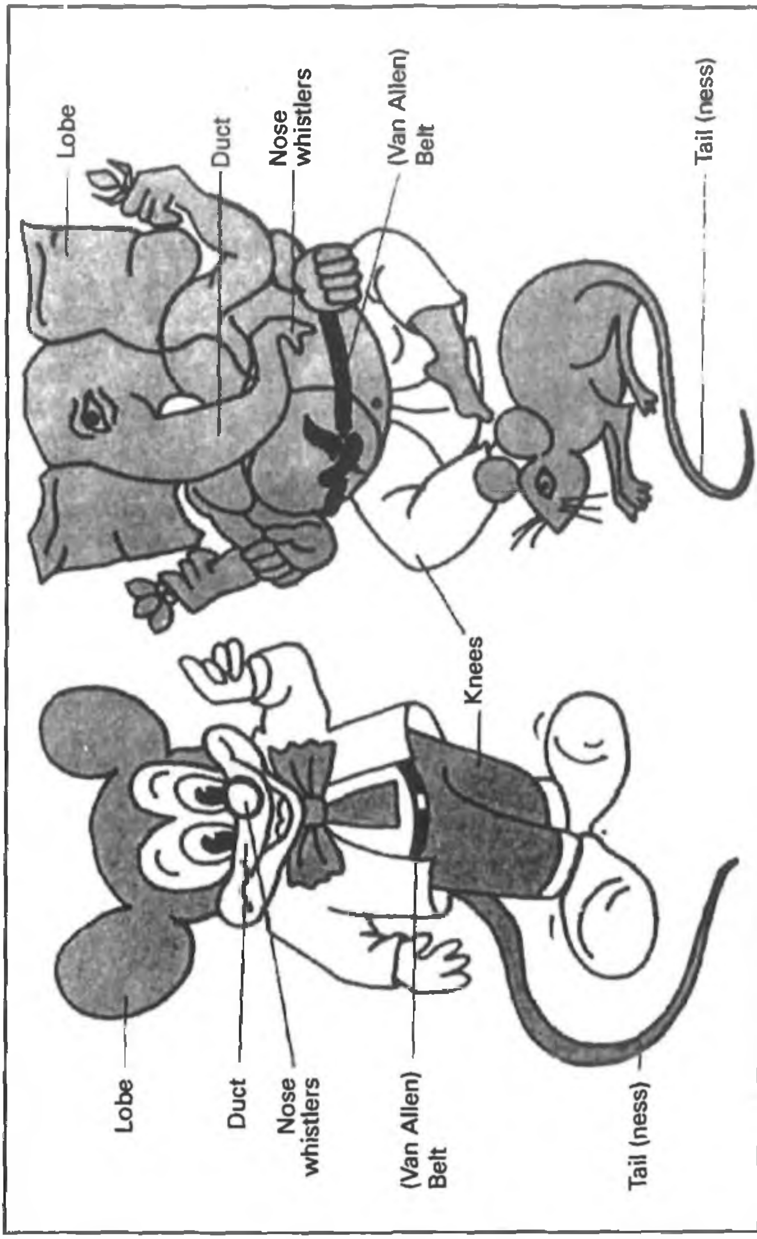

Fig.A.1 Mickey Mouse (drawn after B.J. O'Brien) and Ganesha.

The terms 'nose' whistler, Van Allen Radiation 'belt', plasmaspheric 'knee' and geomagnetic 'tail' inspired Brian J.O' Brien to characterise the anthropomorphic magnetosphere as 'Mickey Mouse', the popular cartoon figure in the U.S.A. In keeping with the spirit of O'Brien in popularising space science, I would like to point out that Hindu mythology offers another characterization of the magnetosphere which besides being familiar to the people in India, and hence more appealing, can cover some more anthropomorphised plasma processes in the magnetosphere.

In Hindu mythology and religion 'Lord Ganesha' is a very popular god, especially beloved by children. He is represented as a short, fat figure with a protuberant belly, four hands and the head of an elephant, which has only one tusk (the other being broken). Every god in Hindu mythology is associated with an animal or bird, acting as a chariot for these gods. Lord Ganesha is attended by a mouse and occasionally he rides on it. The characterisation of the anthropomorphic magnetosphere by Lord Ganesha is now straightforward. The long tail of the mouse, as in the case of Mickey Mouse reminds us of the geomagnetic 'tail'. The ears of the mouse are plasma 'lobes' in the magnetospheric tail region. The bulging stomach of Ganesha is the 'bulge' in the plasmasphere. The bent knee of Ganesha's posture is the 'knee' of the plasmaspheric density profile. The belt round his fat waist represents the radiation 'belts' girdling the Earth. The long elephant trunk (prehensile nose) is the magnetospheric 'duct' guiding the 'nose' whistler. The large elephant ears of Ganesha give rise to 'cusps' representing the polar cusps in the magnetosphere!

Glossary

Alfvén wave : Basic hydromagnetic wave in a plasma containing a magnetic field; the plasma displacement is transverse to the magnetic field, with the propagation direction being along the field.

Apogee : The point in its orbit where a satellite or the Moon is farthest from the Earth.

Astronomical Unit (AU) : Mean distance of the Earth from the Sun, approximately equal to 1.5×10^8 km.

Aurora : Lights in the upper atmosphere (from about 90 to 300 km altitude) produced by the excitation of atmospheric gases by energetic particles; the localised areas in the two polar regions where auroras are typically observed are determined by the detailed topology of the magnetosphere.

Bow-shock : A type of discontinuity formed in the sunward direction of the solar wind because of the interposed obstacle of the magnetosphere.

Coronal holes : Regions in the solar corona in which the solar magnetic fields are not closed but open into the interplanetary medium.

Ecliptic plane : Plane of the apparent, annual path of the Sun in the celestial sphere.

Gamma (γ) : Unit of magnetic field strength equal to hundred thousand of a gauss.
1 gamma = 10^{-5} Gauss = 10^{-9} Tesla

Heliosphere : The region around the Sun in our galaxy (the Milky Way galaxy) influenced by the solar wind.

Ionosphere : Ionised region of the upper atmosphere, generally from about 90 km to about 1 000 km in altitude; the area beyond this is defined as the magnetosphere.

Light-year : The distance that light travels at its speed of 2 97 600 km/sec, traverses in the course of a year, approximately equal to 9.6×10^{12} km.

Magnetopause : The boundary between the flowing solar wind plasma and the magnetosphere.

Magnetosphere : The region of space around the Earth, in which the terrestrial magnetic and electric fields usually dominate the transport and motion of charged particles.

Magnetosphere cusps : Regions in the northern and southern polar areas, separating the magnetic fields that form the dayside magnetopause from those fields that stretch into the magnetotail.

Magnetotail : The region of the magnetosphere in the anti-sunward direction; if visible, the magnetotail would have characteristics like the tail of a comet.

Mean Local Time : Solar time for a given location reduced from apparent to mean.

Photosphere : The visible solar surface with a temperature of about 6 400 K.

Plasma : Gas that is ionised. Naturally occurring plasmas usually contain magnetic fields.

Plasma sheet : A sheet of plasma, several times the Earth radii in thickness in the tail of the magnetosphere, that separates magnetic fields of opposite magnetic polarity.

Plasmapause : The outermost boundary of the plasmasphere.

Plasmasphere : The region of plasma in the magnetosphere with ionospheric character.

Radiation belts : Localised regions in the magnetosphere that contain energetic charged particles whose motions are primarily controlled by the magnetic field of Earth.

Solar corona : The region beginning about 2 000 km above the photosphere, with a temperature of over one million degrees Kelvin.

Solar flare : A sudden brightening, for several minutes to several hours, of a small area of the solar photosphere that contains a group of sunspots.

Solar wind : Expansion of the solar corona, primarily hydrogen ions, into the interplanetary medium.

Substorm : An interval of one to three hours of auroral, geomagnetic and magnetospheric activity, usually followed by a several-hour interval of relative quiescence.

Sunspot cycle : The variation with time of the appearance of the number of sunspot groups on the visible solar photosphere.

Sunspots : The darkened areas of the solar photosphere usually occurring in groups and containing intense magnetic fields.

Thermosphere : The region of the Earth's outer atmosphere, extending above about 85 km altitude.

Universal Time (UT) : Standard time of the Greenwich Meridian.

A Mathematical Supplement

These notes are provided for readers who may like to see some of the mathematics that underlie the non-mathematical exposition presented in the body of this book. It is not necessary to study these notes in order to follow the discussions in the main part of the book.

1. Plasma Oscillations

Consider the electron oscillations with positive ions behaving like a rigid jelly with uniform density of positive charge n_0e. Embedded in this jelly and free to move, is an initially uniform electron distribution of charge density $-n_0e$. While choosing an orthogonal system of co-ordinates, consider the portion of the plasma included between two planes at distance L, each perpendicular to the x-axis. Suppose each electron between these planes is to be displaced in the x-direction by a $\xi(x)$ which is independent of the y and z coordinates and is zero at each bounding plane. If the displacement is a continuous function of x and $\partial\xi/\partial x$ is small when compared to unity, the change in density caused by the electron displacement is

$$\delta n_e = n_0(\partial\xi/\partial x)$$

Originally, the net charge was zero, but after the displacement, Poisson's equation gives

$$\partial E/\partial x = 4\pi e\delta n_e$$

E being the electric field strength. Eliminating δn_e from the equations above, we obtain

$$\partial E/\partial x = 4\pi n_0 e(\partial\xi/\partial x),$$

which, on integrating, gives

$$E = 4\pi n_0 e\xi$$

for the field arising from the electron displacement only. (The neglected arbitrary constant represents a uniform external field.) The force on each electron is

$$-eE = m_e \frac{\partial^2 \xi}{\partial t^2}$$

which gives

$$m_e \frac{\partial^2 \xi}{\partial t^2} + 4\pi n_0 e^2 \xi = 0$$

or

$$\frac{\partial^2 \xi}{\partial t^2} = -\omega_p^2 \xi(x, t)$$

for the equation of motion. The frequency of oscillation is, therefore, seen to be

$$\omega_{pe} = \left(\frac{4\pi n_0 e^2}{m_e} \right)^{1/2}$$

Thus, the electrons in a homogeneous plasma are observed to have a natural resonant frequency, called the plasma frequency or Langmuir frequency. The quantity ω_p is the characteristic oscillation rate for electrostatic disturbances in plasmas. For electron oscillations, the numerical values of ω_p can be given by the approximate formula

$$f_p = \frac{\omega_p}{2\pi} \approx 9000\sqrt{n_e}\, Hz$$

where n_e is expressed in cm^{-3}.

2. Refractive Index of Plasma

(i) Definition of Dielectric Function

It is sometimes convenient to express the displacement vector **D** in terms of polarisation **P**:

$$\mathbf{D} = \mathbf{E} + 4\pi \mathbf{P}$$

Then, the dielectric function is defined as

$$\epsilon(\omega) = \frac{\mathbf{D}(\omega)}{\mathbf{E}(\omega)}$$

and can be written as

$$\epsilon(\omega) = 1 + 4\pi\frac{\mathbf{P}(\omega)}{\mathbf{E}(\omega)}$$

where **E**, **P**, **D** (as the notation emphasizes) have the common frequency ω.

To express $\epsilon(\omega)$ as a function of plasma parameters, we should try to get the relation between $\mathbf{P}(\omega)$ and $\mathbf{E}(\omega)$.

(II) High-frequency Dielectric Constant of Plasma

When a high-frequency oscillating electric field is applied to the plasma, the equation of motion for electron fluid yields

$$m_e\frac{d\mathbf{v}}{dt} = -e\mathbf{E}, \quad \mathbf{E} = \mathbf{E}_0 e^{-i\omega t}$$

which gives

$$\mathbf{v} = -\frac{ie}{m_e\omega}\mathbf{E}.$$

The displacement **r** of the electrons due to the electric field is obtained as

$$\frac{d\mathbf{r}}{dt} = -\frac{ie}{m_e\omega}\mathbf{E}$$

which yields

$$\mathbf{r} = \frac{e\mathbf{E}}{m_e\omega^2}$$

Polarisation is the dipole moment per unit volume which is equal to $-e|\mathbf{r}|$. Summing up all the electrons, we get

$$\mathbf{P} = \sum -|e|\mathbf{r} = -\frac{n_e e^2}{m_e\omega^2}\mathbf{E}$$

Hence,

$$\mathbf{D} = \epsilon\mathbf{E} \equiv \mathbf{E} + 4\pi\mathbf{P} = \left(1 - \frac{4\pi n_e e^2}{m_e\omega^2}\right)\mathbf{E}$$

The dielectric constant for a cold and collisionless plasma at high frequencies is, therefore, given by

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

where ω_p is the electron plasma frequency. The refractive index is given by $[\epsilon(\omega)]^{1/2}$, therefore

$$n(\omega) = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}$$

3. Motion of Charged Particles in a Uniform Magnetic Field

Consider a uniform magnetic field $\vec{B} = (0, 0, B)$. The Lorentz equation of motion when the electric field $\vec{E} = 0$, gives

$$m\frac{\partial \vec{v}}{dt} = \frac{q}{c}\vec{v} \times \vec{B}$$

where q is the particle charge.

From this equation

$$v_z = \text{ constant}, \quad \frac{d^2 v_x}{dt^2} = -\omega_c^2 v_x, \quad \frac{d^2 v_y}{dt^2} = -\omega_c^2 v_y,$$

where $\omega_c = \dfrac{qB}{mc}$, is the Larmor or gyrofrequency. From the equations for v_x and v_y we note that a particle with initial velocity $v_\parallel$ along the magnetic field and $v_\perp$ transverse to the magnetic field will have a constant motion along the magnetic field and a circular trajectory about a point determined by initial conditions (x_0, y_0). The radius of the circular trajectory is the Larmor radius r_L given as

$$r_L = \frac{v_\perp}{\omega_c} = \frac{m v_\perp c}{eB}$$

Thus, the trajectory of a charged particle in the presence of a uniform magnetic field is a helix with its axis parallel to $\vec{B}$.

The pitch angle α of the helical motion is the angle between the vector $\vec{v}$ and the vector $\vec{B}$. It is defined as

$$\alpha = \tan^{-1} v_\perp / v_\parallel$$

Note that $v_\parallel = v \cos \alpha$ and $v_\perp = v \sin \alpha$, where $v, v_\parallel$ and $v_\perp$ are magnitudes of $\vec{v}, \vec{v}_\parallel$ and $\vec{v}_\perp$. When $\alpha = \pi/2, v_\parallel = 0$ and when $\alpha = 0$, $v_\perp = 0$.

4. Refractive Index of Plasma in the Presence of the Magnetic Field

The presence of the magnetic field introduces anisotropy, and the refractive index depends on the angle of propagation of the electromagnetic wave, with respect to the magnetic field direction. Consider the simple and important case of propagation of the wave along the magnetic field. The wave splits into two modes with a right and a left circular polarisation. The refractive index for these modes are

$$n_R^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega - \omega_{ce})} - \frac{\omega_{pi}^2}{\omega(\omega + \omega_{ci})}$$

$$n_L^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + \omega_{ce})} - \frac{\omega_{pi}^2}{\omega(\omega - \omega_{ci})}$$

The new characteristic frequencies which enter the expressions for phase velocities are ω_{ce} and ω_{ci}; the electron and ion Larmor or gyrofrequencies.

(i) Whistler wave

Not considering the ion motion the expression for n_R is given as

$$n_R^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega - \omega_{ce})}$$

For $\omega_{ci} < \omega \ll \omega_{ce}$, it gives the whistler wave with group velocity as

$$v_g = \frac{\partial \omega}{\partial k} \alpha \omega^{1/2}.$$

Hence, the high frequency components of the wave arrive first, followed by the low frequency waves. This produces the whistling tone.

(ii) Alfvén wave

Considering very low frequency waves $\omega \ll \omega_{ci} < \omega_{ce}$, the motion of ions cannot be neglected. In this case, we can show that

$$n_R^2 = n_L^2 = 1 + \frac{4\pi\rho c^2}{B_0^2}$$

where $\rho = n_0 m_i$. From this we get

$$\frac{c^2k^2}{\omega^2} = 1 + \frac{c^2}{v_A^2}$$

which gives $\frac{\omega^2}{k^2} = v_A^2$, the Alfvén wave with velocity $v_A = B_0/(4\pi\rho)^{1/2}$.

5. Magnetic mirrors

The non-uniform configuration of the magnetic field such that grad-$\vec{B}$ is parallel to $\vec{B}$ gives the magnetic mirror effect.

The magnetic moment is given as : $\mu = IA$, where I is the current in the loop with area A. For a charged particle $I = \frac{e\omega_c}{e\pi}$ and $A = \pi r_L^2$, this gives

$$\mu = \frac{1}{2}\frac{mv_\perp^2}{2}.$$

Without formal proof, we would like to point out that when a particle moves into regions of stronger or weaker $\vec{B}$, its Larmor radius changes, but μ, remains invariant of motion.

The invariance of μ is the basis for one of the primary schemes for plasma confinement, the magnetic mirror. As a particle moves from a weak-field region to a strong-field region in the course of its thermal motion, it sees an increasing B, and therefore its $v_\perp$ must increase in order to keep μ constant. Since its total energy must remain constant, $v_\parallel$ must necessarily decrease. If B is high enough in the "throat" of the mirror, $v_\parallel$ eventually becomes zero; and the particle is "reflected" back to the weak-field region due to the magnetic force. The non-uniform field of a simple pair of coils forms two magnetic mirrors between which plasma can be trapped. This effect works on both ions and electrons.

The trapping is not perfect, however. For instance, a particle with $v_\perp = 0$ will have no magnetic moment and will not feel any force along B. A particle with small $v_\perp/v_\parallel$ at the mid-plane ($B = B_0$) will also escape if the maximum field B_m is not large enough. For, given B_0 and B_m, which particles will escape? A particle with $v_\perp = v_{\perp 0}$ and $v_\parallel = v_{\parallel 0}$ at the mid-plane will have $v_\parallel = 0$ at its turning point. Let the field be B_m there. Then, the invariance of μ yields

$$(1/2)mv_{\perp 0}^2/B_0 = (1/2)mv_{\perp}^2/B_m.$$

$$v_{\perp 0} = v \sin \alpha, v_{\parallel 0} = v \cos \alpha$$

Combining the above equations, we find

$$\frac{v \sin^2\alpha_0}{B_0} = \frac{v \sin^2\alpha}{B_m}$$

$$\frac{\sin^2\alpha_0}{\sin^2\alpha} = \frac{B_0}{B_m}$$

For $v_{\perp} = 0$, that is, $\alpha = 0$, $v_{\parallel}$ only exists and therefore the particle escapes. When $\alpha = \pi/2, v_{\perp}$ exists, but $v_{\parallel} = 0$. In this case

$$\sin^2\alpha_0 = B_0/B_m = 1/R_m$$

where R_m is the mirror ratio. This equation defines the boundary of a region in velocity space in the shape of a cone, called the loss cone. For $\alpha > \alpha_0$, particles are confined. Particles lying within the loss cone $0 < \alpha < \alpha_0$ are not confined. Consequently, a mirror-confined plasma is never isotropic. Note that the loss cone is independent of q or m. Without collisions, both ions and electrons are equally well confined. When collisions occur, particles are lost when they change their pitch angle in a collision and are scattered into the loss cone. Generally, electrons are lost more easily because they have a higher collision frequency.

6. The $\vec{E} \times \vec{B}$ Drift

If we allow an electric field to be present, the motion of the charged particle as considered in Section 3 will be found to be the sum of two motions: the usual circular Larmor gyration plus a *drift* of the guiding center, the centre of the circular orbit. We may choose E to lie in the x-z plane so that $E_y = 0$. The equation of motion is now

$$m\frac{d\vec{v}}{dt} = q\left(\vec{E} + \frac{1}{c}\vec{v} \times \vec{B}\right)$$

The z component gives

$$\frac{dv_z}{dt} = \frac{q}{m}E_z$$

or

$$v_z = \frac{qE_z}{m}t + v_{z0}$$

This is a straightforward acceleration along $\vec{B}$. The transverse components of $\vec{v}$ are given as

$$\frac{dv_x}{dt} = \frac{q}{m}E_x \pm \omega_c v_y$$

$$\frac{dv_y}{dt} = 0 \pm \omega_c v_x$$

Here, $\pm$ signs are for positive and negative charges. Differentiating, we have (for constant E)

$$\ddot{v}_x = -\omega_c^2 v_x$$

$$\ddot{v}_y = \pm\omega_c \left(\frac{q}{m}E_x \pm \omega_c v_y\right) = -\omega_c^2 \left(\frac{E_x}{B} + v_y\right)$$

We can write this as

$$\frac{d^2}{dt^2}\left(v_y + \frac{E_x}{B}\right) = -\omega_c^2 \left(v_y + \frac{E_x}{B}\right)$$

so that this equation is reduced to the case in section 3, if we replace v_y by $v_y + (E_x/B)$.

The Larmor motion is the same as before, but there is a superimposed drift v_E of the guiding center in the $-y$ direction (for $E_x > 0$).

The general formula for electric drift can be written as

$$v_E = c\frac{E \times B}{B^2} = \frac{c}{q}\frac{F \times B}{B^2}$$

where $F =$ Electric Force qE. Substitution of various other forces for $\vec{F}$ gives different types of drift velocities.

7. Fluid-like behaviour of plasma

The set of one-fluid equations when a plasma is assumed to behave as a conductor are:

Modified Maxwell's Equations

$$\begin{aligned} \text{curl}\,\vec{E} &= -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \\ \nabla\cdot\vec{B} &= 0 \\ \nabla\times\vec{H} &= \frac{4\pi}{c}\vec{J} \\ \nabla\cdot\vec{D} &= 0. \end{aligned}$$

In the MHD theory the displacement current and free charges are neglected as the phenomena studied are of low frequency and the accumulation of charged particles does not occur as the system is a good electric conductor.

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla\cdot\rho\vec{v} = 0.$$

Equation of Motion

$$\rho\frac{d\vec{v}}{dt} = \frac{1}{c}\vec{J}\times\vec{B} - \nabla p$$

The force $\vec{J}\times\vec{B}$ arises as a coupling between fluid motion and magnetic field.

Ohms Law

$$\vec{J} = \sigma\left(\vec{E} + \frac{1}{c}\vec{v}\times\vec{B}\right).$$

Equation of state

$$\begin{aligned} \frac{d}{dt}(p/\rho) &= 0, \quad \text{for adiabatic fluid motion} \\ \frac{d}{dt}(p/\rho^{\gamma}) &= 0, \quad \text{for isothermal fluid motion} \end{aligned}$$

Here γ is the ratio of specific heat. In addition, we have constitutive relations between the field variables

$$\begin{aligned} \vec{B} &= \mu_0\vec{H} \\ \vec{D} &= \sigma_0\vec{E} \end{aligned}$$

8. Diffusion of the magnetic field in plasmas

Using Maxwell's equations and Ohm's law by taking $\epsilon_0 = \mu_0 = 1$, we get

$$\begin{aligned}\frac{\partial \vec{H}}{\partial t} &= -\text{curl}\frac{\vec{J}}{\sigma} + \text{curl}(\vec{v} \times \vec{H}) \\ &= \frac{c^2}{4\pi\sigma}\nabla^2\vec{H} + \text{curl}(\vec{v} \times \vec{H})\end{aligned}$$

When $\vec{v} = 0$,

$$\frac{\partial \vec{B}}{\partial t} = -\lambda\nabla^2\vec{B}, \quad \text{where } \lambda = \left(\frac{c^2}{4\pi\sigma}\right)$$

This has the form of a diffusion equation, the quantity λ can be called the magnetic diffusivity. The equation thus indicates that the field leaks through the plasma from point to point, resulting in decay of the field.

Dimensional arguments indicate a time of decay of the order of $L^2\lambda^{-1} = t$, where L is a characteristic spatial scale-length of $\vec{B}$.

The diffusion time is proportional to L^2 and σ, since σ is large for MHD fluids the combination $L^2\sigma$ is very large for space plasmas, making the diffusion time for magnetic fields very long.

9. Frozen-in-field concept

Now, consider a different limiting case: suppose the plasma is in motion, but has negligible resistivity. Then the induction equation in section 8 gives

$$\frac{d\vec{H}}{\partial t} = \text{curl}(\vec{v} \times \vec{H})$$

This equation is identical in form to the vorticity equation of an ordinary homogeneous inviscid fluid. An important theorem derived from this equation states that:

> "Fluid elements that lie on a vortex line continue to lie on the same vortex line".

Extending this theorem to conducting fluids, Alfvén in 1942, deduced that

"Fluid elements that lie on a magnetic fluid line remain on the same field line".

This formed the basis for the frozen-in-fluid concept in magnetohydrodynamics.

10. ALFVÉN WAVES

The force $\vec{J} \times \vec{B} \equiv \vec{J} \times \mu\vec{H}$, can be interpreted in terms of Maxwell's stresses:

$$\vec{J} \times \mu\vec{H} = -\text{grad}(\mu H^2/8\pi) + div(\mu\vec{H}\vec{H}/4\pi),$$

where the last term denotes the divergence of a dyad. The first term represents the hydrostatic pressure $\mu H^2/8\pi$ and the second gives the tension $\mu H^2/4\pi$.

From the equation of motion, it is seen that for an incompressible fluid the hydrostatic pressure can be balanced by the pressure of the fluid, so that only the tension $\mu H^2/4\pi$ remains effective. The analogy with the theory of stretched strings suggests that this tension may lead to the possibility of transverse waves along the lines of force, with a velocity V_A given by

$$V_A^2 = \mu H_0^2/4\pi\rho,$$

where ρ is the mass density of the fluid. Since the magnetic lines are frozen in the fluid, the mass density can be taken as ρ, the fluid density.

11. DIAMAGNETIC CURRENT

We shall see how currents are produced in magnetohydrodynamic fluids, taking a simple case when the fluid is not flowing. The equation of motion in this case gives

$$\nabla p = \vec{J} \times \vec{B}.$$

Taking the cross-product with $\vec{B}$, we get

$$J_\perp = \frac{\vec{B} \times \nabla p}{B^2}$$

This current arises from the coupling of the pressure gradient (found usually at a boundary) and the local magnetic field $\vec{B}$.

This is a diamagnetic current as it always flows in such a direction as to reduce the magnetic field intensity in the fluid.

In the Chapman–Ferraro model the solar wind (with no magnetic field assumption) interacts with the planetary magnetic field (with no plasma particles assumption). Hence, $p \equiv p_{sw}$ is the solar wind pressure, $\vec{J}_{mp}$ is the magnetopause current and $\vec{B}$ is the planetary magnetic field. Magnetopause current is, therefore,

$$\vec{J}_{mp} = \vec{B}_p \times \frac{\nabla p_{sw}}{B^2}$$

and since on the equator the magnetic field is pointing outward (for Earth), J_{mp} runs from dawn to dusk along the magnetospheric boundary.

12. MHD GENERATOR

For a conducting fluid in the limiting case when conductivity is infinite,

$$\frac{\partial \vec{B}}{\partial t} = \mathrm{curl}(\vec{v} \times \vec{B})$$

which, in comparison with Maxwell's equation,

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E},$$

shows that the electric field in an infinitely conducting medium is given by

$$\vec{E}_\perp = -\vec{v} \times \vec{B}$$

Taking the cross-product of this equation with $\vec{B}$ gives

$$\vec{E} \times \vec{B} = B^2 \vec{v}$$

which, in turn, yields

$$v_\perp = \frac{\vec{E} \times \vec{B}}{B^2}$$

In an ideal conducting fluid, thereafter, there is a relationship between $\vec{E}$ and $\vec{v}$ across $\vec{B}$, such that the existence of motion implies the existence of the electric field or vice versa. In the direction parallel to $\vec{B}$, charged particles move very freely. This means that the magnetic field acts like a perfect electrical conductor, transmitting perpendicular electric fields and voltages across vast distances with no change in the potential in the direction parallel to $\vec{B}$. Thus, any flowing magnetised plasma can act as a source of voltage if there is a component of $\vec{v}$ perpendicular to $\vec{B}$.

From this, we can briefly describe the interplanetary electric field. Taking to first order that the solar wind is blowing radially outward from the sun with velocity $\vec{v}_{sw}$, then, in the ecliptic plane

$$\vec{v}_{sw} = -|\vec{v}_{sw}|\vec{x}.$$

In a reference frame fixed to the Earth, there will be an electric field given by

$$\vec{E}_{sw} = -\vec{v}_{sw} \times \vec{B}_{sw},$$

where $\vec{B}_{sw}$ is the interplanetary magnetic field. This will generate a potential difference across the Earth's magnetosphere, given by

$$\vec{v}_m = -\vec{E}_{sw} \cdot L\hat{y}$$

where L is the effective width of the magnetosphere perpendicular to $\vec{V}_{sw}$. E_{sw} has a dusk-to-dawn direction when B_{sw} has a positive z-component and, with a negative z-component, the electric field is in the dawn-to-dusk direction. For typical values of $v_{sw} = 500km/s$, $B_{swz} = 5 \times 10^{-9}$ tesla, $E_{sw} = 2.5 \times 10^{-3} V/m, L = 20R_E$, we can get a rough estimate of length across the magnetosphere. This gives the potential difference of the order of 300 000 volts. The Earth is thus immersed in a magnetohydrodynamic electrical generator capable of hundreds of kilo-electron-volts of potential energy.

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Index