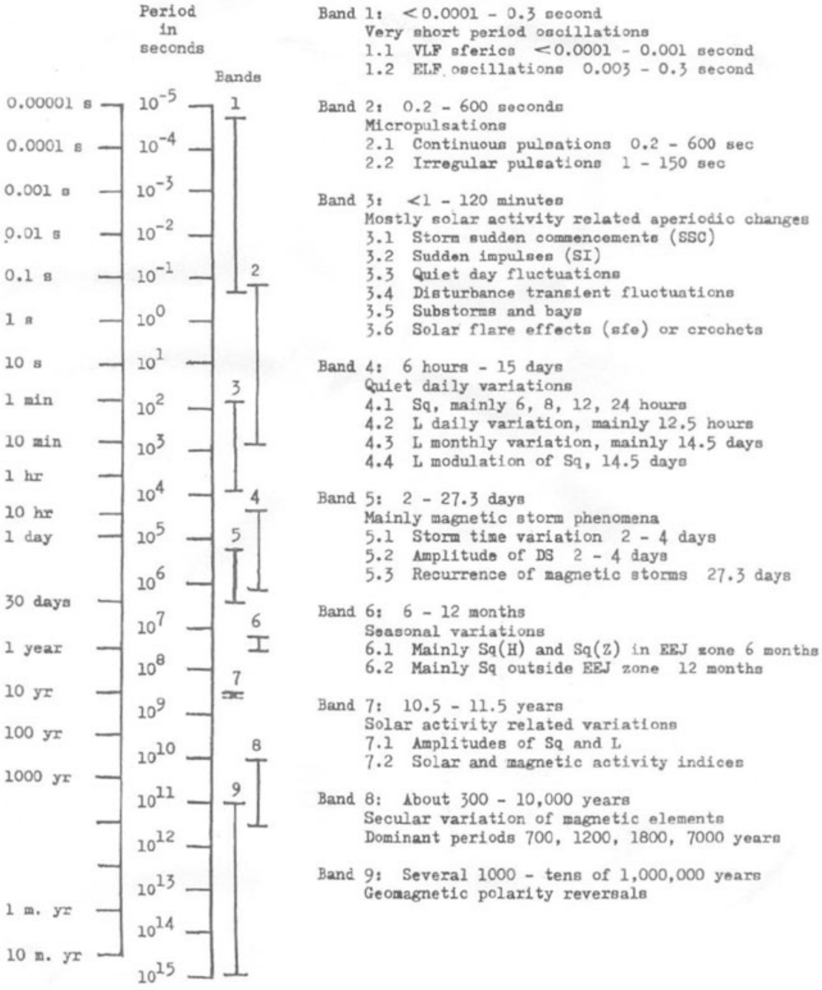
9

USEFULNESS OF GEOMAGNETIC RESEARCH

Geomagnetism has applications in navigation, communication, space travel (manned or unmanned), power generation, in the search for minerals and hydrocarbons, in dating rock sequences and in unravelling past geologic movements such as plate tectonics. For studies related to different fields, suitably located MOs are operated throughout the country (Fig. 1.14) and worldwide (Fig. 5.1) to record strength, intensity, and direction of the geomagnetic field. It varies spatially and temporally on a very wide frequency spectrum of signals, whose characteristic times extend from geological to historical to millennial to centuries to subsec intervals (Figs 5.3b and 9.1). The longer timescales, typically those occurring over decades to millennia, are relevant to discern planetary magnetism. The long-period SVs of the main field are used for studying the dynamo action in Earth's core and the overlying mantle as well as CMB. Short-term variability finds several important applications related to Sun-Earth connection as well as geophysical prospecting of the Earth's deep interior. The transient type of short-period variations are used for studying the mantle and the crust (see EM induction methods). The small-scale anomalies which ride on the expected magnetic field give information about the crust of the Earth and the presence of petroleum and mineral deposits within it. The metal ores are concentrated in rocks rich in magnetites that are highly magnetic. Geomagnetism provides the cheapest geophysical exploration tool, but lacks the precision of seismic methods. The discovery of EM induction provided yet another technique for exploring the Earth's interior. The experimental methods which are employed for this are discussed in Chapters 6, 7 and 8. Variations on timescales of second to many years also occur due to dynamical processes in the ionosphere and magnetosphere (Figs 5.2 and 5.3).

N. Basavaiah, *Geomagnetism*



Band 1: < 0.0001 - 0.3 second
Very short period oscillations
1.1 VLF sferics < 0.0001 - 0.001 second
1.2 ELF oscillations 0.003 - 0.3 second

Band 2: 0.2 - 600 seconds
Micropulsations
2.1 Continuous pulsations 0.2 - 600 sec
2.2 Irregular pulsations 1 - 150 sec

Band 3: <1 - 120 minutes
Mostly solar activity related aperiodic changes
3.1 Storm sudden commencements (SSC)
3.2 Sudden impulses (SI)
3.3 Quiet day fluctuations
3.4 Disturbance transient fluctuations
3.5 Substorms and bays
3.6 Solar flare effects (sfe) or crochets

Band 4: 6 hours - 15 days
Quiet daily variations
4.1 Sq, mainly 6, 8, 12, 24 hours
4.2 L daily variation, mainly 12.5 hours
4.3 L monthly variation, mainly 14.5 days
4.4 L modulation of Sq, 14.5 days

Band 5: 2 - 27.3 days
Mainly magnetic storm phenomena
5.1 Storm time variation 2 - 4 days
5.2 Amplitude of DS 2 - 4 days
5.3 Recurrence of magnetic storms 27.3 days

Band 6: 6 - 12 months
Seasonal variations
6.1 Mainly Sq(H) and Sq(Z) in EEJ zone 6 months
6.2 Mainly Sq outside EEJ zone 12 months

Band 7: 10.5 - 11.5 years
Solar activity related variations
7.1 Amplitudes of Sq and L
7.2 Solar and magnetic activity indices

Band 8: About 300 - 10,000 years
Secular variation of magnetic elements
Dominant periods 700, 1200, 1800, 7000 years

Band 9: Several 1000 - tens of 1,000,000 years
Geomagnetic polarity reversals

Figure 9.1. Spectrum of the periods of characteristic geomagnetic field variation from 1/100,000 sec to 100,000,000 years (courtesy: Onwumechili, 1997).

9.1 OBSERVATORIES AND DATA ANALYSIS

The geomagnetism programme deals with monitoring of the EMF through a network of MOs and conduct scientific analysis on the data collected (Chapters 1 and 5). Magnetic observatories in India have been running for more than 180 years. This network is ideal for studying equatorial, low and mid-latitude geomagnetic phenomena (Chapter 5) and space weather (Chapters 3 and 8). Geomagnetism is a cross-disciplinary science, hence observatories are run by a wide variety of institutes, whose interests range from geology, mapping, geophysics (including seismology and earthquake prediction), meteorology to solar terrestrial physics and astronomy. The practical use of MO includes help in space, ground navigation systems and monitoring earthquake activity. The data at Shillong observatory are found sensitive to local earthquakes, providing useful clues for earthquake precursory studies (Fig. 6.67). The data generated at the observatory are passed through a series of quality control measures that involve data processing. Final observatory products of 1-min means, hourly means, annual means and K-indices are produced and disseminated by yearbooks and CDs. The Indian geomagnetic observatory in Antarctica closely reflects the history of the exploration of this mysterious and barely accessible continent. Its data are particularly useful for southern auroral and polar cap studies as well as tracking changes in the main field in this region (Fig. 8.25).

The geomagnetic field measured at MOs is a sum total of several fields having source both internal to the Earth (main and crustal fields) and external non-dipole field related to electric currents high in the Earth's atmosphere. Annual means of the geomagnetic elements recorded at observatories and those determined at repeat stations contain a solar cycle related variation, which is used to better describe individual observatories as regards the magnetic and electric properties of the Earth's interior; characteristic to the site with possible consequences in improving the SV and the main field models.

I. Application in Communication

Magnetograms recorded at MOs give information on the relationship between solar-terrestrial interaction and the geomagnetic fluctuations (Chapter 5). The daily variations in the EMF allowed Stewart (Chapter 3) to postulate a conducting layer (ionosphere) in the upper atmosphere. Since then, geomagnetograms are used to monitor and even forecast the state of the ionosphere and therefore possible disruptions in radio communication (Chapter 8). In the first half of twentieth century, radio communication was mainly through wavelengths, which are grouped as long and medium waves (frequency in kHz) and short wave bands (frequency in MHz). Such communication is greatly dependent on the EM state of the Earth's environment. Since the satellite era of the 1960s, much of the international communication (both audio and video) depends on the ultra-short wavelength band (frequency in GHz range). Even satellite communication, which is less dependent on the EM state, is affected by phenomena in the geo-atmosphere, e.g. plasma irregularities which produce scintillation and which are governed by the structure of the geomagnetic field and the upper atmosphere.

II. Application in Fundamental Research

The combination of data from magnetic survey satellites such as Magsat, Oersted and CHAMP and observatories worldwide is providing a rich resource for research into core processes. The observatory data are of great importance because of information they give on the SV, providing the basis for estimation of future values of the geomagnetic field at a given location. Observatories also provide data on interactions that arise between the solar wind and magnetosphere as well as the ionosphere of the Earth, generating EM fluctuations with frequencies ≤1 Hz. Also, oscillations of the magnetosphere generate small, almost sinusoidal variations of the geomagnetic field called geomagnetic pulsations (Chapter 8). Inductive and magnetohydrodynamic interactions between the ionosphere and magnetosphere modify these fluctuating fields before they reach the Earth's surface. The largest geomagnetic field variations up to the order of a few hundred nT occur during magnetic storms (Chapters 5 and 8). These frequency ranges are very effectively used to arrive at the subterranean structure of the Earth (Chapter 6).

The EMF to a large extent resembles that of a central dipole. On the Earth's surface, the field varies from being horizontal with a magnitude of ~30,000 nT near the equator to vertical with ~60,000 nT magnitude near the poles; the root mean square (rms) magnitude of the vector over the surface is ~45,000 nT. The internal geomagnetic field also varies in time on a timescale of months and even longer, though yet unpredictable manner. Although this SV has a complicated spatial pattern with a global rms magnitude ~80 nT/yr, some evidence exists that these changes are cyclic with a period of 500 years. Consequently, any numerical model of the geomagnetic field has to have coefficients, which vary with time. These models also help to distinguish the magnetic field contribution of internal source from the external ones.

Also, models like IGRF based on global magnetic data give a reasonable approximation near and above the Earth's surface to that part of the EMF, which has its origin below the surface. However, errors in the coefficients lead to errors in the resulting model field. Because of the time variation of the field, really good models can only be produced for times when there is global coverage either by satellites or through ground magnetic surveys and establishment of MOs measuring the vector field. Appendix 9.1 gives the locations of north and south dip poles and geomagnetic poles that are computed from the eleventh-generation IGRF.

III. Application in Navigation and Geomagnetic Activity Index

Magnetic observatory serves as a singularly important site in a global network of observing stations, whose combined data define the planetary magnetic field and help track its secular change. Ground stations act as controls for field modelling by harmonic analysis. They are essential reference stations for airborne and satellite surveys and absolute calibration locations for field survey instrumentation. They are also essential for a number of applications such as production of angle D charts for navigation, removal of background fields from magnetic survey data collected from ground, aeromagnetic and ship-borne surveys and calculation of field lines and conjugate points for ionospheric and magnetospheric studies, etc. The MOs often provide backup support for temporary field stations and for purposes of calibration of field instruments.

The ionospheric and magnetospheric disturbance fields indicative of space weather conditions are characterized by various geomagnetic activities. Each of the Indian observatories provides data for the computation of the Kp-index. Data generated at different observatories are also used to arrive at various geomagnetic indices like the Dst, AU, AL, EEJ, Kp, AE, aa, PC, MT and so on, to characterize the geomagnetic activity at a particular location.

IV. Other Applications

The data collected at MOs are often sent to the air-force, marine and military installations for use in their operational models characterizing Earth's near-space environment as well as to scientific/technological establishments around the world. These institutions actively produce models of the EMF that are used in host of applications, including GPS receivers, military/civilian navigational systems and in research for studies of the effects of geomagnetic storms on the ionosphere, atmosphere, and near-space environment. India shares its geomagnetic data with a legion of international agencies based in USA, Canada, Japan, France, Brazil, UK and others as part of InterMagnet. The data are made available to the worldwide community via www.wdciig.res.in. Also, calibration of compasses the world-over is carried out at the MOs to account for any changes in angles D and I of a particular region.

9.2 SOLID EARTH GEOMAGNETISM

The extraordinary wealth of information collected in the last few decades has totally transformed our view of the Earth. The earlier notion of a static and placid globe has been replaced by a dynamic Earth, whose core is rotating, mantle convecting and crust drifting. The Earth's crust forms at the spreading mid oceanic ridges and floats on the convective mantle, making it amenable to collisions with each other (Fig. 2.49). The study of this motion helps understand plate tectonics, earthquakes, volcanic activity and even emplacement of natural resources. The mantle is studied, although indirectly, through magnetic field measurements. For at its bottom, the mantle is coupled to the liquid core and at top to the crust. The liquid core kinetically produces the magnetic field, whereas the crust is a repository of potential magnetic field. Both these fields can be measured easily and accurately from land, ocean and space because of which their magnetic properties can be harnessed for understanding multidimensional processes operating inside and outside the Earth.

Studies carried out through the spectrum of geomagnetism have three aspects. The first pertains to the basic urge to know the structure of planet Earth. Second relates to increasing need of the industrialized society for critical estimate of natural resources, to know which, the dynamics of the Earth's interior and the mechanism of resource emplacement need to be understood. Third, the nature of EMF and its variation with time give an opportunity to learn more of the structure of other planets and also of stars.

The geomagnetic field has two internal sources: one due to electric currents in the liquid (outer) core and the other from the crustal magnetization. The former is dynamic and changing, whereas the latter is static and unchanging. The crust has mainly induced magnetization and its magnetic field is often referred to as crustal anomaly, which is caused by nonuniform distribution of magnetic material. The detection of these anomalies forms an important practical application of geomagnetism. Large-scale magnetic anomalies (extending over some hundreds of km) are obtained from satellites, whereas smaller scale anomalies are detected through ground and aeromagnetic surveys. Mathematical and experimental techniques (discussed in Chapters 2, 6 and 7) help determine the contributions from subsurface structures in the observed magnetic records.

I. Interdisciplinary Geomagnetic Techniques and Earth's Interior

The technological impediments in reaching physically down to depths of mantle and core are partially removed by the access to this domain through different instruments (Chapter 4). Certain properties (density, temperature, velocity of seismic waves and so on) depend on physical characteristics, which are used in arriving at many (and diverse) interpretations of the physicochemical realm of the interior of the Earth, leading to an improvement in understanding the formative processes of this planet. Thus, without going down to the core or mantle, the composition of the core is deduced to be mostly Fe and Ni. The dynamo processes are also well understood with an improvement in instrumentation and computer simulation capabilities (Figs 2.40 and 2.45).

Earth's inner realm is consistently under investigation through seismology, terrestrial magnetism and geology. Seismology studies the propagation of seismic waves and is the only method effective enough to delineate principal inner subdivisions of the Earth. The nature of each of its units is identified by its ability to propagate (or block) shear waves (Fig. 2.12). Large fractures and polarity reversals of magnetization all along the mid oceanic ridges have formulated concepts relating to plate tectonics, ocean floor formation and continental drift. Induced and remanent magnetizations reveal polar wandering (Fig. 7.8) and associated theories of crustal movement (Figs 2.50–2.52).

Traditionally, geology has been closely associated with the study of tectonics through mapping (aerial photography) fold, fault trends and geomorphological characteristics. In such cases, however, the dependence is on surface expression of deep structural units and the picture obtained is therefore incomplete.

Some geotectonic aspects are novel to India, like the drifting of Indian plate, its subsequent docking with Eurasian landmass, associated Himalayan orogeny and opening of the Indian ocean, extensive continental flood basalts of the Mesozoic (Deccan and Rajmahal traps) and a complex geoelectric structure (SIOCA) at the dip equator. Also, the physical, morphological, geochemical environment of the peninsular and extra peninsular region give an opportunity to study the ‘contrast’ in order to quantify magnetic and gravity fields, global warming, climate change, monsoon variations and other interesting topics.

Geophysics has injected the precision of exact sciences and methods of mass data processing into geology and physics, making feasible the studies related to seismology, geotherm, tectonophysics, structural and general geology. Applied geophysics, on the other hand, has the character of an applied science, which helps determine the micro and macro geological structures of the crust and upper mantle, delineates raw material deposits and characterizes geological activities pertaining to engineering geology, environmental geology, hydrology and others. Applied geophysics is divided into individual disciplines depending on field surveyed. The gravity field is studied by means of gravimetric methods, the magnetic field by magnetometric methods, the geoelectric field by geoelectrical methods, the field of elastic waves by seismic methods, the radioactive field by radiometric methods and the thermal field by geothermic methods.

The Earth’s crust is an inhomogeneous medium with different physical properties of rocks and tectonic blocks (density, magnetic susceptibility, resistivity, radioactivity and nuclear properties, electrical and thermal conductivity and elastic parameters). The changes in the physical fields of the Earth are used to determine crustal inhomogeneities (structure, occurrence of raw-material deposits, etc.).

Geophysical data are interpreted through direct and inverse means. The solution to a direct problem is sought by determining the effect of a disturbing body of known size, shape, depth and physical properties on the corresponding physical field (e.g. the effect of a regular geometric body of known differential density and susceptibility on the gravity and magnetic field of the Earth). This problem has a unique solution. There is no ambiguity. But the inverse problem is usually ambiguous. In an inverse problem, one seeks to determine the disturbing body corresponding to an anomaly in a physical field. This problem is usually ambiguous. Hence to render it unique, several geophysical methods or supplemental geological information are combined together.

Apart from academic research, magnetic and EM methods find practical applications in: (1) locating mineral and hydrocarbon deposits, (2) in understanding the evolution of the Earth’s crust and the dynamics of the mantle, and (3) possible prediction of earthquakes through the effect of tectonic stress within rocks. The potential uses of geophysical data are described below.

II. Geopotential Field Anomalies and Configuration of Crust

Configuration of the Earth’s crust is done by using principles of geomagnetism. Changes in composition, subsurface temperature and thickness of the crust and mantle cause magnetic anomalies, by identifying which internal Earth features such as hot spots, rifts, seismic zones and tectonically active regions (Figs 6.5 and 6.11) are isolated. Magnetic anomalies also map Curie isotherm depth (a proxy for heat flow), delineate different metamorphic zones and reconstruct tectonic evolution.

What satellite gravity and magnetic data sees: To build a model of the Earth's interior through magnetic measurements, the data are necessary to be global in extent. Satellites provide global uniformly accurate data and since their observation time is brief, secular drift corrections are not needed to apply. Satellite measurements are made with a remotely placed sensor, hence these data are extremely useful in bringing out large wavelength features of size ~1000 km. Remote observation has an advantage and a disadvantage as well. The advantage is that small-scale features present in the ground data, which make isolation of large-scale features difficult, get completely suppressed when observations are made from space. The disadvantage is that the crustal signatures get significantly reduced due to the great distance of the point of observation. To get finer details of the structural blocks, space observations are supplemented with ground, oceanic and aerial surveys.

Magsat satellite anomaly: Magsat anomaly maps (Figs 6.8a,b) have outlined major geological and geophysical structures in the subcontinent. In general, the anomalies depend primarily on the product of the magnetic susceptibility and layer thickness (i.e. 400 m of material with a susceptibility of 0.05 gives rise to almost the same magnetic anomaly as 2 km of material with a susceptibility of 0.01). Further, the geological properties of the Earth's crust cannot be directly derived from magnetic anomaly maps because they are masked by the changing inclination of the main magnetic field responsible for induction. The anomaly is inverted to obtain the depth of the magnetic crust. The crustal depths thus obtained are correlated with major geological lineaments/faults and tectonic features (Fig. 6.11), especially to study similarities and differences between continental and oceanic crusts.

The peninsular shield, the Ganga basin and the Himalayas are three different geotectonic blocks, clearly reflected in the crustal magnetization maps (Fig. 6.11). A thick magnetic crust under Aravalli, Singhbhum and Dharwar suggests these are comparatively stable. In general, seismic, gravity and heat flow data agree characteristically well with the magnetization estimates. It also delineated the cause for unique features of steep rise and fall of the anomaly, the depth structure of many geologic features (Figs 6.5 and 6.11) and the continuation of continental type of crust for some distance on the west coast as well as into the northern portion of Bay of Bengal (Figs 6.7 and 6.11). Magnetic signatures are variable and they appear to depend on the age and conditions of intrusion. The other applications include the creation of updated models of internal EMF and study of fields due to ionosphere and magnetosphere currents. These uses can be enhanced by acquisition of data from MOs and repeat stations at the Earth's surface.

Satellite gravity and isostasy: The satellite free-air gravity anomaly at ground level (Fig. 6.2b) is used for studying the isostatic condition in many parts of

Indian peninsula in general and the Himalayas in particular. These studies revealed that the peninsula is isostatically compensated, whereas the Himalayas are isostatically overcompensated (Fig. 6.3). This result contradicts the positive satellite gravity anomalies. It is stressed that the true nature and extent of isostatic compensation of the Himalayas can only be decided by investigating both the positive and negative anomalies resulting from the mountains and their roots.

Satellite residual gravity and magnetic anomaly: Stable cratonic areas like shields, platforms and flexural basins including the Himalayan foredeep, are overlain by relatively positive magnetic anomalies and negative free-air gravity anomaly values (Figs 6.5 and 6.11). This combination of anomalies reflects displacement of dense nonmagnetic mantle material by thick crustal material. Rifts, aulacogen and rift related basins are generally associated with relatively positive free-air gravity anomalies reflecting the presence of denser material in the crust. High gravity and low magnetization anomaly over the eastern ghats are modelled in terms of crustal thinning (as analogous to high heat flow). Magnetic low values over the Arabian Sea seem to centre near Mumbai—a region associated with local gravity high and also basic and ultrabasic dykes. Other geological features with the axis of inverse correspondence between magnetic low and gravity high are the Konkan coast, hot springs, the Cambay rift and the Panvel flexure. Pinpointing exact locations of these tectonic blocks requires that the satellite study be backed by aeromagnetic and ground survey.

Aeromagnetic studies: Long wavelength (regional) anomalies derived from satellite magnetic and gravity data normally give information about the lower crust. To better understand the overall geodynamics, aeromagnetic (wherever available) and ground surveys are combined. Aeromagnetically limited surveyed areas of the peninsula (Figs 6.13-6.15) show a thin exhumed southern granulite terrain crust, which has a lithological/mineralogical change at ~22 km depth. The inverted crustal model suggests alteration of charnockites into hornblende-biotite-gneiss. This alteration is more towards the north than south, wherein the process of retrogression is high. The exhumation of charnockites is more between Cauvery fault and Salem-Attur fault.

Ground magnetic studies: Compared to Magsat data, ground magnetic anomaly maps (Fig. 6.17) are not able to separate the geological provinces. The distinct Magsat anomaly over the Himalayas and Narmada-Sone lineament are indecipherable in ground data. This is because the strong features of local extent mask the regional features. The results of three basins, viz. Mahanadi, Krishna-Godavari (K-G) and Cauvery (Figs 6.20, 6.23 and 6.28) gave useful information on the breakup of India from Gondwanaland. Curie isotherm depth calculations for Cambay and K-G basins allowed inferring their hydrocarbon bearing potential. A few magnetic-cum-gravity profiles provided information on the basement configuration and the total thickness of sediments to pencil out areas for further intensive studies by electrical resistivity, seismic and EM methods.

III. EM Induction Methods

In gravity or magnetic fields, the anomalies are small perturbations over the normal field, but in transient variations they can be greater than the normal part by a few orders of magnitude. The causative process is the large electrical conductivity contrast of 13 orders of magnitude (e.g. dry crystalline rocks have conductivities $<10^{-6}$ S/m, while ores have conductivities exceeding 10^6 S/m). Electrical conductivity is a sensitive parameter for saline fluids, carbon grain-boundary films, conducting minerals, high heat flow and partial melts (molten rocks or aqueous solutions). This parameter is extensively used in GDS, OBM and MT for mapping geoelectrical structures.

The EM method of GDS and MT types is found to be invaluable tool in probing subsurface conductive structures from measurements carried out in a selected band of frequencies (normally 10^3 to 10^{-4} Hz). A time-varying EM field generated by thunder storm activity, micropulsations, polar substorms and solar activity induces current in the conducting medium to give rise to an associated secondary magnetic field. When the period-dependent spatially anomalous EM fields are isolated, they are used to image structures and lateral conductivity contrasts. For lower frequencies (long-periods), the depth of penetration is more and for higher frequencies (short-periods), the depth of penetration is less. Hence, by measuring the field at different frequencies (time periods), the subsurface information at different depths is obtained.

Applied EM methods map conductivity patterns, which indirectly infer temperature, structural and compositional variations from the crust down to the upper mantle and help in understanding the Precambrian tectonics, crustal evolutionary processes (Figs 6.41, 6.42) and the seismicity. GDS and MT are two complementary geophysical methods; the former has a better lateral (horizontal) resolution, while the latter has a better vertical resolution. The effectiveness of MT data to provide constraints on tectonic configuration under study increases on integrating its information with gravity, seismic wave velocity and heat flow data (e.g. Fig. 6.45). Seismic methods fail to reveal the desired subsurface information in complex sedimentary basins (Fig. 6.18). At such places, MT methods are applied to locate hydrocarbon deposits hidden beneath them. For example, MT methods are useful in Deccan volcanic (Figs 6.43 and 6.44), where the conventional geophysical and seismic methods fail because of high velocity basaltic cover.

The data pooled from GDS and MT studies (Figs 6.30, 6.32, 6.33, 6.40 and 6.44) can synthesize electrical conductance distribution map for the entire subcontinent, which not just demarcate thermally favourable zones of hydrocarbon maturation, but also provide better insight into the seismic patterns. Subsurface electrical structures below the ocean floor are mapped by OBM array studies. The oceanic crust/upper mantle underlying the Bay of Bengal is found more resistive than the one underlying Andaman arc region. This is because the former is older and latter younger.

The Earth's conductivity is also studied with the help of satellites (Magsat). The apparent resistivity of the American and Pacific regions is similar, but it differs in the European-African sector. The oceanic and continental apparent resistivities are seen to differ most at short periods, indicating a possible influence of induction in oceans. The apparent resistivities of the southern hemisphere are significantly higher than those of the northern hemisphere at all periods. This is an unexpected result, since the southern hemisphere is dominated by oceans, and analyses of ocean bottom data with the Z/H method and MT indicate lower resistivity of the oceanic mantle. In the Indian context, magnetization and mass distribution (Figs 6.11 and 6.12) maps prepared from satellite data are found to be consistent with the trans-Himalayan conductor and the Palk strait conductor (Figs 6.32 and 6.33) identified by EM induction methods. This correspondence between the two suggests that both these conductors are associated with either high heat flow or low magnetic susceptibility and density. The anomalous character of the lithosphere immediately south of India is also indicated as low magnetization anomaly, reflecting thin magnetic crust due to rise of the Curie isotherm.

Magnetic field changes originating in the Earth's core cannot reach the surface if their periods are much shorter than one year. Sudden geomagnetic core events called jerks occur at the high-frequency end of the SVs. They last only for ~1 year or so and are clearly observable at the Earth's surface and from satellites. Based on ground observations of the jerks, conductivities of lower mantle are found between 1 and 10^3 S/m (Fig. 6.35).

IV. Earthquakes: Causes and Measurements (GPS Receivers)

Understanding earthquake generating processes, seismic character and seismotectonics are the present topics of research. The ultimate aim and objective however are to forecast earthquakes, since both society and economy are impacted. Seismic zonation map (zones II to V) of India (Fig. 6.56) lists seismic status of the areas and their susceptibility to earthquakes.

The major earthquakes, by and large, are associated with marked crustal movements that lead to volumetric and mass changes aggravating build-up of tectonic stresses. Observations of crustal movements (vertical and horizontal) and deformations are done by GPS satellite receivers (Figs 6.74 and 6.75). GPS data are also supplemented by ground magnetic and gravimetric data to chart models regarding the earthquake preparation processes.

Build-up of tectonic stresses along faults and weaker zones lead to dilatancy and diffusion of fluids; piezomagnetic effect induces temporary changes in magnetic characteristics of rocks and sediments. These are few clues to an impending earthquake (Figs 6.61-6.68). Continuing research showing geomagnetic and geoelectrical precursory signals play pivotal role in earthquake prediction programmes (Figs 6.32, 6.44 and 6.58). Repeat magnetic surveys map distortions in SV trend (Fig. 6.54) in seismic areas due to accumulation of stress. For example, magnetic anomaly contours (Fig. 6.59) in Koyna region represent patterns showing displacement of magnetic rocks by faults and thrusts. In geoelectrical investigations, GDS and MT surveys delineate lateral and radial distribution of the subsurface structures, e.g. fault planes (e.g. Figs 6.58 and 6.60).

Past seismic activities also leave behind tell tale signs of their occurrence in soft sediments in the form of seismites and other cataclysmic features (Figs 6.69 to 6.72). These signs, with the help of palaeomagnetic methods, are deciphered to date the relative time of their occurrence. Since earthquake activity (in some cases) is seen to occur in time bound episodes, the dates acquired by magnetostratigraphy can put a qualitative constraint on future occurrences of seismic episodes at a particular locality.

V. Palaeomagnetism and Continental Drift

Palaeomagnetism revealed significant data about the geomagnetic field's past behaviour and many other aspects of geology and Earth history (Figs 7.1-7.3). From NRM directions, the palaeolatitudes are worked out (Fig. 7.7), giving the probable geographical location of sampling site in the past. The knowledge has validated the hypothesis of continental drift. Alternatively, the position of the pole in the past is calculated to account for the observed direction of magnetization, establishing the theory of polar wandering (Fig. 7.8). Palaeomagnetic studies show that the EMF has been prevalent for at least last two billion years.

Magnetic reversal dating and magnetostratigraphy: Earth's history is chronicled through different methods like radiometric, isotopic, stratigraphic and so on. The joint development of measurements of oceanic anomalies and magnetic stratigraphy, both on oceanic piston cores and on land sections, produced GPTS (Chapter 7). It is the first great synthesis of an absolute chronology for the last 200 Ma in the history of the Earth (Figs 7.10-7.12). Determination of polarity of the remanent magnetism in rocks compared to the present magnetic field provides better scope to date dyke-intrusions in Deccan traps (Fig. 7.13). The GPTS (magnetostratigraphy) documents the changing configuration of continents and oceans as well as is an important method to establish timeline for significant tectonic and geologic episodes. This gives an advantage to date in relative terms the environmental or climatic patterns down the geological ages (Fig. 7.14). Over past three-and-a-half million years, the Earth's magnetic poles shifted approximately nine times. Scientists do not know how or why the magnetic poles reverse, nor do they know exactly what effect this will have on life. The magnetic poles of the Earth reverse on an average every 250 ka, but the intervals between such reversals vary from 10 ka to some Ma. But the Sun reverses its magnetic poles fairly routinely: essentially every 11 years.Studies are also carried out to map details of the magnetic field during polarity transition. Systematic departures from a simple dipolar structure during a reversal are discovered. The non-dipolar character of the transitional field is widely recognized as direct consequence of the systematic drop of dipole intensity. A temporary reduction in the strength of the magnetic field allows the Earth's atmosphere to be less protected from the Sun's lethal radiation. This may cause climatic disruption, destruction of satellites, and eventually loss of life, though not to the extent of extinction, since our ancestors have successfully survived these flips (see Chapters 3 and 8).

Palaeomagnetists recently investigated the progressive evolution of palaeomagnetic directions in two transitional lava flows. Each lava unit recorded a complete sequence of directions going all the way from that of the underlying flow to the direction of the overlying flow. These features are interpreted in terms of very fast geomagnetic changes of 10° and 1000 nT/day. For comparison, values typical of the present-day SV are of the order of 0.1° and 50 nT/yr, i.e. some 10^4 times slower. Recent data reveal that the slow variation of the EMF and also a slow shift in the geographic position of the magnetic poles are roughly cyclic over a period of 500 years. Syntheses of palaeomagnetic records in the past decade yielded some controversial observations like the existence of preferred longitudinal bands for VGP paths over the Americas and eastern Asia, possibly in relation with the cold circum-pacific regions in the lower mantle, outlined by seismic tomography. Such features imply some form of indirect control of the reversal processes by the mantle, generating heterogeneous fluid flow at the core-mantle boundary.

Palaeomagnetic studies have definite relevance for India, which happens to be a fragment broken away from Antarctica and drifted northwards from Gondwanaland (Figs 2.46 and 2.48). These studies yield evidence for or against this hypothesis and these constitute one of the geological investigations taken up by the Indian expeditions to Antarctica. On a much smaller time-scale (a few ka), there is a steady drift of the magnetic north pole. The direction of the magnetic field is frozen in pieces of pottery made at those times. That knowledge is used to 'date' the pottery in archaeological studies; this aspect is called archaeomagnetism, namely the study of the magnetic field in historic times (Fig. 7.2).

AMS technique: The anisotropy of magnetic susceptibility (AMS) is a valuable tool to decipher changing environmental conditions because it reflects various accumulation regimes, e.g. variations of pathways and/or source regions (Fig. 7.15). The AMS allows to discern reworked material from a suite of material whose magnetic mineral content grew in situ. This new technique along with observations of satellite imagery and structural geology is successfully applied on the small Lonar crater (~1.8 km diameter) to evaluate the projectile path of its impactor. The AMS data suggest that the target basalt ~2 km west of the crater is highly shocked due to oblique impact from the east compared to the unshocked target basalt from an equal distance in the east (Fig. 9.2).

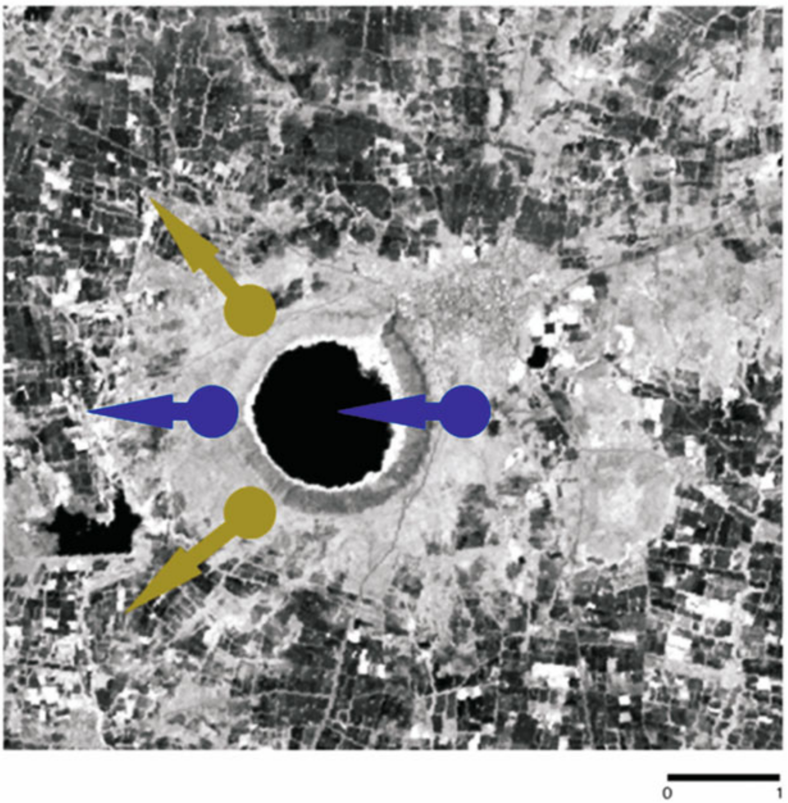


Figure 9.2. Satellite map of Lonar crater showing distribution of impact stress. The result is obtained by AMS study showing impactor direction from east and it had trifurcated into southwest, west and northwest directions after the impact (Saumitra et al., 2009).

VII. Geomagnetic Environmental Change

In recent years, laboratory-based environmental geomagnetism is fast catching up with other established geophysical streams. This uses hysteresis cycle (Chapters 2 and 7) of lumps of sediment, to obtain the parameters of coercivity (remanence), and saturation (isothermal) remanence magnetization of the ferri(o)magnetic component of the sediment. These parameters yield information on the 'domain' structure, and hence are able to determine the level of natural processes and human activity, which occurred over the years at the site of the sediment.

Extreme cases of environmental disturbances such as floods in Mumbai, hurricanes off the coast of America, heavy rains in south India and other similar cases are all a manifestation of increased precipitation due to warm atmosphere. Short-term climatological factors like the El Nino effect (periodic warming of the Pacific waters) could influence seasonal climate even in regions far away from the Pacific waters. The question whether global warming is to be blamed for the vagaries of nature is debated. However, CO_2 levels are substantially higher now than at any time in the last ~800 ka, according to the latest study of ice drilled out of Antarctica. As fears grow over global warming, modelling and predicting climate change has become more important than ever. Such issues of climate change and environmental processes (environmental change and pollution) can be studied using environmental geomagnetism techniques. The approach essentially links the magnetic properties of rock and soil with changes in climate and the environment of natural and anthropogenic type.

In environmental geomagnetism, samples from lakes (wet and dry; spanning ages from ~50 ka to present), sea, land and atmosphere are used, where rock magnetic properties are tested with respect to their palaeoclimatic (temperature and humidity) implications. India has diverse climatic and environmental zones; the samples from which have improved understanding of how the subcontinent's complex climate (monsoon) system works and deciphered the elements sensitive to change. The research has also played a key role in predicting future climatic trends.

Rock magnetic properties can evaluate the remanence acquisition processes, since magnetic minerals are both stable and unstable, though not at the same time. Under a given set of physicochemical environment, magnetic mineral remains stable and unchanged. However, exposure to the atmospheric realm brings about transformations in them which enable palaeoenvironmental/palaeoclimatic reconstruction (Figs 7.36–7.41; 7.43, 7.44 and 7.48–7.55). Magnetic investigations also provide lithostratigraphy in addition to chronostratigraphy, besides offering considerable potential for studying correlation between marine and terrestrial sequences.

In some environmental contexts, there are strong links between the magnetic properties of a sediment and pollution levels. It helps in finding out the provenance of sediments (Figs 7.36–7.41) and performs studies on historical and contemporary particulate pollution in storm water sewers, estuaries and other coastal contexts. It is also a valid tool that brings out differentiation of atmospheric dusts to aerosols and the historical records of their deposition into lakes and mangrove sediments. By detecting magnetic materials within mudflat/peat sediments, it has been possible to obtain detailed records of industrial pollution over the last 200 years in a rapid and economical way.

9.3 UPPER ATMOSPHERIC STUDIES

With advancements in science and technology, the visit to Mars and other planets is increasingly possible. But, there is a need to understand the Earth-Sun connections to safely move out into space and inhabit other planets. Hence, different experiments are designed to explore the fundamental physical processes involved with the Sun, Earth, and other planets by collecting information about the flow of energy within the solar system (Figs 8.1 and 9.3). The research will thus allow to prepare for the harsh effects the solar environment can have on life and technology. Advances in technology help to look deep into the internal workings of the Sun and understand how magnetosphere and EMF work and respond to solar activity (Chapters 3 and 8).

Magnetograms recorded at MOs provide information on how solar plasma interacts with the Earth's upper atmosphere above 100 km, which is also a plasma. The effects of this interaction appear as fluctuations in the magnetic records (Chapters 1, 3, 5 and 8). Data from instrumented satellites together with physical insight indicate the relationship between the solar-terrestrial interaction and the geomagnetic fluctuations. Thereafter, the magnetic records are used to monitor radio communication and even forecast space-weather, i.e. the interactions of the solar and terrestrial plasmas in space (Figs 3.7, 3.13–3.15, 5.5–5.22, 8.6–8.23). Forecast of such interaction, notably during periods of storms in space is likely to assume great importance in coming years. Evidence is gradually mounting that not only radio communication, which is affected during such space-storms, but the pervading energetic wave and charged particle radiations are also capable of causing total power breakdown in auroral regions (Figs 9.4 and 9.5) and of causing corrosion in long pipelines through their ability to induce electrical currents in long conductors on the Earth. These radiations also present health hazards to astronauts and equipment aboard satellites in geospace and in the interplanetary environment (Figs 9.6 and 9.7).

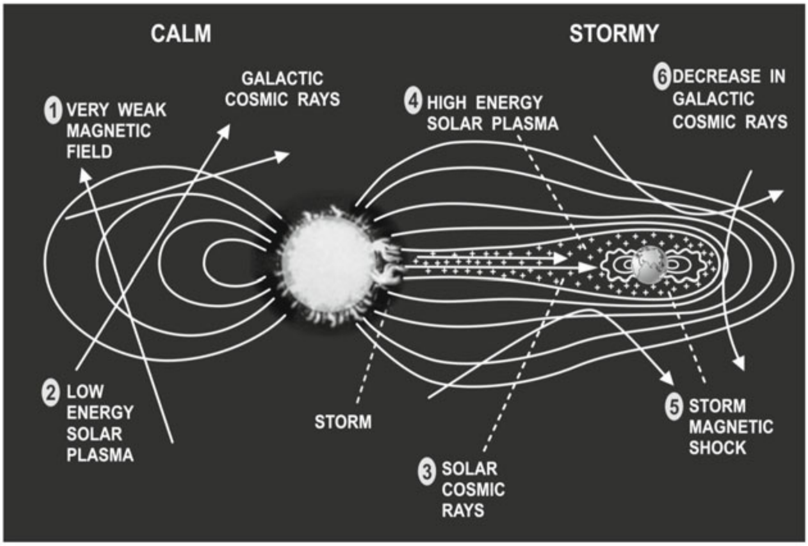


Figure 9.3. Early NASA photo showing just some of the elements in the EM spectrum. The atmosphere blocks harmful waves.

I. Sunspots and Terrestrial Phenomena

The importance of research dealing with solar-terrestrial physics is immense. Monitoring and prediction of the sunspot activity is being carried out for radio communications. Sunspots and solar activity are studied to understand the transfer of energy from the Sun to the Earth's atmosphere (Chapters 3 and 8).

The number of sunspots is strongly related to the occurrence of number of auroras (and violent magnetic storms in EMF) and variations in ozone concentration. An inverse correlation is established between air-Earth conduction current density and the sunspot cycle. The state of the ionized layer in the upper atmosphere is affected very critically by solar activity (sunspot number). The Sun's role in altering the Earth's weather and climate is a subject of popular and practical interest. From historical records, the Maunder minimum from 1645 to 1715 coincides approximately with the 'Little ice age'. This high latitude climatic event is also found in magnetic proxy records (Fig. 7.55) of the mudflat sediment cores. Furthermore, a recurrent period of ~22 years is identified in the pattern of droughts in the western US coinciding with the 22 year magnetic cycle (i.e. two 11 year sunspot cycles) of the Sun. These correlations suggest that the sunspot activity can be used to predict changes in electrical, magnetic and meteorological environment of Earth. Even the satisfactory working of the communication satellite depends critically on the solar activity.

II. Magnetic Storms and Society

The modern society is relying more and more on technology that is affected in some way by conditions in the space environment. Magnetic storms form a major component of space weather. The most dramatic events on the Sun are solar flares and coronal mass ejections during solar maximum (Figs 8.9–8.11). Intense and super-intense geomagnetic storms create hostile space weather conditions that can generate many hazards to the spacecraft as well as technological systems at ground (Figs 8.11–8.12). Several NASA missions reported loss of instrument data and damage of two spacecraft instruments during 30–31 Oct 2003 storms. The Swedish power grid reported failure of transformer at some stations for several hours. Adverse space weather conditions during intense magnetic storm can pose threat to astronauts and jetliner passenger due to both high radiation dosage and loss of contact with the ground station. Several trans-polar flights were cancelled during Oct–Nov 2003 intense magnetic storms. There can be malfunctioning or even permanent damage to spacecraft, e.g. one Japanese spacecraft was probably damaged beyond salvage during Oct–Nov 2003 magnetic storms. The geomagnetically induced currents (GICs) during intense magnetic storms can damage power transmission lines and corrode the long pipelines and cables.

How GIC affect power systems: Geomagnetically induced currents are driven by electric fields produced by magnetic field variations that occur during a

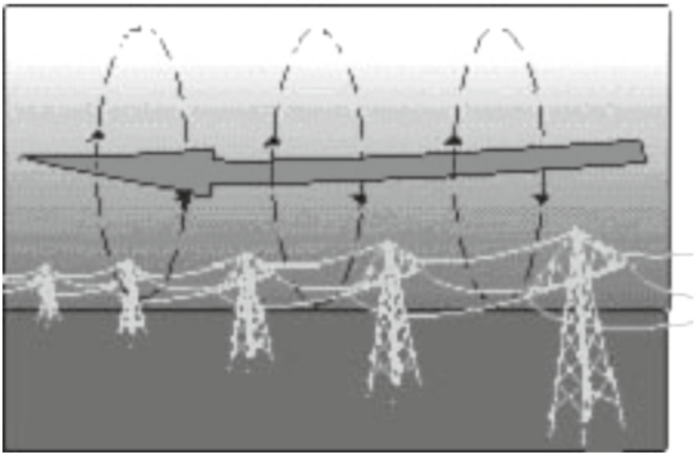


Figure 9.4. GIC flowing through the transformer winding (http:/ www.spaceweather.gc.ca/effects_e.php).

geomagnetic disturbance. Because of their low frequency compared to the AC frequency, the GIC is reckoned by a transformer as a slowly varying DC current. GIC flowing through the transformer winding produces extra magnetization during the half-cycles and can saturate the core of the transformer (Fig. 9.4). This results in a very spiky AC waveform with increased harmonic levels that can cause misoperation of relays and other equipment on the system and lead to problems ranging from trip-outs of individual lines to a total collapse of the whole system.

Continental cable systems: On 4 Aug 1972, an outage of the L4 coaxial cable system in the mid-western US occurred during a major geomagnetic disturbance. An examination of this disturbance showed that at the time of the outage, the EMF was severely compressed by the impact of high speed particles from the Sun. The resulting magnetic disturbance had a peak rate of change of 2200 nT/ min and a rate of change of the magnetic field at the cable location estimated at 700 nT/min. The induced electric field at the cable was calculated to have been 7.5 V/km, exceeding the 7.4 V/km thresholds at which the line would experience a high current shutdown.

Transformer heating in power systems: Saturation of the transformer core produces extra eddy currents in the transformer core and structural supports which heat the transformer. The large thermal mass of a high voltage power transformer means that this heating produces only a negligible change in the overall transformer temperature. However, localised hot spots can occur and cause damage to the transformer windings (Fig. 9.5). Also, extra harmonics generated in the transformer produce unwanted relay operations, suddenly tripping out power lines. The stability of the whole system can also be affected as compensators switch out of service. Such a sequence of events led to the

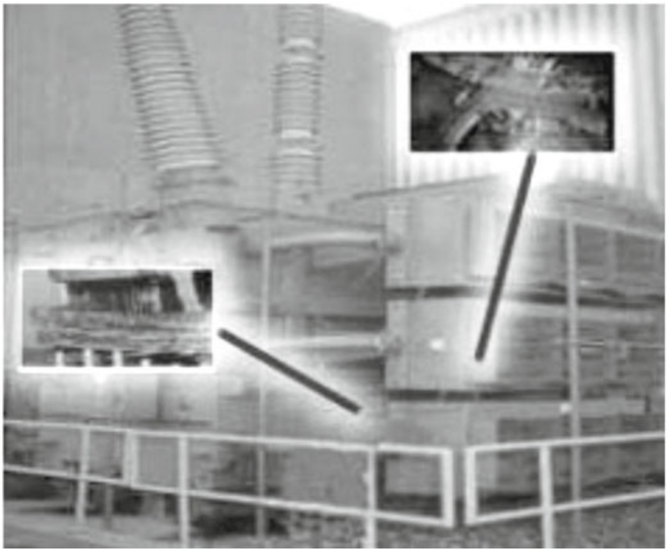


Figure 9.5. Damaged transformer (http://www.spaceweather.gc.ca/effects_e.php).

Quebec blackout of 13 March 1989, which left the whole province without power for over nine hours.

III. Geomagnetic Hazards

The geomagnetic hazard to technology results from the strengthening of magnetospheric and ionospheric current systems by the solar wind and by CMEs. A common theme that emerges from a study of geomagnetic hazards is a need for accurate geomagnetic storm forecasting in terms of onset time and duration, maximum amplitude, and variation period (Chapter 5). The close connection of geomagnetic hazard with solar activity is also clear. Some practical applications of geomagnetic variations will clearly benefit from a thorough physical understanding of the Sun-Earth magnetic interaction and in particular accurate prediction of geomagnetic variations. For instance, the response of the EMF to solar conditions is useful in investigating Earth structure using MT (see magnetotellurics in Chapter 6), but it also creates a hazard. This geomagnetic hazard is a risk to technology, rather than to health (Chapters 3 and 8).

Space weather effects on technology are far reaching and diverse as also expensive. Astronauts are definitely at risk from bursts of ionizing solar energetic particle radiation. Astronaut protection involves appropriate spacecraft shielding relative to Sun. Modelling and predicting the changing morphology of the geomagnetic field is important in determining, where charged particles may enter into the lower atmosphere (Chapters 3 and 8). The overall space weather effects can be summarized through Fig. 8.12.

IV. Satellite Operation, Navigation and Radio Communication

The ionosphere plays a significant role in VLF through to HF radio communication and in navigation systems. Ionospheric conductivity is partly affected by geomagnetic storms but more significantly by solar UV and X-ray control of the ionospheric D, E and F layers (see Chapters 3 and 8). Solar flares cause signal-phase anomalies and amplitude variations to occur (fades and enhancements) and conditions can persist for minutes to hours. Solar flares and CMEs are also important as sources of solar energetic particles, affecting radio communications at high latitudes. Ultrahigh-frequency (UHF) radio signals are central to the GPS that utilizes satellites in Earth orbit for precise ground position determination.

Space weather effects on GPS: UHF waves pass largely unattenuated through the ionosphere but the system accuracy is sensitive to variations in the TEC in the path between ground and satellite. The TEC determines the signal propagation delay. Varying propagation delays cause errors in the determination of the range (or distance), or 'range errors' (Fig. 9.6). TEC variation occurs during geomagnetic storms and these particularly degrade the accuracy of GPS equipment. Geomagnetic storms also produce ionospheric irregularities and scintillations. Ionospheric scintillation may cause problems such as signal power fading, phase cycle slips, receiver loss of lock and degraded quality of satellite navigation systems (Chapter 8).

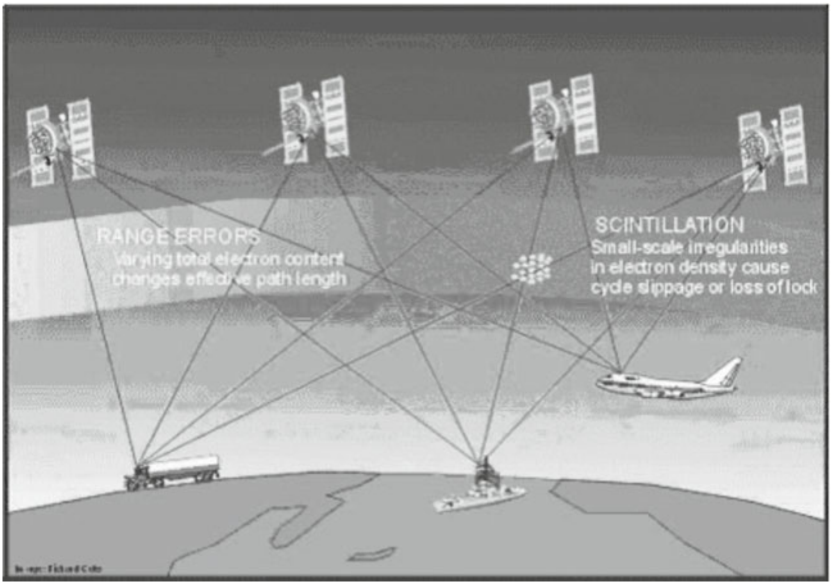


Figure 9.6. Space weather effects on GPS (http://www.spaceweather.gc.ca/ effectsgps_e.php).

Another GPS technique uses carrier phase tracking. In this technique, the phases of individual cycles of the carrier waves are compared. However, if the TEC along a signal path from a satellite to a receiver changes very rapidly as a result of space weather disturbances, the resulting rapid change in the phase of the radio wave causes difficulties for the GPS receiver in the form of 'loss of lock'. Temporary loss of lock results in 'cycle slip', a discontinuity in the phase of the signal. Scintillations (<15 sec) are particularly troublesome for receivers that are making carrier-phase measurements, resulting in inaccurate or no position information. Code-only receivers are less susceptible to these effects.

From another viewpoint, the GPS system provides continuous routine measurements of the TEC along the multitude of varying signal paths to each receiving station in a regional or global network. These measurements permit the mapping of variations in the ionospheric TEC over a region. Such information can be useful for studying space weather phenomena.

Effects on satellites: Low Earth orbit satellites and space stations (up to ~1000 km altitude) experience increased air drag during geomagnetic storms. Satellites operate in an environment filled with charged particles (Fig. 9.7). These particles can affect satellites in a variety of ways, either directly by penetrating into the satellite electronics, or indirectly through spacecraft charging with the resulting discharge causing problems. For example, these processes can result in dummy commands, damage to electronic devices, loss of control, and even satellite failure.

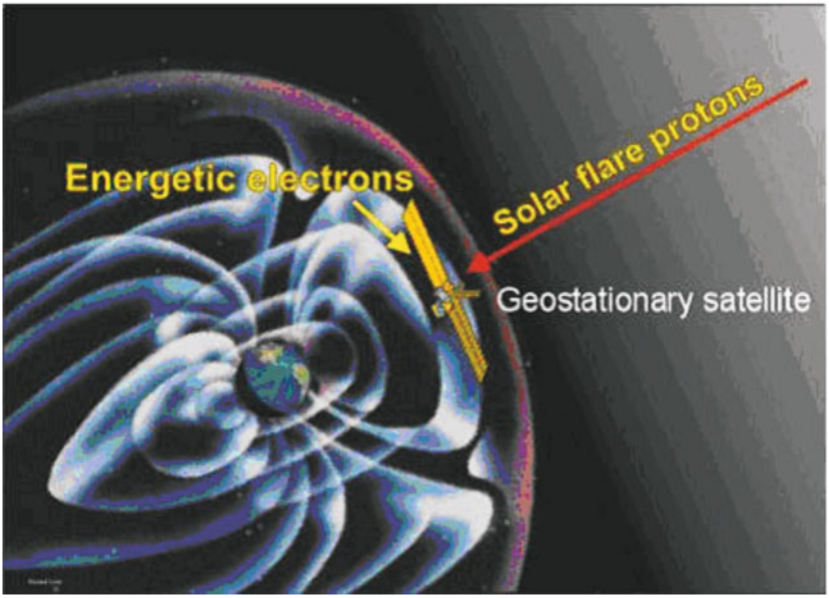


Figure 9.7. Geostationary satellite swamped by charged particles.

Several satellites are disrupted since high energy particles (solar wind) flow through sections of the satellites and damage their sensitive electronic devices. For instance, in 1979, the Skylab space station prematurely re-entered Earth's atmosphere due to a malfunction caused by increased solar activity, and consequently rained debris over the Indian ocean and parts of western Australia.

Solar proton effects: When high velocity ions (Fig. 9.8) plough through semiconductor devices of the satellites, they produce a large number of electrons and holes that carry currents within these devices. Large numbers of electron-hole pairs introduced into sensitive regions like memory cells can alter information and result in phantom commands. Effects can be devastating if ion impacts occur in control systems or decision-making circuits. In addition, these impacts degrade semiconductor lifetimes.

Surface charging: Surface charging of spacecraft in a synchronous orbit can occur due to incidence of a large incoming flux of electrons in the absence of sufficient charge drainage by mechanisms such as photoemission. 'Hot' electrons with energies in the range of several keV are mainly responsible for surface charging. Intense fluxes of these electrons are closely related to substorm activities. Hence, surface charging occurs more often in the midnight to dawn period. The differential charging of spacecraft surfaces can give rise to destructive arc discharges, causing satellite operational anomalies.

Internal charging: The occurrence of highly energetic electrons with energies >2 MeV represents adverse space weather conditions hazardous for geosynchronous satellites. When this happens, there is an internal charging of satellite components by energetic electrons with possible electric discharges, resulting in malfunction of the satellite. Such an event was the likely cause of a number of satellite operational anomalies in January 1994.

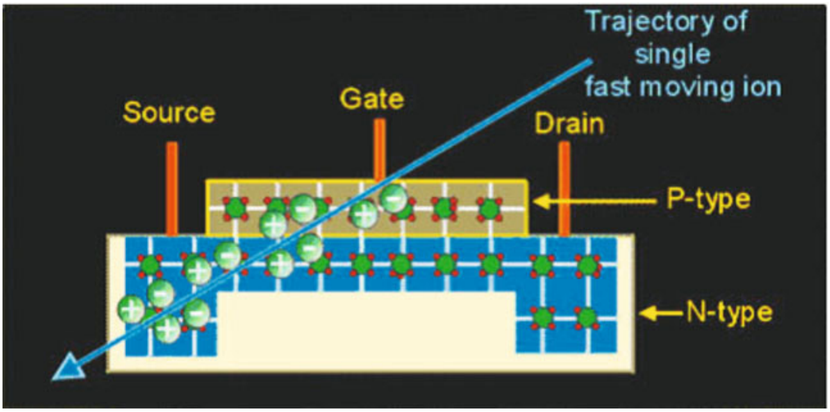


Figure 9.8. Solar proton effects on satellite devices (http://www.spaceweather.gc.ca/satellites_e.php).

V. Magnetism in Power Generation

The use of magnetic and electric fields for power generation is likely to become widespread in coming years. Such power generators are called magnetohydrodynamic (MHD) devices. In these devices, energy of thermal or kinetic nature is directly transformed into electricity. Magnetohydrodynamics is the behaviour of electrically conducting fluids in electric and magnetic fields at high temperature. Most of the MHD devices are still under research and at present are used for small power requirements, but applications have already commenced. There was recently a report of a ship having been developed in Japan to operate on MHD power.

It was mentioned in Chapters 3 and 8 that the Earth's magnetospheric tail is a site, where energetic solar wind particles rush at very high speeds (few hundred km/sec) through time-varying electric and magnetic fields. A NASA satellite made several attempts to tap this power, which is dormant in distant space. The idea is as follows. A space shuttle was to drag along with it a satellite tethered to it by a 20 km long electrically conducting cable. As the cable traversed the Earth's magnetic field lines, an electric potential of ~5,000 V will setup between shuttle and satellite—this attracts free electrons from the ionosphere to the satellite. In order to close the circuit, astronauts were to fire an electron gun from the shuttle to the ionosphere and an electric current flow through the circuit. This is schematically illustrated in Fig. 9.9. Unfortunately, the tether got stuck at a distance of 260 m from the shuttle and for fear of losing the satellite, the astronauts reeled it back. As the whole setup is intact, it is fairly certain that after a check-up, this experiment for generating power

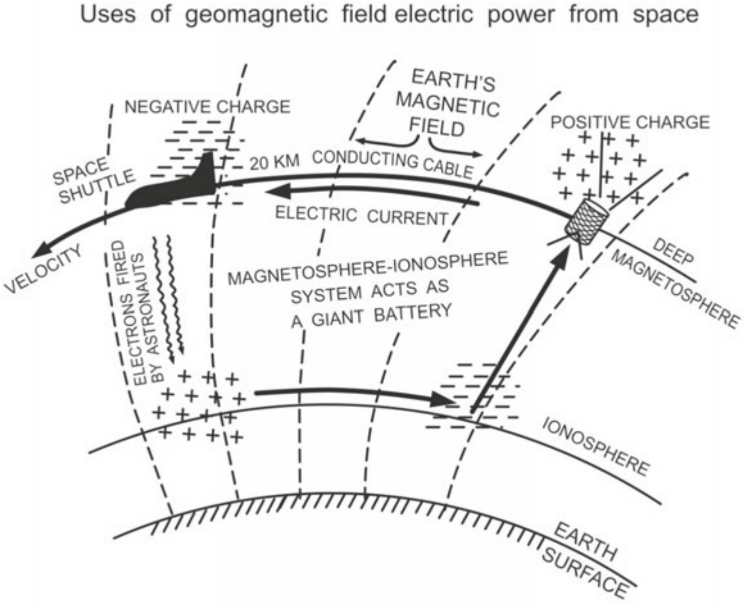


Figure 9.9. Tapping power which lies dormant in distance space is likely to become reality in the near future (Rajaram and Pisharoty, 1998).

from geospace will be flown again in the near future. If the idea should indeed work, the possibilities for power on Earth are limitless.

VI. Conclusions

The household applications of magnetism are too numerous to be pointed out here: the door-bell, the telephone, the television set, audio tapes, video cassettes. The list is endless. Indeed much of today's world just would not work if it were not for magnets and magnetism. Our emphasis in this chapter has been mainly on the applications of geomagnetism.

To conclude, it can be emphatically stated that geomagnetic studies are not at all 'ivory tower studies'. As shown in the foregoing sections, they have very wide and useful applications. What a society can derive from such studies, for economic and societal welfare, partly depends upon the degree of the nation's development in science. It also depends on the ability, mutual cooperation and the attitude of the scientists and planners involved. The required attitude is a cultural one. Geomagnetism also has many applications in defense especially in missile technology. It is the intention not to elaborate on this aspect here, since science and technology should be used for the benefit of humankind, not for its destruction.

Medical applications: It is shown that many degenerative diseases are connected with the disruption of normal iron homeostasis in the brain. Nanoscale magnetic biominerals (primarily magnetite and maghemite) may be associated with senile plaques and *Tau* filaments found in brain tissue affected by these diseases. These findings have important implications for our understanding of the role of iron in neurodegenerative diseases as well as profound implications for their causes. In addition, the presence of biogenic magnetite in affected tissue should also provide improved mechanisms for early detection through modification of magnetic resonance imaging (MRI) pulse sequences.

Recent evidence points to magnetic technique being more sensitive in assessing lung contamination than the traditional methods like radiography. Magneto-pneumography has been successfully applied to meet the needs of many workers employed in places like shipyard and foundry, where metal work is done. Nowadays, the magnetocardiogram is used as a supplement to electrocardiogram. MRI has become a preferred tool over other traditional methods like X-rays. MRI or NMR, nuclear magnetic resonance, is a technique that involves subjecting certain atomic nuclei to very strong stationary magnetic fields and then observing how they selectively absorb VHF radio waves. MRI is a relatively hazard-free, non-invasive way to generate visual images of thin slices of the body by measuring the characteristic magnetic behaviour of specific nuclei in the water and fats of the body. MRI images show great sensitivity in differentiating between normal, diseased and damaged tissues. This technique works better in imaging brain, heart, liver, kidneys, spleen, pancreas, breast and other organs. Thus, the applications and utilities of geomagnetism are many (Appendix 9.2).

APPENDIX 9.1

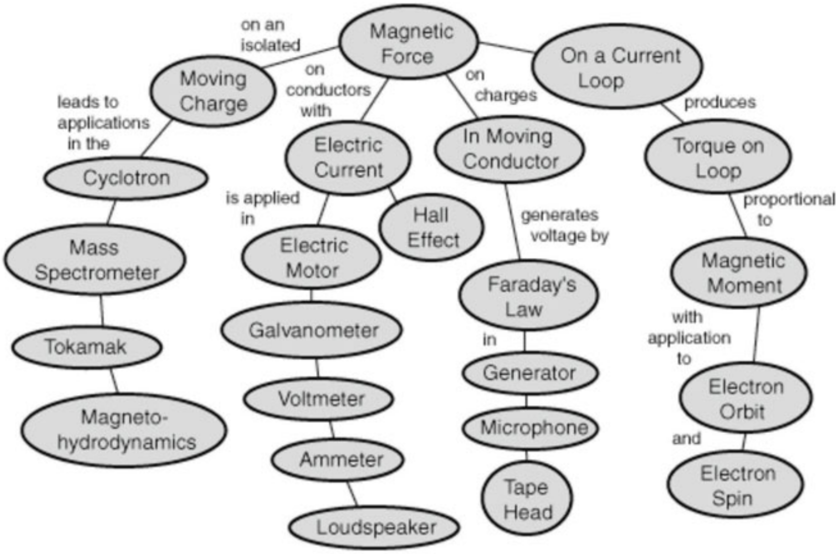
Locations of the North and South Dip Poles and Geomagnetic Poles

	North dip pole		*South dip pole*		*North geomagnetic pole*		*South geomagnetic pole*	
Epoch	*Latitude*	*Longitude*	*Latitude*	*Longitude*	*Latitude*	*Longitude*	*Latitude*	*Longitude*
1900	70.46	-96.19	-71.72	148.32	78.68	-68.79	-78.68	111.21
1905	70.66	-96.48	-71.46	148.55	78.68	-68.75	-78.68	111.25
1910	70.79	-96.72	-71.15	148.64	78.66	-68.72	-78.66	111.28
1915	71.03	-97.03	-70.80	148.54	78.64	-68.57	-78.64	111.43
1920	71.34	-97.39	-70.41	148.20	78.63	-68.38	-78.63	111.62
1925	71.79	-98.00	-69.99	147.63	78.62	-68.27	-78.62	111.73
1930	72.27	-98.69	-69.52	146.79	78.60	-68.26	-78.60	111.74
1935	72.80	-99.34	-69.06	145.77	78.57	-68.36	-78.57	111.64
1940	73.30	-99.87	-68.57	144.60	78.55	-68.51	-78.55	111.49
1945	73.93	-100.24	-68.15	144.44	78.55	-68.53	-78.55	111.47
1950	74.64	-100.86	-67.89	143.55	78.55	-68.85	-78.55	111.15
1955	75.18	-101.41	-67.19	141.50	78.54	-69.16	-78.54	110.84
1960	75.30	-101.03	-66.70	140.23	78.58	-69.47	-78.58	110.53
1965	75.63	-101.34	-66.33	139.53	78.60	-69.85	-78.60	110.15
1970	75.88	-100.98	-66.02	139.40	78.66	-70.18	-78.66	109.82
1975	76.15	-100.64	-65.74	139.52	78.76	-70.47	-78.76	109.53
1980	76.91	-101.68	-65.42	139.34	78.88	-70.76	-78.88	109.24
1985	77.40	-102.61	-65.13	139.18	79.04	-70.90	-79.04	109.10
1990	78.09	-103.68	-64.91	138.90	79.21	-71.13	-79.21	108.87
1995	79.09	-105.42	-64.79	138.76	79.39	-71.42	-79.39	108.58
2000	80.97	-109.64	-64.66	138.30	79.61	-71.57	-79.61	108.43
2005	83.19	-118.24	-64.55	137.85	79.82	-71.81	-79.82	108.19
2010	85.01	-132.66	-64.43	137.32	80.08	-72.22	-80.08	107.78
2015	86.07	-153.27	-64.30	136.74	80.36	-72.62	-80.36	107.38

Locations are computed from the 11th generation IGRF. (http://www.geomag.bgs.ac.uk/poles.html)

APPENDIX 9.2A

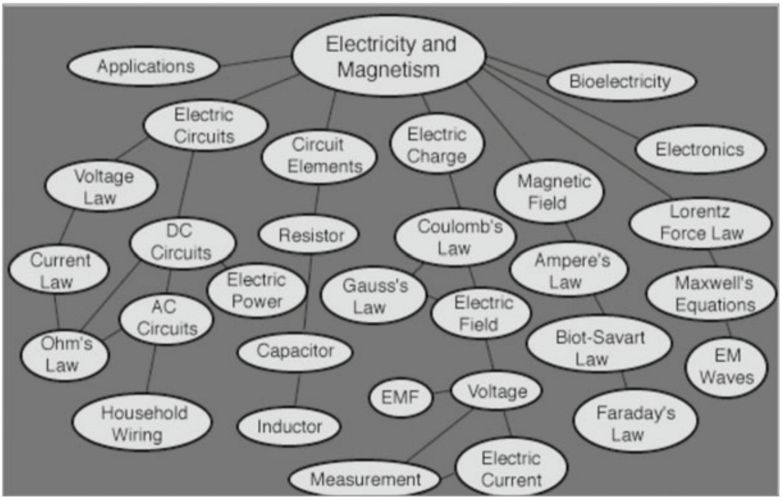
Day-to-day Applications of Magnetic Force



(http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/magforcon.html#c1)

APPENDIX 9.2B

Day-to-day Applications of Magnetism and Electricity



(http://hyperphysics.phy-astr.gsu.edu/hbase/emcon.html#emco)