3

MAGNETIC FIELD THAT EXTENDS INTO SPACE

The advent of balloons, rockets, satellites and space probes is of great help in exploring external magnetic field and aeronomic changes. This study requires sophistication achieved by USA, Russia, and European community. The contribution by India is limited to the analyses and studies of these procured satellite and space data. The geomagnetic surface data alone provide no clue, unless the process of solar wind and solar plasma stream interactions with the geomagnetic field are better understood and modelled. The cause in the form of solar wind interaction produces various effects such as ring current, charged particle diffusion, scattering and final precipitation in the auroral zone. Simple Ohm's law and Ampere's law are at work in the production of various currents and geomagnetic field changes on the global scale. The morphological changes in the geomagnetic field play an important role in generating micropulsations and accelerating charged particles by annihilating magnetic field at the X-type neutral point in the geomagnetic tail.

Significant insight into the nature of changing geomagnetic field has been obtained only during the course of the early twentieth century, after the advent of the satellite era. While the major part of EMF emanates from within (the main field), a small but potentially significant fraction (~1 to 2 per cent) has its origin external to the Earth (the variation field), with the Sun as the main source. Even as one is separated by ~150 million kilometres from it, continuous changes in the thermal and magnetic state of the Sun are manifested in the EMF variations down to fluctuations of even very small magnitude. At the same time, observed variations of the surface magnetic field serve as a very useful diagnostic tool for deciphering the transformation processes that occur in the vast open space 'between the Sun and Earth'. Currents flowing in the ionospheric E-layer result in transient variations of magnetic field that are fairly smooth. In contrast, rapid and irregular variations are usually produced by charged particles of

N. Basavaiah, *Geomagnetism*

solar origin. Geomagnetic field variations covering a wide range of frequencies are also very useful in understanding the physical and chemical properties of the interior of the Earth at different depths and provide clues to the locations of nonrenewable resources (chapters 2 and 6).

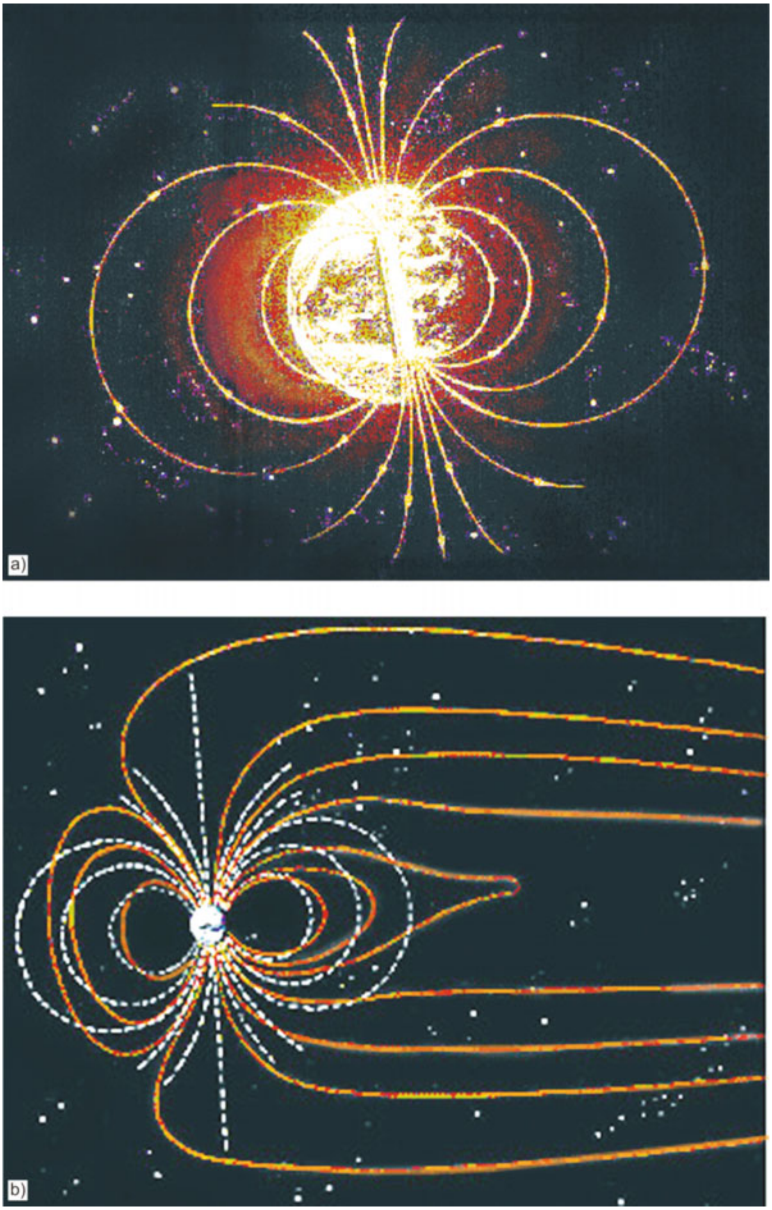

Figure 3.1. (a) Ideally the magnetic field of the Earth defines symmetry. (b) Earth's magnetic field is roughly that of a bar magnet but the solar wind tends to contract from one side (http://www-istp.gsfc.nasa.gov/Education/Imagnet.html).

The lines of force of the dipole (main field) component of EMF leave the Earth from its southern end to rejoin the globe at the northern defining symmetry (Fig. 3.1). This sphere along with the magnetic lines of force can be cut along its axial plane into two identical halves. However, in reality, this is not the case. The magnetic field lines are contracted from one side (Fig. 3.2) and the opposite side is stretched. The symmetry is lost because of the Sun. Of all the celestial bodies, Sun is the sole source of light and energy that supports and sustains life on Earth. However, if the EMF was not in its place, the Sun and other celestial bodies would (probably) have extinguished the flames of life. Sun emits visible and ultraviolet light, X-rays and charged particles, which have deleterious effects on life. Magnetic field lines that flank the Earth deflect the charged particles. This chapter focuses on the historical note of rocket-borne–balloon experiments, aeronomy, ionospheric-magnetospheric interaction, equatorial magnetic field and its solar-lunar characters, solar-interplanetary parameters and their association with low latitude geomagnetic field variations, electrojet-counter electrojet studies and low latitude scintillations/micro-pulsations/airglow.

3.1 STRUCTURE OF THE EARTH'S ATMOSPHERE: TRADITIONAL VIEW

The invention of mercury barometer (Fig. 3.2) by Torricelli and Viviani led to the discovery of finite weight of air, which was fourteen and seven tenths pound/sq inch. It also later became known that temperature changes with height.

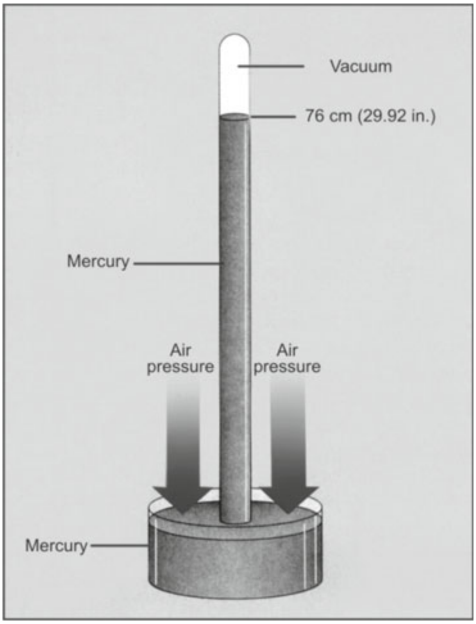

Figure 3.2. The mercury barometer (Tarbuck and Lutgens, 1994).

But there isn't any definite boundary to the atmosphere. It is transient, which fades off gradually into far-off space.

To reach physically to a height of more than few kilometres is impossible. In 1749, Wilson used a kite attached with thermometers to measure atmospheric temperatures at different altitudes. The first balloon was launched in 1782 by two French brothers Michel and Montgolfier. Three men reached an elevation of 10 km, but only one, Tissandier survived. By 1892, however, unmanned balloons with instruments went higher and came back with the data on pressure and temperature conditions which revealed temperature dropped in the first few miles in the sky. It was –55°C at 11 km, above which the temperature increased slightly.

Traditionally, the Earth's atmosphere has been studied by dividing it into various regions based on temperature profiles, conductivity or electron density (Fig. 3.3a). Each region is studied in isolation as far as the electrodynamical processes are concerned. In initial years, it was thought that atmosphere had two layers. Bort in 1908 named these two layers as troposphere and stratosphere (Fig. 3.3b).

Troposphere: In Greek, troposphere means 'the sphere of change', and is the most turbulent. It extends from the Earth's surface to ~10 km. Stratosphere means 'sphere of layers' and contains sublayers of lighter gases such as helium

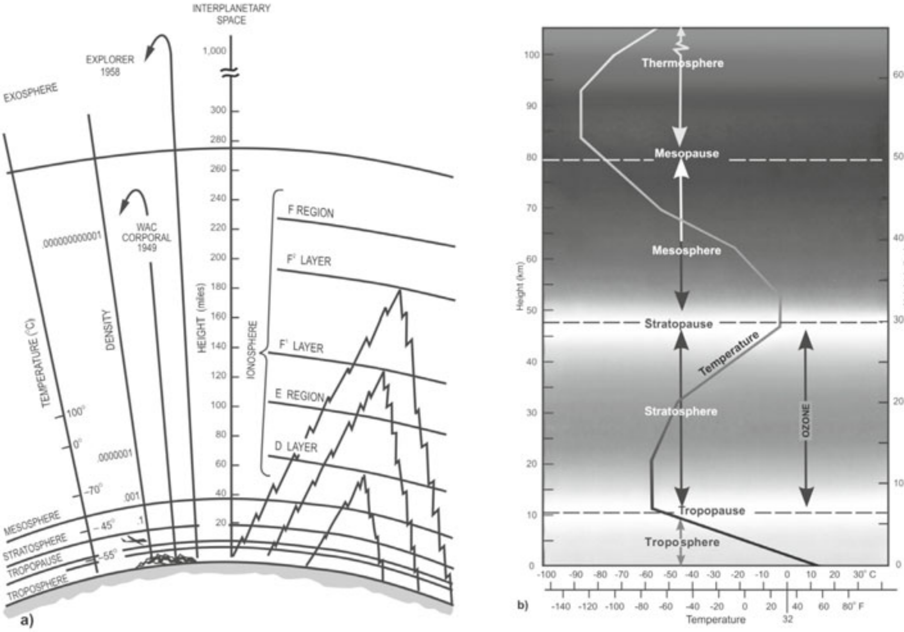

Figure 3.3. (a) Different layers of atmosphere, with their temperature and density profile (Asimov, 1979). 1 mile = 1.6 km. (b) Different layers of atmosphere with their temperature profile.

and hydrogen. Sandwiched between troposphere and stratosphere is ‘tropopause’ meaning ‘end of change’. This was so-named because here the temperature drops from an average of 20°C on the Earth’s surface to –60°C at the tropopause, whose height varies from ~16 km above msl at the equator to just ~8 km over the poles.

Stratosphere: It starts from above the tropopause (~10 km) and extends up to stratopause (~50 km), where the temperature profile attains the maximum value (Fig. 3.3b). Galactic cosmic rays are the prime source of ionization in this region. The conductivity, which is roughly of the order of 10^{-14} S/m at the Earth’s surface, increases exponentially with altitude in the troposphere-stratosphere region; the main charge carriers being the small positive and negative ions.

Ten kilometres is the upper limit beyond which man cannot survive without oxygen. Hence, sealed cabins were designed, in which pressure and temperature at the Earth’s surface was maintained, helping to touch the stratosphere. In 1931, Auguste and Felix reached a height of 18 km with the help of sealed cabins. Later, lighter and plastic balloons enabled man to go even higher and helped prolong his stay up there. A balloon named Explorer I went up to 21 km in 1938. By 1960, however, manned balloons had gone as high as 34 km and unmanned balloons almost to 46 km.

Rockets utility in space research: With the scaling of newer and higher altitudes, the impermanency of constant temperature established itself. The atmosphere above stratosphere was penetrated by rockets. The primitive form of rocket was used by Chinese in the thirteenth century as a means to frighten away the enemy. But, it was Tipu Sultan, who was the first to design and develop rockets in Srirangapatna (Karnataka) for their use during the Mysore wars waged against the British.

The World War II witnessed American ‘Bazooka’ and the Soviet ‘Katusha’, which were basically rocket-propelled packets of explosives. But, the use of rockets was not meant for just destructive purposes. At the fag end of the twentieth century, an idea occurred independently to Tsiolkovsky and Goddard, wherein they proposed the use of rockets to explore upper atmosphere and space. The publications of these two launched an era of space research. Telemetering was also a great help in this endeavour.

Telemetering: Telemetering measures a particular component like temperature or pressure from a ‘distance’. For instance, it measures temperature in an electrical impulse, which is transmitted back to the Earth’s surface, where it is ‘translated’ and then quantified. Molchanoff was the first to send the telemeter to atmosphere enclosed in a balloon.

Mesosphere: By the potent combination of rockets and telemetering, it was seen for the first time that above stratosphere at a height of ~48 km, the temperature rose to a maximum of –10°C. It then again dropped to a low of –90°C at 80 km height. Sydney Chapman coined the term ‘mesosphere’ in

1950 for this region, which witnessed the rise and fall in temperature. The major sources of ionization in the mesosphere are the solar Layman-alpha radiation, X-ray radiation and the intense auroral particle precipitation. The conductivity increases sharply in this region. The main charge carriers are electrons, positive ions (e.g. N_2^+, O_2^+, NO^+) and the negative ions (e.g. O_2^-).

Thermosphere: This is the outermost region of the Earth's atmosphere. It extends from a height of 80 km to the outer edge of the atmosphere at ~400 km above the Earth's surface. Since it receives energy directly from the Sun, the temperature in it rises from –95°C to ~400°C. Although the air is very thin, the scattering of air atoms steadily increases in temperature to ~1000°C at 480 km and above. Hence, this region is called 'thermosphere', i.e. 'the sphere of heat'. Above 480 km lies 'exosphere' which extends to as high as 1600 km and gradually merges into interplanetary space. Spitzer coined the term 'exosphere' in 1949.

Ionosphere: On account of low air pressure, the UV rays and X-rays coming from the Sun cause heavy ionization in this region. In other words, the ionosphere, which starts from the top layers of mesosphere, overlaps the thermosphere from 60 to ~500 km above the Earth's surface. The D-region of the ionosphere extends from ~60 to 90 km. The ionosphere proper (e.g. E and F regions) starts from above the mesosphere, and extends to ~500 km. The major sources of ionization in the ionosphere are EUV and X-ray radiation from the Sun and energetic particle precipitation from the magnetosphere into the auroral ionosphere. The current carriers are electrons and positive ions like NO^+, O_2^+ and O^+. Electrical conductivity becomes anisotropic in this region with parallel conductivity (with respect to geomagnetic field) exceeding the transverse conductivities by several orders of magnitude.

Svante August Arrhenius's genius: Arrhenius suggested that 'ions' were charged atoms to explain the behaviour of certain solutions that conducted electric current. He advanced this notion through his doctoral thesis in 1884. But his idea of charged atoms was revolutionary since many were unaware of charged particles residing within an atom. The electron was discovered in 1890, which made phenomenal sense of Arrhenius's doctoral thesis and was awarded the Nobel Prize in chemistry in 1903.

The discovery of ions in atmosphere came much later, made possible mainly by experimental endeavours carried by Marconi with the wireless. Marconi on 12 Dec 1901 sent signals (Morse code) from Cornwall, England to Newfoundland, Canada across the Atlantic ocean covering a distance of ~2900 km. The passage of the signal across the two cities baffled those who know that radio waves travel only in a straight line. But the distance from Cornwall and Newfoundland formed a curvature. The travel of radio waves in a curved manner became an enigma for all scientists of the day. Just a year after the Marconi's experiment, in 1902, Heaviside and Kennelly suggested a layer of charged particles situated high up in the atmosphere reflected the radio waves.

This layer was located in 1920, which has since been called the 'Kennelly-Heaviside layer'.

Discovery of Kennelly-Heaviside layer: Appleton discovered the Kennelly-Heaviside layer, which reflected back radio waves. Appleton wondered on the fading of the signal. Musing over it, he decided the fading occurred because of interference of two versions of the same signal. He reckoned that if the fading was to occur, there has to be a signal, which directly hit the receiver that was released from a transmitter and the other reached the receiver via a circuitous route by reflection from upper atmosphere. This second wave was a delayed one and so was out of phase with the first one. They thus interfere with each other partly canceling each other out causing the fading out of the signal.

Appleton located this reflecting layer by sending signals of a particular wavelength, and found to be at 104 km. Appleton also noticed the radio signals generally faded during night. He reckoned that shortly before dawn, radio waves are not reflected by the Kennelly-Heaviside layer but are reflected back from still higher layers, which begin at 224 km height. These are called the 'Appleton layers', an honour as magnificent as the Noble Prize (physics) awarded to Appleton in 1947 for these stupendous discoveries.

Ionospheric layers and space communication: Watson-Watt introduced the term 'ionosphere' in 1930 (Fig. 3.3a). The electron density in the ionosphere is especially very high in the region extending from 90 to 150 km. It is called the Kennelly-Heaviside layer (D-layer) and above which at a height of 224 km is the E-region. Another region in which electron density is very high extends from ~250 to 350 km and is called Appleton layers (F-layers) – the F_1 layer at 224 km and F_2 layer at 320 km. F_1-layer is the richest in ions, while F_2-layer is significantly stronger only during the daytime. The ionosphere reflects radio waves ranging in frequency from 2 to 30 MHz. Hence, it plays an important role in space communication. Electromagnetic waves of frequencies higher than 30 MHz penetrate through the ionosphere.

Ionosondes: Most of the data on space communication have come from ionosondes. For each concentration of electron densities, there is a plasma frequency below which all radio signals are refracted back to Earth regardless of the angle of incidence used. If the plasma frequency of the ionosphere is 5 MHz, then all radio signals transmitted vertically to the ionosphere that are <5 MHz return back to the Earth and all frequencies >5 MHz pass through the ionosphere into space. It is this characteristic of the ionosphere that is exploited to probe its properties through the ionosonde. An ionosonde is a device which combines a radio transmitter and receiver capable of transmitting pulses toward and above the ionosphere and receiving the same signal pulse as it returns back to the receiver. The pulsed ionosonde works by transmitting a series of pulses vertically upwards into the ionosphere, whereas the digisonde is highly sophisticated pulse amplitude sounder. The ionosphere is also studied through the chirp and oblique sounding methods.

3.2 STRUCTURE OF THE SUN: ASSOCIATION OF SUNSPOTS WITH TERRESTRIAL PHENOMENA

The Sun (Fig. 3.4) is the brightest star visible from Earth having surface temperatures close to 6000°C with a magnetic field strength of 0.1 to 0.2 nT. The Sun is entirely gaseous—a glowing ball of mainly incandescent hydrogen. Other elements all in gaseous state are ~10 part hydrogen to 1 part helium with a pinch of other elements like oxygen, carbon, nitrogen, magnesium and iron. The mass of the Sun is $\sim 2\times10^{30}$ kg. The density of the Sun at photosphere is ~140 kg/m^3, the density increases as one goes inwards to the core or the centre of the Sun, where the density is ~16000 kg/m^3 or 10 times that of ordinary metal.

Sunspot formation and magnetic fields: Magnetic fields play a great role on the Sun's photosphere. When solar material over a small area gets highly magnetized, a significant part of its thermal energy is converted into magnetic field energy and its temperature falls to ~4000 K from its initial value of ~6000 K. That is a sunspot (Fig. 3.4), an area of intense magnetic field, less bright than the surrounding area and therefore relatively dark. Sunspots greatly influence the electromagnetic state of the Earth.

The first features observed on Sun's surface are credited to Galileo, Scheiner and Fabricius. They observed the sunspots, which were first reported in 1609. The observation of the sunspots was aided by the invention of telescope designed

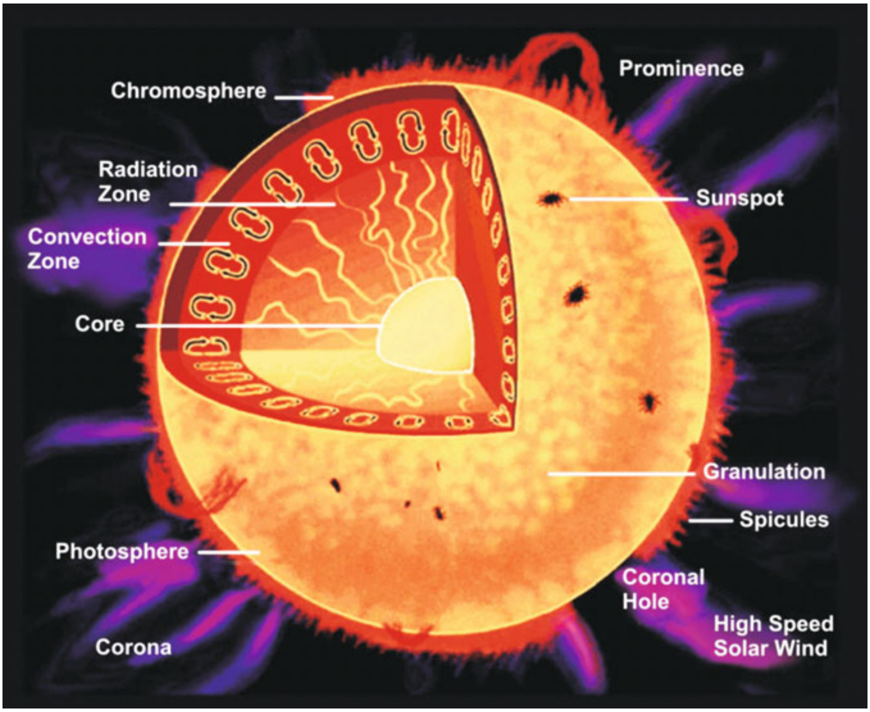

Figure 3.4. Different features associated with the Sun.

by Galileo. Scheiner later invented a safe method to project the Sun's image on a screen, so that it did not pose any threat to health. However, large sunspots are seen even with a naked eye. The initial enthusiasm for observing sunspots waned after 1645 because the sunspots disappeared completely for almost 70 years when Sun-gazers lost interest and went on to explore other phenomena.

Heinrich Schwabe perseverance: Schwabe was interested in spotting an unknown planet of the Sun. He tracked the planet that could be detected as a dark spot while passing against the bright background of the Sun. He maintained a strict vigil and kept a record of all the dark patches on the Sun. He observed the Sun for 17 years. Although he did not find the elusive planet, with the compiled observations that were at his disposal, he discerned a regular pattern in the appearance and disappearance of sunspots.

He published his findings in an article entitled 'solar observations during 1843'. Schwabe, however, found very few takers and none shared his excitement except Wolf, who was greatly impressed by his systematic observations. Some of Schwabe's excitement rubbed off on Wolf, who himself started looking out for sunspots. He collected all available sunspot data to devise the 'Zurich sunspot number' a statistical measure that gave the 11-year sunspot cycle.

The turning point came when Humboldt laid his eyes on Schwabe's article and included an updated version of the same writeup in his 'Kosmos'. This proved to be a great impetus. It acted as a catalyst and inspired many researchers to revive their interest in this neglected phenomenon. One such celebrated researcher was Carrington. His book 'observation of the spots of the Sun' published in 1863 contained observations from 1853 to 1861. Carrington on 1 Sept 1859 saw two patches of intensely bright and white light break out on the Sun. The patches grew in brightness that later faded out completely. What Carrington had seen was a solar flare, which are the great bursts of flaming hydrogen and these affect the Earth, the first inclination of which came to Carrington himself. After no more than 17 hours from the solar flare of 1 Sept 1859, Earth was bathed in a magnetic storm. '*This magnetic storm was recorded at all the Indian magnetic observatories that were in operation and the data are now used by national and international scientists to arrive at the intensity of the solar flare of 1 Sept 1859*'. The aurora produced by this storm was seen as far away as Cuba. Generally the aurora is only visible in the nearby polar region. Sabine also found an association between the sunspot cycle and occurrence of large magnetic storms. Sabine identified the source of magnetic storms with activity on the Sun.

Sunspot spectrum: Hale discovered the most prominent feature from the point of view of studies on magnetism in 1908. He deduced that the sunspots were greatly magnetic.

Newton in 1666 showed that light can be separated into a 'spectrum' of colours by passing a beam of light through a triangular-shaped prism of glass (Fig. 3.5), wherein it spreads out into a band made up of red, orange, yellow, green, blue, indigo and violet light.

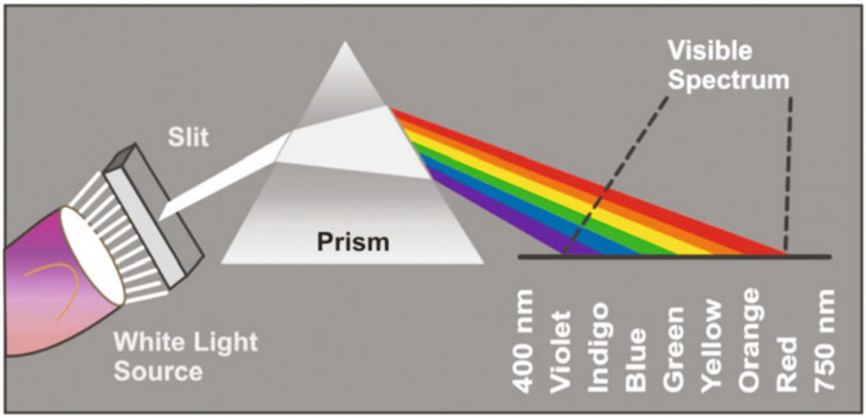

Figure 3.5. Newton showed that white light, on passing through a prism, split into 'rainbow' colours.

He also noticed that each colour faded gently into the other. By this experiment, Newton showed that sunlight (white light) is a mixture of many specific radiations. A prism separates (disperses) the colours because on passing from air into glass and from glass into air, light is bent or refracted, wherein each wavelength undergoes a different amount of refraction. The shorter the wavelength, the greater is the refraction. The short wavelengths of violet light are refracted the most, while the long wavelength of red light is refracted the least.

Utility of spectral lines: Angstrom identified hydrogen in the Sun in 1862 by the presence of spectral line characteristics of that element. Later, in 1868, Janssen while observing a total eclipse of the Sun in India sighted a spectral line that he could not identify with any known element. The line represented a new element, and so Lockyer named it helium from the Greek word for 'Sun'. Using this principle of spectral lines, a spectrograph was designed by Deslandres that produced photographic image of the Sun in a single spectral colour. However, in white light the Sun presented a dull appearance (Fig. 3.6a).

Spectroheliograph, an improvement over the spectrograph, invented by Hale, isolated light from higher layers in Sun's atmosphere and revealed many new features like the mottling of the surface, dark linear features and bright areas near sunspot (Fig. 3.6a-c).

Zeeman effect and sunspot magnetism: Hale and his collaborators found the first evidence of solar magnetic oscillation in their measurements of sunspot spectra. During these spectral studies, they discovered certain absorption lines in the spectra broadened and polarized. A strong similarity with absorption lines obtained in laboratory spectra of magnetized gases was also revealed. Zeeman, who in 1896 had discovered the 'Zeeman effect', studied such magnetized spectra. The Zeeman effect is one, where the spectral lines

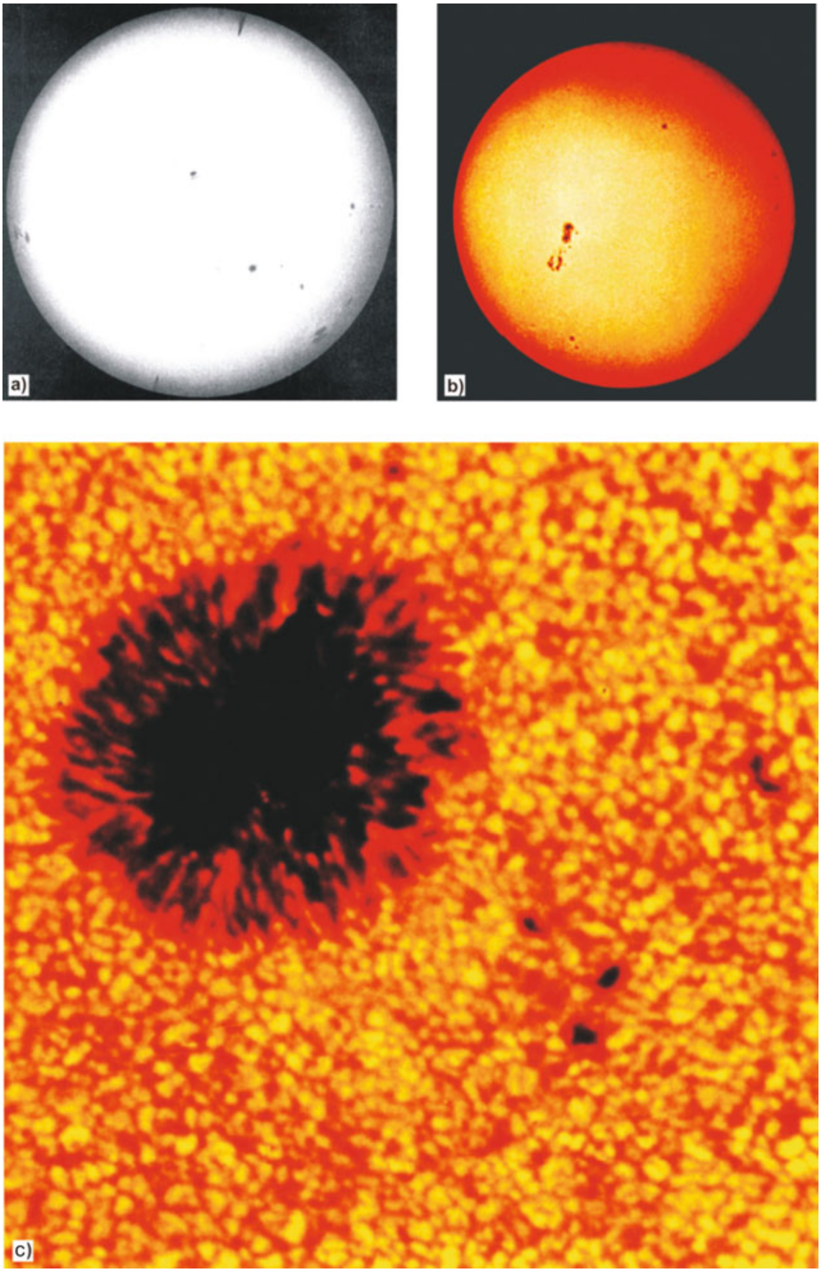

Figure 3.6. (a) A visible light photograph shows sunspots and bright areas called faculae, on the Sun's surface (http://www.eaas.co.uk/news/solar_features.html). (b) Sunspots seen over the surface of the Sun (Tarbuck and Lutgens, 1994). (c) Closer view of the 'sunspot' and the surrounding region. The fact that a magnetic field can occur in a hot, molten or gaseous body is a powerful argument in favour of the dynamo theory (Tarbuck and Lutgens, 1994).

(characteristic colours) of elements when emitted by a gas located in a magnetic field, split into two or more components of slightly different wavelengths. This separation is dependent on the intensity of the field as well. By analyzing this effect, Hale and his associates determined the strength of the magnetic field around sunspots to be between 100 and 400 nT, and also that these spots occurred in pairs that resembled giant magnetic dipoles oriented roughly parallel to solar equator. Hale's further studies enabled him to discern the so-called 11-year cycle to be actually the half of a 22-year solar magnetic cycle. During this 22-year cycle, sunspot groups reverse their polarity, wherein the switch occurred at minimum activity.

Hale's method of studying the magnetic field of sunspots and its adjoining areas were greatly refined by others like Babcock and Leighton, who used polarization of Zeeman lines and constructed a solar magnetograph. This enabled them to delineate an approximate dipole field of the Sun, which is of the order of 0.5 nT. Nevertheless, it was the confirmation of a long held view that the Sun has a magnetic field akin to that of the Earth. The Sun's magnetism is identified to extend to a substantial depth into its interior.

Variation in sunspot number and solar activity: The number of spots on the solar surface varies with time. Continuous observations for two centuries established sunspots reach a maximum number every 11.2 years on the average (Fig. 3.7a). Between, times of maxima, their number falls to a well defined minimum. During maximum of the sunspot cycle, more than 100 spots are seen on the Sun at a time. During sunspot cycle minima, very few spots are seen on the Sun. At the beginning, a few spots or group of spots appear at latitude of ±30° on the Sun. As the cycle progresses, the successive spots originate closer to the equator and by the end of the cycle they are ±5° away from the equator.

The sunspot number variation over the years 1601 to 1960 AD are computed by Waldmeier in 1961 (Fig. 3.7b). Notable highs in sunspot numbers are seen around 1725, 1780, 1840 and 1957. Since then, the highest activity seems to have occurred in 1990, in the current phase of high activity. In contrast to these notable highs in solar activity are extreme lows in activity. It was first pointed out by Spörer, Maunder and Clerke in 1890, 1894 and 1894 respectively (Table 3.1). This was confirmed by Eddy and Stuiver and Quay in 1976 and 1980

Table 3.1 Solar activity events and approximate period

Event	*Start*	*End*
Oort minimum	1040	1080
Medieval maximum	1100	1250
Wolf minimum	1280	1350
Spörer minimum	1450	1550
Maunder minimum	1645	1715
Dalton minimum	1790	1820
Modern maximum	1950	Ongoing

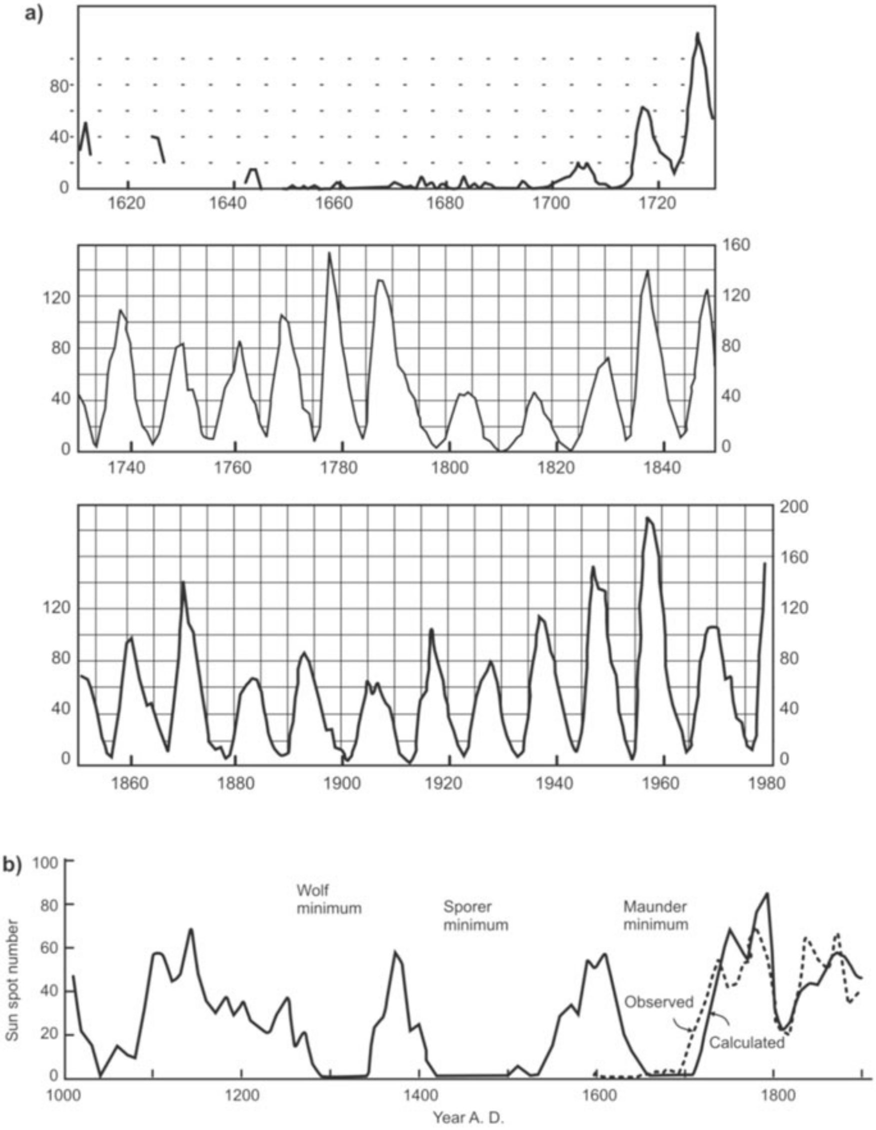

Figure 3.7. (a) Variation of the annual mean sunspot number from 1610 to 1700. The sunspots come and go on the Sun in an irregular cycle of ~11 years. (b) The Carbon-14 content in tree-rings is used to estimate the sunspot number of past centuries. The graphs for the period 1700-1900 AD show that the value calculated from ^{14}C content tally quite well with the actual values observed. This graph suggests three defined periods of very low solar activity ~1300, 1500 and 1700 AD, which are called respectively the Wolf minimum, Sporer minimum, and the Maunder minimum (Stuiver and Quay, 1980).

respectively from the examination of Carbon-14 abundances in tree rings. The work of Stuvier and Quay shows clear periods of almost zero sunspot at ~1040, 1300, 1480 and 1680 (Fig. 3.7b). Eddy in 1977 using Carbon-14 technique extended the sunspot number back to over 7000 years. It is tentatively attributed that these epochs of low solar activity coincided with ice ages on the Earth.

Sun's magnetic field: A magnetohydrodynamic dynamo operating in the Sun is most likely responsible for producing solar magnetic cycle. This dynamo is of the flux-transport type, which involves processes pertaining to generation of toroidal fields by differential rotation called the Ω-effect, regeneration of poloidal fields called the α-effect, and flux transport by meridional circulation. Thus, they have two separate components, the poloidal and toroidal field. Poloidal is a dipole field, which permeates the entire Sun and is closely aligned with the rotational axis. At the surface, it is concealed by much stronger elements of the toroidal field. The toroidal field, on the other hand, is wound from the poloidal field by differential rotation at latitudes below ~35°, where they emerge from the solar surface and are then carried polewards. An important feature of solar magnetic field is that all flux is concentrated into flux tubes and that these flux tubes are helically twisted into flux ropes. These concepts are helpful in satisfactorily explaining the equatorward migrating sunspot belt and the poleward migrating diffused fields. Lennard Fisk published a new model of the Sun's magnetic field and is quite different from other models. He suggested the magnetic field lines look like a wild tornado (Fig. 3.8), wherein in the older models they look like the path water takes while coming from a lawn sprinkler. Fisk's model takes into account the fact that the gases at the Sun's equator rotate faster than the gas at the poles and the Sun's magnetic field is constantly expanding. However, many knotty issues still remain unresolved with regard to genesis of solar magnetic field.

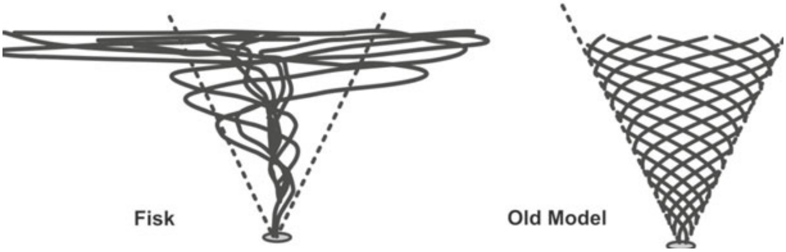

Figure 3.8. Comparison of Fisk's model to an older model (http://www.windows.ucar.edu/tour/link=/headline_universe/fisk.html).

Plasma is an ionized gas (deuterium or tritium which are isotopes of hydrogen) consisting of ions and electrons moving freely. It is found between stars and planets, where it takes the form of the solar wind. The Sun's atmosphere is overwhelmingly composed of such plasma. High temperatures reside at the surface of the Sun and its interior and because the gas is hotter at the Sun, its atoms get converted to ion. When this ion recombines with an electron, it reverts back again to being an atom. At lower temperatures, especially at Earth's atmospheric levels, this recombining phenomenon is possible because of which there are changes in ionospheric heights. However, the chances for an ion to revert back to its atomic state are slim in solar environment.

The plasma temperature in different layers of solar atmosphere like the chromosphere, corona and solar wind (Fig. 3.4) is above millions of degrees wherein the temperatures are even more than that observed at photosphere—the layer that forms the Sun's visible surface. These hot layers of the Sun are responsible for its highly variable emissions of X-rays and of extreme ultraviolet radiation (EUV) or the wavelengths between ~100 and 1000 Angstrom units ($1\ \text{Å}=10^{-10}$ m). The chromosphere also emits a substantial fraction of the Sun's UV radiation at wavelengths between ~1600 and 3200 Å. The solar wind seems to originate from areas of corona.

Auroras: High energy particles and intense electromagnetic radiations from the Sun impinge on the Earth's upper atmosphere and produce beautiful optical displays known as aurora, which are recorded at MOs by significant changes in the geomagnetic field components. The auroras observed at northern (aurora borealis) as well as southern (aurora australis) polar regions are an absolutely magnificent display of light with brightness and incredible splendour. Figure 3.9 shows the aurora observed over Indian Antarctic station Maitri. Auroral displays are reported as far back as 1759 and credited to Canton. The aurora, however, does not occur exactly over the magnetic pole, but tends to maintain a constant distance of ~2000 to 3000 km from the respective magnetic pole.

The connection of auroral displays with the EMF was first noted by Celsius in 1741. The light that descended down from atmosphere seemed to follow the EMF. Birkeland in 1896 thought these auroras emanated by fast moving electrons that hit the higher altitudes of atmosphere. He resolved to have an experimental evidence for his reasoning. So he constructed a 'terrella', a miniature model of the Earth. He kept this terrella inside a glass vacuum chamber and directed an electron beam towards it. It travelled along the magnetic field lines right up to the poles of the terrella. By the close of nineteenth century, realization had dawned on the cognoscenti that auroral lights were associated with solar activity. Birkeland guessed that they originated in beams of electrons emitted from the Sun. In practical terms, he seemed to mean magnetic storms occurred when there was a solar flare. The flare spewed out charged particles and sent them hurtling towards the Earth. Birkeland, however, was wrong on this count. Later research proved it is not just the beams of electrons that are emitted from Sun, but there is something 'more and continuous' that is being given out, which Chapman showed are the charged particles.

Figure 3.9. Pictures of (a) bright and (b) curtain auroras observed at Indian station Maitri at Antarctica on 19 June 2003 (photo: Hanchinal).

Detection of solar wind and realisation of magnetosphere: Chapman in 1931, while studying the Sun's corona was greatly impressed by its geographical extent. He tended to consider the charged particles that swarmed over the Earth were in fact part of the corona. He visualized either the Earth was moving around the Sun in very close proximity of its atmosphere or that the corona expanded outwards continually. If the corona expanded incessantly then it had to be perpetually renewed and rejuvenated at the surface of the Sun. Thus, there would be continuous outflow of charged particles that streamed out of the Sun in all directions. They then disturbed the EMF as they passed close to it.

The veracity of the above supposition was reinforced by work carried out in 1950s by Biermann. It was felt that the cometary tails were formed by the pressure of light from Sun. The cometary tails, however, always point away from Sun and increase in length as they approach the Sun. Biermann showed that the light pressure alone was not responsible for producing cometary tails. There was something else which had to be stronger and of the nature such that it gave a ‘push’ to the cometary material to turn it into a tail. These were the charged particles emitted out from the Sun. Parker went a step further and announced his proclivity for a steady outflow of particles, with additional bursts at the time of solar flares. It was Parker himself who coined the term ‘solar wind’ in 1958 to explain this phenomenon (Fig. 3.10).

The world did not have to wait long for the confirmation of the solar wind. The Soviet satellites Lunik I and Lunik II demonstrated their presence in 1959 and 1960, respectively. The American planetary probe Mariner II also confirmed

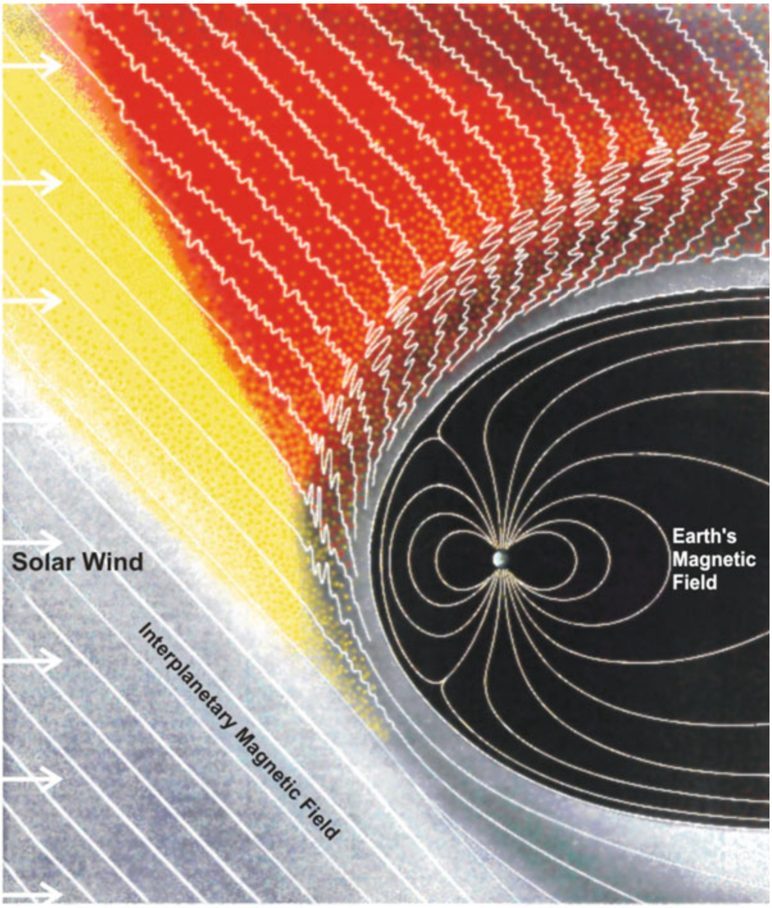

Figure 3.10. Solar wind and the interplanetary magnetic field (Sagdeev and Kennel, April 1991).

the presence of solar wind. This wind flows with a speed of as low as 260 km/sec and as fast as 750 km/sec, but typically its speed lies about 400 km/sec, whereas its density is more variable than the velocity, ranging from ~100 to 10^5 kg/m^3. Actually, it is the density fluctuations in the solar wind, which control the size of the magnetosphere. The solar wind carries magnetic field of ~5 nT that lies near the ecliptic plane in an Archimedean spiral pattern. The escape velocity of the solar wind is 625 km/sec from the surface of the Sun and because the pressure gradient falls off with radial distance more slowly than the gravitational force, the solar wind is accelerated to supersonic velocities. The solar wind is not confined to a small area, but fans out to a considerable extent in space. How far was the task given to man-made satellites to probe the levels of radiation in the topmost atmospheric layers and nearby space. They were also given the job of grading the intensity of cosmic rays beyond the atmospheric domain.

To probe the existence of charged particles, the satellites were fitted with Geiger counters, designed by Geiger in 1907, but later vastly improved and provided by Van Allen and his team. The instrument, in essence, counts the particles or the flux of radiation.

Van Allen radiation belts: The IGY was an exercise unparalleled in the history of scientific cooperation, where more than 70 nations joined the endeavour to study Earth— from within and outside. The IGY marked an 18-month period from July 1959 through Dec 1958 spanning the period of maximum sunspot activity.

The Soviets put Sputnik I that weighed 184 pounds into orbit on 4 Oct 1957. It carried with it instruments to determine and relay back to Earth, the data on pressure and temperature conditions prevalent in the atmosphere. They again sent another satellite Sputnik II into orbit on 3 Nov 1957. The US hastened its efforts and put its first satellite, Explorer I into orbit on 31 Jan 1958.

Sputnik I did not carry any Geiger counter, but Sputnik II did. It rose to a height of 1680 km. Vernov reported an increase in radiation rate between 500 and 700 km. This, as it turned out later, marked the fringes of radiation belt. However, the significance of this finding was lost on Vernov. Explorer I took to skies with a Geiger counter provided by Van Allen's team. According to Stoermer's theory, cosmic ray intensity was expected to increase with magnetic latitude. Its predicted counting rate was ~30 counts/sec. The counter detected almost the same concentrations of particles as predicted for heights below 600 km. But, at higher altitudes the count dropped. At certain heights, the count became almost zero. Explorer I had gone as high as 2520 km. The count reducing to zero would have been dismissed as an aberration with either the counter or the atmosphere, had the same pattern not been observed with Explorer III as well (Explorer II had failed to orbit). Sputnik III had also experienced the same phenomenon.

However Explorer III had carried with it a special tape recorder. Carl McIlwain, an associate of Van Allen had shown experimentally that very high particle fluxes would overwhelm the counter and consequently produce zero counts. Van Allen and his colleagues reasoned that the count fell virtually to zero not because there was little or no radiation, but because there was too much. Hence, they fortified their old counters to handle heavy loads and launched them again into space with Explorer IV on 26 July 1958. This satellite reached the height of 2189 km and disclosed radiation intensity to be much higher than what the scientists had expected. Further, the 'Moon probes' Pioneer I and Pioneer III reached 112,000 km and 104,000 km respectively and showed two main bands of radiation. These radiation bands were named 'Van Allen radiation belts'. However, they were later renamed 'magnetosphere' by Tom Gold in line with the names given to other sections of space.

Christofilos effect: Explorer IV was launched on 26 July 1958 to know how far the magnetosphere extended, configuration of its structure, dynamical processes operative in the region and to explore the newly discovered radiation belt in greater detail. Also, under the project 'Argus', it was proposed to observe an artificial radiation belt produced by exploding nuclear bombs in the Van Allen region to release charged particles. This project was initiated to check the 'Christofilos effect' and to know whether the effect really occurs.

Christofilos studied independently the motion of charged particles in magnetic fields. He had predicted in 1957 the entrapment of charged particles along the magnetic lines of force and sent his calculations to 'experts'. However, nobody paid much heed to his erudition. It was only when they themselves arrived at the same results, they welcomed Christofilos into the California University. His idea about particle entrapment is now called 'Christofilos effect'. To check out this effect, the USA fired three rockets in Aug and Sept 1958 with nuclear bombs that were exploded into space at 480 km height.

After the explosions, the released charged particles spread out and were trapped along magnetic lines of force. The charged particles took a joy ride along the field lines and eventually ended up at polar regions to give rise to feeble auroral displays. They also had disrupted the radar for a short while.

3.3 STRUCTURE OF MAGNETOSPHERE

Gilbert proclaimed Earth to be a giant magnet and the notion of field lines forming symmetry was prevalent for a long time. This erroneous notion was abandoned once the satellite data started pouring down to Earth, especially the one sent by Explorer XIV and IMP I (interplanetary monitoring platform).

Unlike the atmosphere, the magnetosphere has a very sharp boundary (Fig. 3.11), which is called the magnetopause. The magnetosphere itself is caused by interaction of solar wind and the geomagnetic field. The solar wind is obstructed by EMF and finds it difficult to pierce through. But it is able to 'squash' it (Fig. 3.11). Thus, the observable result is the geomagnetic field on dayside compressed to a distance of 10 R_E. The opposite side of dayside, the nightside extends to ~1000 R_E and more, owing to pressure exerted by the solar wind.

Magnetosheath: The solar wind defines a direct link between Earth and Sun. The wind travels unhindered for millions of km and meets its first obstacle at the EMF, which deflects most of the tiny particles that make up its constituents. These deflected particles continue on their odyssey in a curved path called the 'bow shock' (Fig. 3.11). The particles cling along the field lines and gyrate

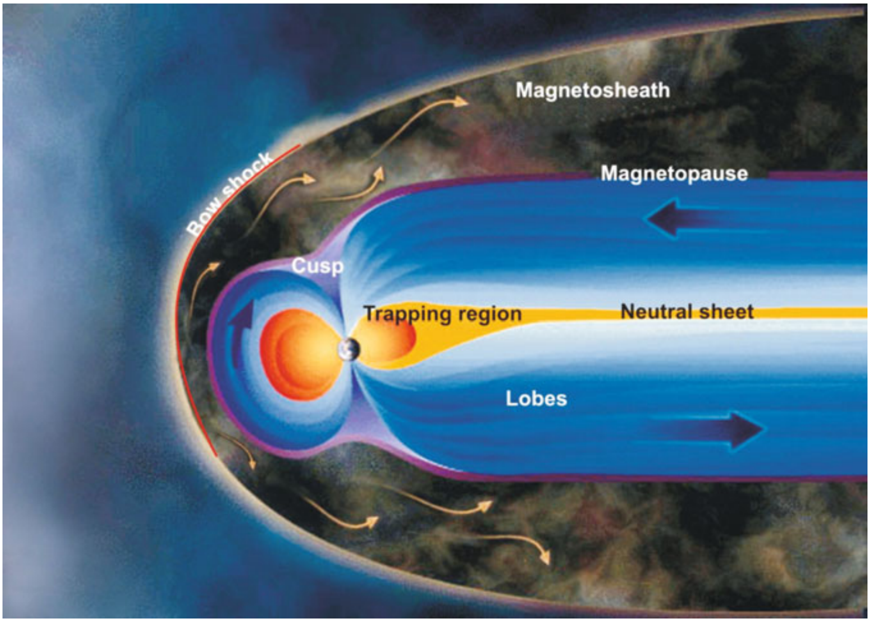

Figure 3.11. The expansive magnetosphere (http://www.windows.ucar.edu/tour/link=/earth/images/earth_magneto_gif_image.html&cdp)=/windows3.html&frp=/windows3.html).

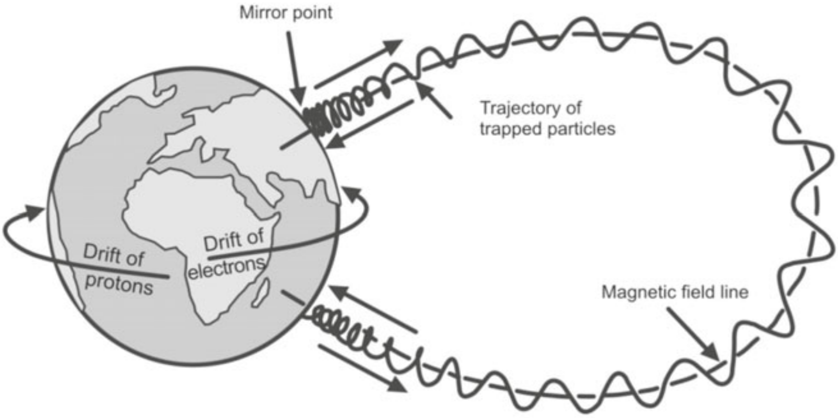

Figure 3.12. Trajectory of trapped particles through the magnetosheath (http://www.spenvis.oma.be/help/background/traprad/motion.gif).

about it and also push the magnetic field in a long tail. However, some sneaky particles leak through the magnetic barrier and are trapped inside. Some of the solar particles also rush through funnel-like openings, called cusps, at the north and south poles, releasing tremendous energy when they enter the atmosphere leading to the magnificent play of auroral lights. The particles then follow a trajectory path that goes round the Earth in a sort of cover or sheath called the 'magnetosheath' (Figs 3.11 and 3.12).

3.4 SOURCES OF ELECTRIC FIELDS

Thunderstorms are considered as the main source of electric fields in the lower atmosphere comprising troposphere-stratosphere and mesosphere. The thunderstorm activity produces vertical electric fields on a global scale. In the ionosphere, the electric fields are produced by dynamo action. Atmospheric winds and tides pull the weakly ionized ionospheric plasma across the geomagnetic field. This movement produces electromotive force and generates electric currents and fields. This is the ionospheric wind or Sq (for solar quiet) dynamo. Solar wind/magnetosphere dynamo is the major generator of electric fields in the magnetosphere.

Magnetospheric currents: The geomagnetists are sure now about the presence of number of magnetospheric and ionospheric electrical current systems. Of the magnetospheric currents, the first is the magnetopause current and the second is the ring current which is closely associated with magnetic storms. During a geomagnetic disturbance, the ring current has a global expanse, which flows in the westward direction and encircles the Earth's atmosphere over the equatorial region (Fig. 3.12). Ring current particles are identified through satellite-borne particle detectors in 1967. However, their signatures manifest on the magnetographs and magnetometers stationed at MOs across the globe in the form of magnetic storms. The third is the neutral sheet current, which divides the magnetospheric tail into two lobes of oppositely directed fields. The drifting plasma sheet particles provide energy and material for the initiation and sustenance of this current.

Geomagnetic storms: A geomagnetic storm is caused by sunspots and eruption of flares on Sun. The EMF that is continuously monitored at the MOs records the dynamical processes occurring at Sun, Earth and the intervening space between the two. For an event to be characterized as a magnetic storm, it should clearly have three phases: the initial phase (also referred to as the sudden storm commencement, SSC), the main phase and the recovery phase (Fig. 3.13).

Ionospheric currents: Some currents are also generated in the ionospheric regions. In 1839, Gauss while interpreting the fluctuations that occurred in a magnetic compass envisioned the fluctuations to be the handiwork of electric currents in atmosphere. Later, Stewart in 1882 talked of a 'great dynamo in the sky' in an article written for Encyclopedia Britannica. It was proposed that the

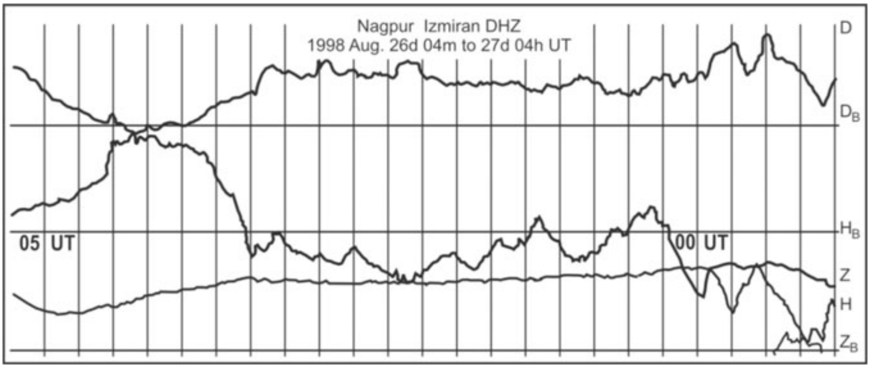

Figure 3.13. Magnetic storm recorded at Nagpur on 26-27 August 1998. Note the sudden storm commencement (SSC), the initial rise in 'H' and then the steep decline.

currents were generated in the atmosphere by the dynamo action of airflow across the geomagnetic field. Later research proved this to be correct. These ionospheric currents mainly flow in E-layers and are generated by tidal movements of ionized matter aided by solar heating (Fig. 3.14). This horizontal current sheet lies at an altitude between 100 km and 150 km in a concentric pattern over the Earth's surface. These currents are a regular feature of ionosphere irrespective of whether the solar wind is of quiet (Sq) or disturbed type.

Focus of Sq current: The Sq current system consists of two loops. The first hovers over the northern hemisphere and the second hangs in space of the southern. These currents are confined to sunlit hours. The northern hemisphere currents that define a loop, flow in an anti-clockwise direction while those in the southern flow in a clockwise manner (Fig. 3.14). The centre of each of the

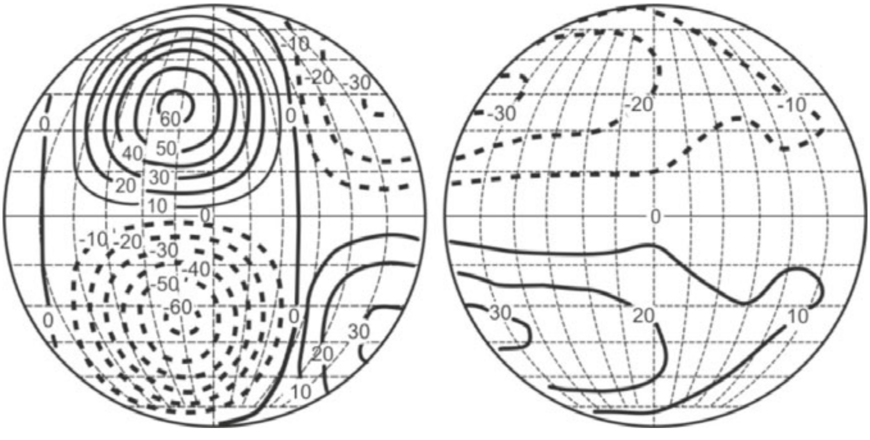

Figure 3.14. Solar daily magnetic variation on quiet days, over the day-time hemisphere (left) and the night hemisphere (right) (Jacobs, v3, 1989).

loops is called Sq focus and is situated (at 35° latitude) on either side of the equator. Sq focus and its strength change considerably from day to day or over the seasons. The current intensity between consecutive field lines is ~10^4 Å. Since these currents are tied with the Sun's energy, they are absent during the night time hours.

Equator to poles D, H and Z pattern: When variations in D, H and Z components are examined at different stations from equator to either of the poles, then a systematic variation is observed. D increases from equator to high latitudes in the northern hemisphere. In the southern hemisphere, a reverse trend is observed. This happens because in the northern hemisphere, the positive D variation reflects the eastward magnetic field generated by southward current that forms during forenoon hours. The negative D variation in the same hemisphere reflects the westward directed magnetic field formed due to northward current in afternoon hours. The H component increases systematically in the positive direction from equator to Sq focus (35° latitude) and it decreases from the Sq focus towards the pole in the northern hemisphere. The same trend can be observed in the variation of H in the southern hemisphere as well.

In terms of the current system, the variation in H in positive direction (northward) reflects the effect of the eastward flowing electric current formed during forenoon hours above MOs located between the equator and the Sq focus. Conversely, the variation in H in negative direction (southward) reveals the effect of westward flowing electric current formed during afternoon hours above MOs located between the Sq focus and poles (Fig. 3.14).

Equatorial electrojet: India occupies a unique location on the world atlas as far as geomagnetism is concerned. It is the only political entity in the world which encompasses the magnetic equator as well as the Sq focus within its boundary. The observatories situated along the magnetic equator, not just in India but everywhere else in the world, record various features in their H. It was observed that the range of daily variation in H at equator was larger by a factor of 2 to 2.5 compared to other stations several degrees beyond the equator (Fig. 3.15). This enhancement is due to a strong jet of current flowing mainly in the E-region of ionosphere during day light hours on either side of dip equator.

This phenomenon was first noticed at Hunacayo in Peru soon after the establishment of MO in 1922. The same phenomenon was also observed at Trivandrum, Annamalainagar and Tirunelveli in India, which are situated along or very close to the magnetic equator. The circulating electric currents of opposite symmetry join at the equator to form a strong flow from west to east at about 11:00 hr LT. This enhanced current flowing eastward was first identified by Egedal and the name equatorial electrojet (EEJ) was given by Chapman in 1951. Curiously, this electrojet has been discovered to reverse its direction, westward, during certain hours of the day and is known as the counter electrojet (CEJ). There is also the auroral electrojet, which is caused by field aligned currents, also known as Birkeland currents.

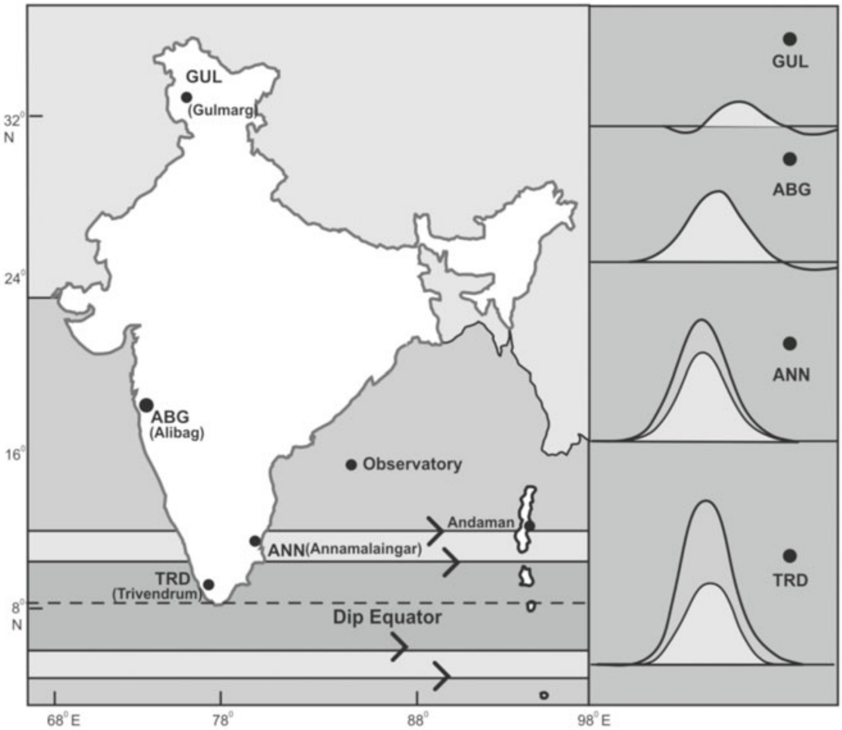

Figure 3.15. The EEJ. Note the pronounced effect seen at TRD (Trivandrum) and ANN (Annamalainagar) and lack of it at ABG (Alibag) and GUL (Gulmarg), which are located far away from the equator (Campbell et al., 1993).

3.5 RADIO WAVES: SCINTILLATION

The ionospheric irregularities are monitored with the help of radio beacons carried onboard satellites through yet another technique called scintillation. Scintillation is a rapid change in the phase or amplitude or both of a radio signal as it passes through small-scale plasma density irregularities in the ionosphere. This technique is ground based, inexpensive and highly economical. It yields information about the strength, spectrum and dynamical behaviour of metre to sub-km scale wavelength of ionospheric irregularities.

The radio waves were produced and detected by Hertz in 1887. He was generating an oscillating current from the spark of an induction coil when he detected radiation of extremely long wavelengths. These came to be called the radio waves and served a purpose by providing indirect evidences that the Earth is flooded with charged particles. It was found that a part of the radio waves generated by lightning travelled along Earth's magnetic lines of force. These waves are called 'whistlers' and was discovered by Barkhausen. The radio waves cannot follow the magnetic lines of force unless charged particles are present.

The discovery of radio waves opened a window to the far off galaxies, which later gave birth to radio astronomy. Radio astronomy has made many exciting discoveries of far off space and galaxies, the matter of which is beyond the purview of this book. However, scintillation studies, based on rapid changes encountered in phase and/or amplitude changes of a radio signal, provide useful information and clues to small-scale plasma density irregularities in the ionosphere.

The upper regions of the Earth's atmosphere (namely the mesosphere and thermosphere) and ionosphere are strongly coupled to the lower and middle atmosphere by means of chemical, dynamic and electro-dynamic processes. The observed influence of the upward propagating gravity and planetary scale waves and atmospheric tides on the thermosphere and the ionosphere is an example of dynamical coupling. The giant global electrical circuit linking the lower atmosphere to the ionosphere and the magnetosphere provides an adequate link for the electrodynamic coupling, which warrants the studies into space weather conditions.

Night airglow: The ionospheric region and beyond is composed of plasma, but below into our very own atmosphere are the gases. What might those gases be and of what composition, none had a clue before the 1930s. It was believed that hydrogen and helium may be floating over the heavier gases in the stratosphere. This was the belief of Bort. However, he was proved wrong by air samples that were brought down by Soviet balloonists in the middle of the 1930s. The upper stratosphere was found to contain oxygen and nitrogen. Troposphere, too, had these gases. But there was reason to believe that there existed some unusual gases that gave off 'airglow'. Night airglow is the feeble illumination of night sky even in the absence of moonlight.

What caused the feeble light that thinly illuminates the sky remained a mystery for quite a while. Then in 1928 came a breakthrough. Slipher, while analyzing the spectral lines obtained for the airglow of the nebulae in 1864 by Huggins, considered it to be an unfamiliar element 'nebulium'. In 1927, several experiments were carried out in the laboratory where the same kind of spectral lines as that considered to be of nebulium were generated. Ira Bowen showed it to be coming from the 'atomic oxygen'. Atomic oxygen is a single atom and not a combined two-atom molecule that is normally encountered. During the same period, research was going on over the spectral lines emanating from aurora. These spectral lines turned out to be the handiwork of 'atomic nitrogen'. The two, atomic oxygen and nitrogen, are produced by energetic radiation of the Sun, which breaks down the molecules into single atoms. This suggestion came in 1931 from Chapman and is one mechanism out of many others by which nature absorbs or weakens the harmful radiation before reaching the Earth.

Chapman further elaborated that the airglow was caused by the recombination at night of atoms that are split apart by solar energy during the day. During the recombination process, atoms give up some of the energy they absorbed in splitting. Thus, the airglow is some kind of a delayed and very feeble return of sunlight in a new and specialized form.

Direct evidences of airglow were found by rocket experiments carried out in the 1950s. Spectroscopes carried by rockets recorded the green lines of atomic oxygen most strongly at a height of 96 km. The red light of atomic nitrogen was prominent at a height of 250 km. Slipher also found spectral lines in the airglow emitted by sodium. But the idea of sodium existing high up in the atmosphere was so embarrassing that it was rejected immediately. The reason, sodium is not a gas. It is a reactive metal and is always combined with other elements. In 1938, French scientists were emphatic in their suggestion of existence of sodium, based on the characteristics of spectral lines. The rocket experiments again gave concrete evidence. Their spectroscopes recorded the yellow light of sodium. Lithium was also found, in 1958, to be contributing to the airglow.

Creation of artificial airglow: Murray Zelikoff and his team created artificial airglow in 1956. They carried nitric oxide gas on a rocket and released it in the atmosphere at an altitude of 96 km. This gas accelerated the process of recombination of oxygen atoms. The observers on land easily sighted this glow. A similar experiment was also carried out with sodium vapour. It too created a clearly visible yellow glow.

Like night-time, there is also a daytime airglow, but because of the presence of strong solar background brightness, its contribution cannot be easily deciphered. There have been only a few ground and satellite-based measurements of visible airglow emissions during the daytime. The daytime airglow emissions are obtained by comparing blue-sky spectrum with solar spectrum, since the former is different from the latter in terms of atmospheric emissions, atmospheric scattering, and depth of the telluric absorption lines.

Space weather: The importance of research dealing with solar-terrestrial physics carried out through geomagnetic studies has helped understand the more distant universe, the intricate web of plasma phenomena, magnetic fields and particle acceleration. But there also exists a practical angle to this research. In a world increasingly dependent on electricity and electronics, the ‘space weather’ outside the atmosphere can have serious effects, in particular on human communications (Chapter 8).

APPENDIX 3.1

Plasmas in the Earth's Magnetosphere

	Density N	*Electron velocity Ve*	*Proton velocity Vp*	*Electron temperature Te*	*Proton temperature Tp*	*Magnetic field*	*Comments*
Solar wind	1-10 cm^{-3}	200-600 km/sec	200-600 km/sec	6×10^4 to 3×10^5 °K	2×10^4 to 2×10^5 °K	2-15 nT	• High speed streams associated with coronal hole • Low speed streams near sector boundaries
Magnetosheath	2-50 cm^{-3}	200-500 km/sec	200-500 km/sec	10^5 to 10^6 °K	5×10^5 to 5×10^6 °K	2-15 nT	• Turbulent solar wind plasma and magnetic fields
High latitude boundary layer	0.5-50 cm^{-3}	No reported measurements	100-300 km/sec	10^5 to 10^6 °K	5×10^5 to 8×10^6 °K	10-30 nT	• Entry layer into the magnetosphere of magnetosheath plasma
Plasma sheet boundary layer	0.1-1.0 cm^{-3}	500-5000 km/sec	100-1500 km/sec	2×10^6 to 10^7 °K	10^7 to 5×10^7 °K	20-50 nT at 20 Re	• Region which maps to auroral zone producing discrete auroral arcs
Plasma sheet	0.1-1.0 cm^{-3}	10-50 km/sec	10-1000 km/sec	2×10^6 to 2×10^7 °K	Always hotter by a factor of 3 to 5 such that Tp/Te>1	9 nT in deep tail	• Thickness of 4 to 6 Re • Forms into the ring current at 5-6 Re from Earth
Lobe	10^{-3} to 10^{-2} cm^{-3}	No reported measurements	No reported measurements	<10^6 °K	<10^7 °K	Increases with southward IMF	• Lowest densities found in the magnetospheric cavity

(http://ssdoo.gsfc.nasa.gov/education/lectures/magnetosphere/Table_1.jpg)

APPENDIX 3.2

Classification of Geomagnetic Variation with Typical Periods, Amplitudes and Penetration Depths

Type of variation	*Symbol*	*Typical period*	*Typical amplitude*	*Typical penetration depth*
Solar cycle variations		11 yrs	10-20 nT	>2000 km
Annual variation		12 months	5 nT	1500–2000 km
Semi-annual variation		6 months	5 nT	
Short-time variation	Dst	Hours to weeks	50–500 nT	300–1000 km
Regular daily variation		24 hrs and harmonics		
at mid-latitudes	Sq		20-50 nT	300–600 km
at low latitudes	EEJ		50–100 nT	
Substorms	DP	10 minutes to 2 hrs	100 nT (1000 nT at p.l.)	100–300 km
Pulsations	ULF	0.2–600 sec		20–100 km
(=Ultra low frequency waves)				
regular	pc	150–600 sec (pc5)	10 nT (100 nT at p.l.)	
continuous		45–150 sec (pc4)	2 nT	
pulsations		5–45 sec (pc2,3)	0.5 nT	
		0.2–5 sec (pc1)	0.1 nT	
Irregular transient pulsations	Pi	1-150 sec	1 nT	
Extreme low frequency waves	ELF sferics	1/5–1/1000 sec	<0.1 nT	Tens of metres – kilometres
Schumann resonance oscillations		1/8 sec	<0.1 nT	
Very low frequency waves, whistlers	VLF	10-5–10-3 sec		Few metres – tens of kilometres

Note: If amplitude depends significantly on latitude, values are also given for polar latitudes (p.l., dipole latitude>65°)
(courtesy: Olsen, 2007 and Schmucker, 1985).