GEOMAGNETIC FIELD VARIATIONS

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Abstract. In this review, an attempt has been made to describe the large variety of geomagnetic variations, both regular and irregular. After a brief description of the Earth and its environment, different types of quiet-day variations are described and present ideas regarding their possible mechanisms are discussed. In general, periodicities exceeding several tens of years can be attributed to changes in the interior of the Earth while periodicities of 22 years or less seem to be related to phenomena connected with the Sun, through the interaction of solar wind with the Earth’s magnetosphere. The morphology of irregular storm-time variations and its relationship with interplanetary plasma parameters is discussed with particular reference to the orientations of interplanetary magnetic field, particularly the southward $B_z$ component which seems to play a crucial role. Various storm-time phenomena occurring in the polar, auroral, mid-latitude and equatorial regions and their interconnections are described. Theoretical models offering explanations of many of these phenomena are discussed, the unsolved problems are outlined, and the direction of the present effort in solving these is indicated.

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1. Introduction

When God created Earth, He must have inadvertently left a bar magnet in its core. Or so it would seem. Because the distribution of magnetic field lines on the surface of the Earth resembles very closely that of a dipole, its axis not quite coincident with the axis of rotation of the Earth (the angular distance being about 11.5°) and the centre shifted by about 450 km. The dipole pattern would have extended out in space too but for the fact that the Earth is immersed in the so-called 'solar wind' which is a continuous flow of solar plasma (mostly electrons and protons) emitted radially outward from the Sun at supersonic speeds of about 300 km s⁻¹ during quiet periods, increasing to even 1000 km s⁻¹ or more during solar disturbances. The Earth may be compared to a beautiful modern lady rushing on a two-wheeler with wind blowing in her face, her mass of beautiful long hair trailing behind. The dipolar geomagnetic field pattern is appreciably compressed on the sunward side so that beyond about 10 Rₚ (Earth radii), the geomagnetic field ceases to have any influence and the interplanetary magnetic field takes over. On the anti-sunward side, geomagnetic field lines are 'swept back' giving the geomagnetic 'tail field' configuration extending to several Earth radii, often far beyond the orbit of the Moon (about 60 Rₚ), when the Moon basks in the beauty of dame Earth, entangled in her tresses around full moon days. The region in which geomagnetic field gets confined due to the impact of solar wind is termed as 'magnetosphere' though its shape is by no means spherical but looks more like a bullet with the snubbed nose facing the Sun. The geomagnetic field is thus
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considerably modified by the solar wind. This is reflected not only in the overall asymmetric topology of geomagnetic field around the Earth but also in the time-variations of geomagnetic field which have a wide variety of periodicities ranging from fractions of a second (micropulsations) to several years (solar cycle and secular variations). In this review, an attempt is made to describe the main characteristics of these variations and their utility in understanding the environment of the Earth. The early history of this subject and several other aspects have been dealt with in considerable detail in the monumental work *Geomagnetism* by Chapman and Bartels (1940), as also in the other standard books *Physics of the Geomagnetic Phenomena* (1967) edited by Matushita and Campbell, and *Solar-Terrestrial Physics* (1972) by Akasofu and Chapman (henceforth referred to as Book I, II and III respectively) and hence will be dealt with here only in a cursory way while the main emphasis will be on the progress made in recent years by using geomagnetic variations as a tool for understanding the near environment of the Earth and the impact of solar disturbances on the same. The literature on this topic is colossal indeed and hence mostly selected recentmost literature is referred to, the list being thus only representative and by no means comprehensive.

2. The Earth’s Main Field

The Earth could be considered a perfect sphere of radius about 6370 km, a good approximation for many purposes. A better approximation is that of an oblate spheroid, formed by rotating an ellipse around its minor axis. For Earth, the bulge is at the equator and the flattening at the poles, the equatorial radius larger than the polar radius by about 20 km. However, recent satellite observations indicate that the Earth is slightly asymmetric (pear-shaped) with respect to the equator. The geodetic potential of the Earth is much more complex than the simple \( V = GM/r \) type of spherical symmetry. Terrestrial satellites do not move along an ellipse in a fixed plane with the Earth’s centre of mass at one focus. Instead, their plane shows a longitudinal precession of a few degrees a day over and above the apparent longitudinal movement because of the 24-hourly rotation of the Earth. There is enough evidence to speculate that the relative positions of continents and seas on the surface of the Earth have not remained constant in geological time and most probably movements of the order of a few cm/year are going on even at present (continental drifts).

The nature of the interior of the Earth is guessed mostly by seismic investigations which show regions of sudden transitions indicating a layered structure. There is an upper crust about 30 km thick on the continents and about 5 km thick under ocean beds. At about 35 km below the continents and about 10 km below ocean beds is the Mohorovicic discontinuity followed by the upper mantle up to a depth of about 400 km and consisting mainly of dunite-periodotite type rocks. After a transition zone from about 400–1000 km, there is the lower mantle at 1000–2900 km consisting of pyroxene-olivine type rocks. Then follows a liquid outer core composed of molten iron and nickel and their oxides from about 2900–5130 km followed by a solid inner-most core of radius about 1240 km. Knowledge about the exact internal structure of
the Earth is important not only for studying the processes of the formation of the Earth but also for understanding the mechanism which would create the main geomagnetic field. It is believed that the Earth was formed by accretion of pyrolite, chondrites and other kind of meteorite substances which after radioactive heating and compression melted fractionally to give the basaltic magma leaving behind dunite-peridotite type rocks. The geomagnetic field is supposed to be created by a self-excited dynamo action firstly due to convective motions in the liquid core caused perhaps by heating due to radioactive materials and secondly due to a possible differential rotation of the liquid core (Elsasser, 1956; Bullard and Gellman, 1954). The actual validity of such a mechanism is by no means established and much further investigation is necessary.

The geomagnetic field, predominantly dipolar, is specified in several ways viz. by the three components, X (northwards), Y (eastwards) and Z (vertically downwards) or by the Horizontal component \( H = (X^2 + Y^2)^{1/2} \), the Declination \( D = \tan^{-1}(Y/X) \) and the Inclination (or Dip) \( I = \tan^{-1}(Z/H) \). The total field \( B \) (or \( F \) or \( T \)) = \( (X^2 + Y^2 + Z^2)^{1/2} \) and the components \( X, Y, Z, H \) are measured in the c.g.s. unit called gauss (G) and have values of a fraction of a gauss on the surface of the Earth. For expressing small changes, a smaller unit called gamma (\( \gamma = 10^{-5} \) G) is used. The components \( D \) and \( I \) as defined above are in radian measure and are usually converted into degrees, minutes and seconds of arc. The locus of a point showing \( I = 0 \) is called the magnetic or dip equator on which \( Z = 0 \) and the total field there is completely represented by the horizontal component \( H \) only. In contrast, there are points (poles) in high latitudes where \( H = 0, I = 90^\circ \) and the total field there is completely represented by the vertical component \( Z \) only. The Arctic and Antarctic magnetic dip poles were at about 76°N, 101°W and 66°S, 141°E in 1965. The positions change slightly with time.

If no electric currents are flowing across the Earth's surface, the geomagnetic potential \( V \) satisfies Laplace's equation and can be represented by a series of spherical harmonics in spherical polar coordinates \((r, \theta, \phi)\) as:

\[
V = a \sum_{n=0}^{\infty} \sum_{m=0}^{n} P_n^m(\cos \theta) \left[ \left\{ (1 - C_n^m) \left( \frac{a}{r} \right)^{n+1} + C_n^m \left( \frac{r}{a} \right)^n \right\} A_n^m \cos m\phi + \left\{ (1 - S_n^m) \left( \frac{a}{r} \right)^{n+1} + S_n^m \left( \frac{r}{a} \right)^n \right\} B_n^m \sin m\phi \right].
\]

Here \( C_n^m \) and \( S_n^m \) are positive numbers representing fractions of the harmonic terms of external origin. Actually, \( V \) is not observed directly but the worldwide distribution of the components \( X, Y, Z \) can be used for determining the various coefficients involved in (1), because of the relations

\[
X = \frac{1}{r} \frac{\partial V}{\partial \theta}, \quad Y = -\frac{1}{r \sin \theta} \frac{\partial V}{\partial \phi} \quad \text{and} \quad Z = \frac{\partial V}{\partial r}.
\]

Though \( V \) consists of the component \( V^e \) of external origin and \( V^i \) of internal origin, the external component \( V^e \) is very small and contributes fields of the order of 100
gamma or less on the surface of the Earth while fields due to $V^i$ are of several thousand gamma. The component $V^i$ on Earth may be expressed approximately in terms of the harmonic terms of the first degree only ($n=1$) as:

$$V_i = \frac{a^3}{r^2} \left\{ g_1^0 \cos \theta + (g_1^1 \cos \phi + h_1^1 \sin \phi) \sin \theta \right\},$$

where according to the International Geomagnetic Reference Field (GRF) 1965.0 (Cain and Cain, 1968), $g_1^0 = -30339 \gamma$, $(h_1^0 = 0)$, $g_1^1 = -2123 \gamma$ and $h_1^1 = 5758 \gamma$ with an equatorial value of $H$ as $H_0 = 30950 \gamma$ for $r = a = 6370$ km. The term $g_0^0$ does not appear as it refers to monopoles only. Higher order terms ($n = 2$ and higher) are smaller and can be neglected for some purposes. However, in the magnetospheric region the effects due to the external potential $V^e$ may be appreciable and should be taken into account as we shall discuss later. The possibility of a non-potential component for $V$ should also be borne in mind (Chakrabarty, 1954).

On the surface of the Earth, the potential represented by (3) is that of a centred dipole tilted at an angle of 11.5° with the axis of rotation of the Earth and the position of the corresponding geomagnetic north pole is 78.5°N, 291°E which is different from that of the actual magnetic dip dipole mentioned earlier. Nevertheless, a complete description of the global surface in terms of geomagnetic dipole coordinates is available. A corresponding geomagnetic equator can also be defined. However, this description is not fully satisfactory at all locations. The geographic, geomagnetic and magnetic dip equators differ from each other in varying degrees (0±10°) at different locations on the Earth. A better matching between the observed dip configuration and the calculated geomagnetic coordinates is obtained if it is assumed that the dipole referred to above is not a centred dipole but an eccentric dipole, the centre shifted about 450 km (in 1965) from the centre of the Earth and its axis intersecting the surface of the Earth at about 81°N, 85°W and 75°S, 120°E. It reproduces satisfactorily the very low values of about 25000 γ for the total field at the South American equator and about 40000 γ at the Australasian equator. For some purposes, it may be adequate to represent the geomagnetic field as that due to this eccentric dipole with coefficients as given in Equation (3). However, for many other purposes, it is necessary to use Equation (1) with $n$ values up to 6 or 8 or sometimes even higher, for example in the study of geomagnetic conjugacy where phenomena in the northern hemisphere are expected to be related to those in the southern hemisphere at the feet of common connecting field lines. Also, many of the major geomagnetic anomalies on the surface of the Earth (e.g. the Brazilian and Central African anomalies) are not completely reproduced by any of the models referred to above. On the other hand, for studying the effect of geomagnetic field at distances away from the Earth, the local anomalies can be safely neglected.

Till the advent of satellites, all geomagnetic data were obtained from ground and sea surveys which had sometimes very serious geographical limitations. With satellites, surveys covering the Earth uniformly were possible. Several such surveys have been conducted so far, though mostly for the total field rather than for the individual
components, with low altitude (less than 1500 km) satellites. Comparisons with
ground surveys have been quite satisfactory, specially those based on POGO data
(Cain and Cain, 1968; Cain, 1971). Values for the various coefficients \( g_n \) etc. mentioned
in Equation (3) are given for values of \( n \) up to 8 in Cain and Cain (1968) and also in
Book III (p. 80). An interesting exercise has been to compare the residuals of the
survey data from the averaged field model using terms up to \( n = 13 \). The residuals show
large areas of magnetic anomalies on the surface of the Earth, originating mostly in
the upper mantle or crust (Benkova et al., 1973; Cain, 1973).

According to Roederer et al. (1973) it may be more appropriate to interpret the
physical properties of the field expansion terms in the tilted, centred or the off-set
dipole coordinate systems.

The various geomagnetic components do not remain constant with time. The
various long-term and short-term variations are discussed further on. From earlier
data, the yearly changes \( g_n^m \) and \( h_n^m \) in the coefficients \( g_n^m \) and \( h_n^m \) have also been esti-
mated. These are given in Book III (p. 80) and can be used for estimating \( g_n^m \) and \( h_n^m \)
for any particular period after 1965. Roederer (1974) has reported secular-invariant
relationships among some field coefficients. Hurwitz et al. (1973) have given fresh
estimates of \( g_n^m \) and \( h_n^m \) for 1964–70 for \( n \) and \( m \) up to 13. In recent years, it has also
been possible to have vector measurements of geomagnetic field in spacecraft experi-
ments and valuable information is obtained about currents in the magnetospheric
region as will be described later.

Instruments for measuring the magnetic field components, essentially based on the
rotation of a carefully balanced magnet are in use all over the world for several
decades. Book I gives relevant details. In recent years, space measurements have used
analog devices like the flux-gate saturable core and spinning coil magnetometers or
resonant frequency devices like the proton precession or rubidium vapour optical
pumping magnetometers. Details are given in Book II (p. 939).

3. The Earth's Atmosphere

At the surface of the Earth, the atmosphere has a pressure of about 1000 mb (76 cm of
Hg), a temperature of about 300 K and a density of about \((1/1000) \) g cm\(^{-3}\). The
major constituents are nitrogen (73%) and oxygen (21%) while argon, CO\(_2\), H\(_2\)O etc.
are in minor quantities (less than one percent). With altitude, the pressure and density
decrease very rapidly (reducing to about \(1/10\)th every 16 km) up to about 120 km and
less rapidly thereafter (about \(1/10\)th every 80 km). The temperature profile is more
complicated. From a surface value of about 300 K, it decreases to about 200 K at
about 20 km (tropopause), increases again to about 300 K at about 50 km (strato-
pause), decreases again to about 200 K at about 80 km (mesopause) and then rises
first slowly up to about 100 km, then rapidly up to about 300 km and then less rapidly
till after about 2000 km the change is negligible (thermopause).

The structure of the upper atmosphere is greatly affected by solar radiations of a
variety of wavelengths from hard X-rays (fractions of an ångström) to ultraviolet,
visible, infrared and radiowavelengths (several metres). Some of these radiations produce ozone at about 25-30 km which is partly responsible for the peculiar temperature profile. Other radiations weakly ionise the atmospheric gases and produce ionospheric layers D, E, F₁ and F₂ from about 80 km to 300 km. Figure 1 shows the height distribution of the number density of N₂, O₂, O (atomic oxygen), Ar (argon),

![Diagram](image)

Fig. 1. The distribution with height of the number density of N₂, O₂, O, Ar, He and H, electron component (see inset) and atmospheric temperature for an exospheric temperature of 1000 K (based on Jacchia, 1971).
He (helium) and H (hydrogen) and the atmospheric temperature. Ionospheric electron densities are shown separately in the inset. In the region from ground to about 100 km, atmospheric turbulence is very effective and all constituents are well mixed forming a homosphere with a mean molecular mass of about 30. Above the homopause or turbopause at about 100–120 km, turbulent mixing is less and less effective and the region is called heterosphere. Mainly because of the dissociation of molecular oxygen into atomic oxygen, the mean molecular mass in this region reduces considerably, individual gases start separating by diffusion and the lighter gases extend to greater heights. Thus at about 500–700 km in quiet sun years and at higher altitudes in years of high solar activity, a helium layer (heliosphere) is formed. At still higher altitudes, a region (exosphere) containing mostly hydrogen is obtained. A substantial portion is ionised and forms a belt of low energy particles (plasmasphere) extending to a few Earth radii. The exosphere has also two high energy belts called the inner and outer radiation belts, and perhaps a third one at a much lower altitude (thermosphere).

The basic processes that influence the static structure of the Earth’s atmosphere are (i) the photoionisation due to solar radiations of various frequencies and the interactions between neutral molecules, (ii) ions and electrons causing dissociations, and (iii) recombinations and energy transfer due to collisions. These have been studied in considerable detail and several features like the gross height distributions of various parameters are understood in some detail (Book III, pp. 109–189). The main complication arises because of the dynamic processes that move the ionised and neutral gases and electrons due to winds and electric fields which are caused by solar heating as well as due to the entry of solar wind plasma mainly in the polar regions. Particularly, for sustaining atmospheric current systems producing observable variations on the geomagnetic field at ground, the E region of the ionosphere seems to be most suitable, as the electron densities and collision frequencies are appropriate to create differential motions between electrons and positive ions, thus forming currents. The daily variation of geomagnetic field is supposed to be due to overhead ionospheric current systems in the E region due to a sort of dynamo action caused by the wind-driven plasma across the geomagnetic field lines. It is obvious, therefore, that information about the wind structure at different altitudes is very vital for studying the geomagnetic effects of ionospheric currents.

The atmospheric pressure and temperature on ground are recorded continuously at several locations for the last several decades. Charts are available with the Meteorological Departments of various countries. Records of upper air data (up to about 20 km) obtained by balloons at a few selected LT hours are also available at some locations. Rocket soundings have been conducted at a few locations and have yielded fairly accurate data up to about 90 km. From these, the international Committee for Space Research (COSPAR) prepares from time to time a Cospar International Reference Atmosphere (CIRA) model (e.g. CIRA 1965 model, Champion, 1967). The region from 90 to 200 km has not been investigated very thoroughly. Rocket shots as well as vapour trail experiments have been few and far between and the structure of the atmosphere in this region is still uncertain. Above 200 km, a systematic study of
the motion of satellites has revealed variations in the satellite drag which may be interpreted in terms of density variations. A significant difference was noticed between day and night. Jacchia (1971) evolved static models for the atmosphere for different local times, seasons and solar activity levels incorporating the very conspicuous feature of a bulge in the thermosphere near the subsolar point. Figure 1 is based on Jacchia model (1971) for an exospheric temperature of 1000 K and additional corrections have to be applied to evaluate the diurnal, geomagnetic, semi-annual and seasonal-latitude effects as described by Jacchia. In recent years, the satellite OGO-6 yielded useful information about the thermospheric composition by mass spectrometer measurements from which Hedin et al. (1974) have evolved an empirical model with spherical harmonics which is an improvement on Jacchia's models. Another technique used recently is that of incoherent scatter radar observations (Alcayde et al., 1974) where considerable seasonal changes in the thermal structure of the atmosphere between 100-400 km seemed to cause considerable changes in composition not accounted for in the earlier models of Jacchia. Jacchia (1974) has recently proposed fresh empirical models for seasonal, latitudinal and diurnal variations of thermospheric composition.

The bulge in the thermosphere is expected to produce winds. Model calculations by Kohl and King (1967) and Challinor (1969) show for an altitude of about 300 km a wind blowing from the equator towards the poles and across the polar cap during the day and from the polar cap towards the equator during the night during quiet periods.

A very puzzling phenomenon, suspected since long and confirmed recently (Blamont and Luton, 1972; Keating et al., 1973; Barlier et al., 1974) is the hemispherical asymmetry in the thermosphere. Thus, besides the seasonal variation which is expected due to different solar energy inputs in summer and winter in the northern and southern hemispheres, there is a significant annual variation, the density minimum being systematically deeper in July than in January. Even at equinoxes, helium concentrations and exospheric temperatures are more in the southern hemisphere. The density bulge also tends to stay over the southern hemisphere and winds seem to blow northward across the equator. Whereas a part of this behaviour could be due to the annual variation in the Earth-Sun distance, there is little doubt that the southern hemisphere seems to receive and/or absorb more solar energy. It is conjectured that this may be related to the hemispherical asymmetry in geomagnetic field as also due to asymmetric dissipation of tidal waves due to the asymmetric world-wide ozone distribution though there might be other causes too.

4. Magnetosphere and Radiation Belts

Due to a continuous flow of solar plasma (called solar wind) across the Earth, the geomagnetic field gets confined to a cavity called magnetosphere. The impact of such a plasma, was initially examined several decades ago by Chapman and Ferraro (Book I). Their model has undergone several modifications since then. Assuming that
the plasma particles are specularly reflected in a transition layer at the magnetospheric boundary and that there is no ionised gas inside the magnetospheric cavity, Mead and Beard (1964) computed the shape of the possible three-dimensional magnetospheric boundary and evolved a potential function $V^e$ in terms of a spherical harmonic series which would represent the external field. For a boundary located at about $10 \ R_E$, it gives a magnetic field at the surface of the Earth of about 25 $\gamma$ which is too low to be detected by the present network of geomagnetic observatories. Figure 2 shows Mead's model (Mead, 1964) for distorted field lines due to the impact of solar wind. The geomagnetic field is compressed on the sunward side and extended on the anti-sunward side. This model differs from actual magnetospheric observations in several important ways. Firstly, the field lines in the tail region are observed to be directed towards the Sun in the northern hemisphere and away from the Sun in the southern hemisphere with a neutral sheet in between, thus indicating extra thin current sheet in the tail. Williams and Mead (1965) have refined the earlier Mead model by introducing a truncated current strip in the tail and the resulting field lines show a better resemblance with actual observations. Secondly, the dayside neutral points seem to occur at a latitude of about 80–85° while actual observations indicate the auroral oval at 76–78° on the day side.

![Fig. 2. The dipole pattern (dashed lines) of the geomagnetic field and its distortions (full lines) due to the impact of solar wind (Mead, 1964).](image-url)
A different approach to the problem was suggested by Axford (1962) and Kellog (1962) who treated the problem magnetohydrodynamically as a steady flow of a frictionless perfect gas around the magnetosphere causing tangential discontinuities. Several workers contributed to the further development of this idea (see Spreiter and Alksne, 1969). The shape of the magnetosphere was calculated in a way similar to Mead's model while the formation of the bow-shock and the flow of plasma around the magnetosphere was treated as a problem of fluid dynamics for a solid obstacle. The models have offered reasonable explanations to the observed magnetospheric features (1) the bow-shock where the solar wind has its first impact, (2) the magnetosheath where the initially unidirectional solar wind gets largely thermalised, (3) the magnetopause separating the magnetosheath and the magnetosphere, and (4) magnetosphere where the geomagnetic field gets confined, and finally (5) the magnetotail which is an extended region in the anti-sunward side roughly like a long cylinder with field lines pointing towards the Sun in the northern half and away from the Sun in the southern half of the cylinder with field intensities decreasing slowly but extending up to several tens of Earth radii. Figure 3 shows the magnetospheric configuration based on actual observations by satellites.

![Magnetospheric model](image)

Fig. 3. Magnetospheric model based on satellite observations (Ness, 1969).

All the models in which the magnetopause is a tangential discontinuity and the field lines from one hemisphere loop across the equatorial plane into the other hemisphere are called closed models and the magnetic field contained in the solar wind (if any) does not have any role to play. However, Dungey (1961) made an interesting suggestion that the southward component of interplanetary field (if there was any) could merge in some regions with the geomagnetic field, giving X-type neutral points at the apex and the backside of the magnetosphere. Further investigations by him and several other workers (see Book II, p. 1291) led to the conclusion that such a merging would have a profound effect on the field lines. The magnetopause would no longer be a tangential discontinuity and there will be a magnetic field
component perpendicular to the magnetopause causing tangential stresses. Also an electric potential would be developed across the magnetopause directed from the morning to the evening side and would appear across the polar cap. Magnetic field lines from the front side neutral point would be dragged by the solar wind towards the tail increasing the tail field. Since this would be a powerful mechanism for giving energy input from the solar wind to the magnetotail, it would have important consequences leading to magnetospheric storms as will be discussed later. Models in which geomagnetic field lines can merge with interplanetary field lines are known as open magnetosphere models.

Recently, observations carried out by OGO-3 and OGO-5 have revealed significant deviations $\Delta B$ from the average field $B$ as predicted by IGRF model in the magnetosphere. This is indicative of magnetospheric currents which, though producing negligible effect on the surface of the Earth, become increasingly important at higher altitudes. Gross features of the magnetospheric field morphology at magnetically quiet times as given by Sugiura (1973) are reproduced in Figure 4. The magnetosphere seems to be divided into three broad regions (a) the equatorial $-\Delta B$ region encircling the Earth, indicating ring current effects, (b) the $+\Delta B$ regions in the magnetotail plasma sheet outside the equatorial $-\Delta B$ region and also on the dayside, and (c) the $-\Delta B$ pockets at middle and high latitudes near noon in both the northern and southern hemispheres. A quantitative model which takes into account the magnetopause, tail and quiet time ring currents and a main dipole field has been recently developed by Olson and Pfister (1974) in the form of a sixth order series expansion with exponential terms and reproduces the above $\Delta B$ pattern reasonably well. A model for distributed magnetospheric currents has also been proposed by Olson (1974)

![Fig. 4. Schematic views of the $\Delta B$ distributions in the noon-midnight (left) and dawn-dusk (right) meridian plane (based on Sugiura, 1973).](image-url)
and would have implications for the daily variation of geomagnetic field as is discussed later. The usage of magnetospheric models for the study of low energy solar and galactic cosmic rays has been reviewed by Gall and Orozco (1974).

The region inside the magnetosphere is by no means empty but is populated by plasma of varying densities in different parts. While studying the motion of charged particles in a dipole field, Stormer (1955) had indicated the possibility of a crescent-shaped inner allowed region where charged particles would be trapped and could not normally escape to infinity. During the IGY (1957–58), the early satellites Explorers, Pioneers and Sputniks discovered two such radiation belts around the Earth, the inner one at about 1.5 $R_E$ consisting mainly of protons with energies exceeding 30 MeV and the outer one at about 3.5 $R_E$ consisting mainly of electrons with energies exceeding 1.6 MeV. However, the whole region is also heavily populated with low energy electrons and protons extending right from about 2 $R_E$ to 10 $R_E$, thus forming an extensive belt in the trapping region. Figure 5 shows the distribution of these particles, and the radiation belts. Besides these, there is of course the thermal plasma (energy about 1 eV or less) which forms the plasmasphere occupying a small part of the trapping region. The plasmasphere is not symmetric but has a bulge in the evening sector, whose boundary (plasmapause) is at about 4–5 $R_E$ in contrast to about 3–4 $R_E$ in other LT sectors. Its particles are mainly of terrestrial (ionospheric) origin and participate in the Earth's rotation; but the evening sector bulge is maintained. In the magnetotail, there is an extensive plasma sheet, in which is embedded the neutral sheet having oppositely directed field lines above and below it.
Figure 6 shows the flow pattern of magnetospheric plasma in the equatorial plane (Schulz, 1974), clearly demarcating the plasmasphere (inner shaded area) from the tail plasma sheet and indicating the magnetopause and dawn-dusk neutral sheet currents. During disturbed periods, these flow patterns get modified considerably and produce peculiar geomagnetic disturbances as will be discussed later. The noon-midnight meridian cross-section of the plasma distribution (Frank, 1971b) is shown in Figure 7. The trapping regions would be the ones where the field lines are dipolar and extend up to the magnetopause on the day side and up to about 10 $R_E$ on the night side. Magnetosheath plasma would enter the dayside polar cusps $B$, $b$ and reach the magnetotail to form and/or enrich the plasma sheet.

The sources of plasma in the various regions are yet somewhat obscure. Some interesting aspects of particle motion in the dipole field need to be borne in mind. The motions are essentially characterised by the three adiabatic invariants connected with (a) the particle’s gyration about a guiding field line, (b) the bounce motion of the particle from one hemisphere to the other and back between magnetic mirror points and (c) an azimuthal drift around the Earth. If these invariants are not violated, a trapped particle will remain trapped for ever inside the allowed region and no new particles will be added to the trapping region nor would the older particles disappear. However, if for some reason the first two invariants are violated, particle diffusion in pitch angle and/or energy would occur. If only the third invariant is violated, particles would suffer a radially inward diffusion getting energised in the process. Morfill (1973) has shown that in excessively curved fields, the first invariant breaks down. Magnetosheath plasma can penetrate into the magnetosphere through the dayside polar cusps.
Fig. 7. Distribution of plasma in the noon-midnight cross-section of the magnetosphere (Frank, 1971b).

Fig. 8. Quasi-trapping regions (Q) in the noon-midnight meridional plane. Shaded regions show the radiation belts (Schulz, 1974).
(neutral points or lines in Figure 7) as also through the flanks of the magnetotail 
(Frank, 1971a, b; Bird, 1975). Such access to synchronous altitudes ($6.6 R_E$) for 
10–90 MeV protons has actually been observed (Blake et al., 1974). In fact, the day-
night asymmetry in the magnetospheric configuration causes two interesting kinematic 
phenomena known as shell-splitting and quasi-trapping which can allow a trapped 
particle to escape or conversely may allow an outside particle to enter the magneto-
sphere. Figure 8 shows the location of such quasi-trapping regions which have a direct 
access from the neutral points. Thus, it seems quite plausible to conclude that the 
plasma in the outer magnetosphere (outside the plasmasphere) has its origin mostly 
in the magnetosheath and hence in the solar wind (see review by Hill, 1974) though 
the possibility that the plasma sheet receives some material from the polar ionospheric 
regions via the geomagnetic field lines in the form of a polar wind (Axford, 1970) 
should also be borne in mind. For the inner radiation belt protons, an interesting 
injection mechanism is the CRAND (Cosmic-ray albedo neutron decay) effect. Also, 
during geomagnetic storms, an intense proton belt having proton energies of about 
10–50 keV develops in the trapping region at about 3–6 $R_E$ (Frank, 1971a, b) entering 
mostly through the night side tail region plasma sheet. Due to the azimuthal drift an 
intense ring current is formed around the Earth which causes violent geomagnetic 
field depressions of several hundred gamma on the surface of the Earth as will be 
discussed later.

Copious information pertaining to the magnetospheric region has been obtained 
recently by ATS, OGO, POGO and Injun satellites orbiting at various altitudes from 
about 400 km to several Earth radii. As expected, events occurring at high altitudes 
in the magnetosphere in the equatorial plane seem to be related to polar and auroral 
phenomena via the crescent-shaped geomagnetic field lines. Of particular interest are 
the electric field measurements in the polar region (Heppner, 1972a, b). These show 
two distinct magnetospheric convection regions viz. the polar cap and the auroral belt. 
In the polar cap, plasma seems to enter from the magnetosheath through the daytime 
polar cusps (or neutral points or more realistically, neutral lines) and convects in an 
anti-sunward direction. The electric field in the polar cap is in general from dawn 
toward dusk. On emerging from the polar cap the plasma bifurcates near midnight in 
an area called the Harang discontinuity and flows back to the dayside (sunward 
convection) via the auroral belts on either side. The electric field in the auroral belts 
is therefore poleward in the midevening sector and equatorward in the midmorning 
sector. The convective flow patterns and the associated electric fields are illustrated 
in Figures 9(a), (b). This pattern may be considerably modified by the different 
orientations of the interplanetary magnetic field. There is also considerable evidence 
now (Sugiura, 1974) for field-aligned currents at the polar cap boundary. On the 
night side, the polar cap boundary seems to coincide with the high latitude boundary 
of the plasma sheet and thus the field-aligned currents are also the surface currents of 
the plasma sheet, flowing towards the Earth after midnight and away from the Earth 
before midnight. Also, on the outer (low latitude) side of the auroral belt, field-
aligned currents seem to flow from the morning ionosphere to the magnetosphere,
Fig. 9. (a) Convective flow patterns, and (b) Associated electric fields, in the polar ced region (Heppner, 1973).
join the magnetospheric equatorial current and then descend into the auroral ionosphere on the afternoon side.

In the magnetospheric equatorial plane, there would also be a radially inward electric field due to corotation of plasma (Ferraro and Bhatia, 1967).

To summarise, the major features of the magnetospheric region may be stated as follows:

(a) **Physical features.** From the sunward side towards the tail: (i) Bow-shock, the main interaction boundary between the solar wind and the geomagnetic field obstacle, (ii) Magnetosheath where solar wind gets thermalised and is diverted to the back side of the Earth around the magnetosphere, (iii) Magnetopause, the boundary between the Magnetosheath and the Magnetosphere, (iv) Magnetosphere, the cavity looking like a paraboloid on the day side, (v) The dayside polar cusp neutral points (or lines), (vi) Magnetotail region, roughly like a cylinder, partitioned by the plasma sheet into two semi-infinite cylinders, having current systems which flow from dawn to dusk along the plasma sheet partition and back from dusk to dawn along the surfaces of the cylinder, (vii) Neutral sheet in the equatorial plane in the tail.

(b) **Plasma regions.** From the earth outwards: (i) The neutral atmosphere of the earth up to about 80 km, (ii) The ionospheric D, E, F₁ and F₂ regions up to about 1000 km (peaking at about 300 km), (iii) The plasmasphere extending up to about 3–4 $R_E$ (slightly more in the evening sector) containing thermal plasma mostly of ionospheric origin, (iv) The radiation belts containing high energy protons and electrons, the inner proton belt at about 1.5 $R_E$, the outer proton belt at about 2.2 $R_E$ and energetic electrons in the region 2–4 $R_E$, (v) Low energy protons and electrons occupying almost the whole of the trapping region 1–10 $R_E$, (vi) Ring current protons entering through the geomagnetic tail during disturbances and enriching and modifying the proton belts, (vii) Plasma sheet beyond about 7 $R_E$ in the magnetotail having a thickness of a few $R_E$ on either side of the roughly equatorial neutral sheet embedded in it, (viii) Polar cusps, the two funnel-like dayside regions, one in each hemisphere (northern and southern) at about 80° latitude, merging with the plasma sheet in the night sector.

(c) **Convective motions.** (i) Plasma corotating with the Earth inside the plasmasphere, (ii) Plasma from the tail rushing sunward engulfing the Earth and terminating on the dayside magnetopause, (iii) Magnetosheath plasma entering the magnetosphere through the polar cusps as well as the flanks of the magnetotail, (iv) Polar ionospheric plasma escaping along open field lines in the form of polar wind to enrich the plasma sheet.

(d) **Current patterns.** (i) Ionospheric current systems in the E-region, (ii) Ring currents around the Earth in the proton belts, (iii) Dayside magnetopause currents, a system of close loops around the polar cusps, (iv) Tail currents in the plasma sheet from dawn to dusk and back via the surface of the cylindrical tail, (v) Field-aligned currents from auroral ionosphere to magnetospheric equatorial regions and vice versa (Birkeland currents).

(e) Electric and magnetic field patterns. (i) Dawn to dusk electric fields in the polar
cap, (ii) Poleward field in the evening sector and equatorward field in the morning sector in the auroral belt, (iii) Electric fields associated with the ionospheric currents, ring currents, magnetopause currents and tail currents, (iv) Radially inward electric fields due to plasma corotation, (v) Peculiar $AB$ (magnetic field) patterns associated with all these.

As will be shown later, all the above features and their modulations by interplanetary plasma parameters and solar radiations are related directly or indirectly to one or more of the geomagnetic field variations recorded on the surface of the Earth.

5. Sun and Interplanetary Plasma

The Sun, the main source of energy for our planetary system, is a typical main-sequence star of spectral class G and is completely gaseous. Born about $5 \times 10^9$ yr ago, its present mass is about $2 \times 10^{33}$ g and the radius of its visible disc (photosphere) is about $7 \times 10^5$ km, about 100 times the radius of Earth. Thermonuclear reactions involving the proton-proton and carbon-cycle chains resulting into the conversion of protons into helium nuclei are occurring continuously at the centre of the Sun where the temperature is estimated to be as high as $15 \times 10^6$ K. An enormous amount of heat is produced in the core and is transferred outward by radiative transfer and convection. However, at the surface, convection is more effective and ascending hot gases carry the heat outward. The photospheric surface has a temperature of about 5800 K and shows granulations of sizes about 1000 km. Above the photosphere is a dark-red layer of thickness about 1500 km termed as chromosphere. This layer has a non-uniform cellular structure which is associated with large-scale convective cells (super-granulations) of sizes about 30000 km on the photosphere, having on their edges short-lived upward jets (spicules) often rising as high as 3000 km. Above the chromosphere is the Corona, a vast region containing a tenuous gas at very high temperatures (about $10^6$ K). It is surmised that magnetohydrodynamic shock waves emanating from the granulations on the photosphere are transmitted almost unabated through the chromosphere but get finally dissipated into the corona, thus increasing the corona temperature enormously. Part of this heat is conducted downwards to increase the temperatures of the upper chromosphere to about 10000 K. The corona has a complicated fine structure with rays, plumes, arches etc. indicative of peculiar magnetic field line configurations. Optical coronal emissions are of three types, L type due to highly ionised atoms (e.g. the 6374 Å red and 5303 Å green lines of iron), K type due to scattering of photospheric light by coronal electrons and F type due to scattering and polarisation of photospheric light by interplanetary dust.

A large part of the solar energy is let into the interplanetary space in the form of radiation. The flux of solar radiation integrated over all wavelengths (solar constant) is presently estimated to be $1.952 \text{ cal cm}^{-2} \text{ min}^{-1}$ at the top of our atmosphere. Several types of radiations viz. X-rays, ultraviolet, visible, infrared and radiowaves are emitted by the Sun, some from the photosphere and others from the chromosphere and corona. Their fluxes show fluctuations, some connected with the long-term
variations in solar activity and others with singular events on the sun (solar storms).

The structure of the solar atmosphere is not static. There is a continual expansion of the corona resulting into a continuous emission of a fully ionised solar plasma (termed by Parker as solar wind) consisting of about 95% protons, 4.5% alpha particles and 0.5% other positive ions with, of course, electrons. Even in quiet times, there is a solar wind flow velocity of about 300 km s\(^{-1}\) which may increase to 1000 km s\(^{-1}\) or more during disturbed periods. The temperature in this plasma is about \(5 \times 10^4\) K for protons and about \(10^5\) K for electrons. The interaction of this solar wind with the geomagnetic field is of vital importance for the study of the field variations.

The magnetic field of the Sun (in contrast to that of the Earth) is very complicated, indeed. The corona shows an apparent dipole-like field configuration. However, the surface is full of weak extensive unipolar regions and small intense bipolar regions. Individual granules and super-granules show their own field configurations. In the middle and low latitude regions of the Sun (with respect to the equator of the Sun which has a rotation period of about 25 days) well-developed bipolar regions (sunspots) are often seen, consisting of two spots of opposite polarity. Amongst these, one spot appears first (preceding spot \(p\)) followed later by the other spot (following spot \(f\)). In each solar hemisphere (northern or southern) there are several unipolar regions having the same polarities as that of the \(p\) spots in that hemisphere, which seems to change every 11 years. Also the number of sunspots has an 11-year cycle. Such a cycle was explained by Babcock (1961) in terms of an originally poloidal (dipole like) solar field being stretched and twisted due to the differential rotation of the Sun (period of rotation 25 days at equator increasing gradually to 35 days at the poles).

If the solar wind is blowing continuously and radially outwards from the Sun, it would stretch the surface fields outwards. Combined with the rotation of the Sun, the magnetic field configuration in interplanetary space would look like an Archimedes spiral. Such a structure has actually been observed by space-crafts. If the interplanetary magnetic field \(B\) is resolved into the radial component \(B_x\), the azimuthal component \(B_y\) and the perpendicular north-south component \(B_z\), the \(B_{xy}\) component in the solar equatorial plane was found by IMP-1 satellite (November 1963 to February 1964) to be as shown in Figure 10. The Archimedes spirals showed a four-sector structure of roughly, 8, 8, 8 and 3 days having grossly unidirectional fields alternatively away from or towards the Sun. In later periods, the number of the sectors has not always remained four but the spiral structure with alternate sectors (not necessarily 8 days wide) having opposite polarities has been observed (Wilcox and Colburn; 1972; Fairfield and Ness, 1974). Also, a semi-annual and solar cycle variation of the sector structure pattern is reported (Sawyer, 1974). Many attempts have been made to identify magnetic structures on the photosphere which could be related to this spiral sector structure observed in interplanetary space. In some cases, identification with peculiar photospheric structures has been possible (e.g. Severny et al., 1970). However, the transition from photospheric fields of 1–1000 G to the streamlined interplanetary fields of only a few gamma is still something like an enigma. The conventional explanation given by Ahluwalia and Dessler (1962) and Dessler (1967) envisages
isolated flux tubes emanating from the photosphere and extended by the solar wind flow deep into space, each tube considered as surrounded by a neutral surface quite stable in the plasma dynamical sense. Recently, Schulz (1973) has worked out a mechanism earlier suggested by Rosenberg (1970) in which solar wind stretches the surface dipole field to form a warped annular neutral surface in the heliomagnetic equatorial plane which intersects the ecliptic plane in four corotating arcs, giving an apparent sector structure. The model has many other desirable features, and could be responsible for sector structure variability observed by Sawyer (1974).

The most spectacular short-lived phenomenon occurring on the Sun is the solar flare. Optically, it manifests itself as a sudden intensification of the Hz line in a restricted area on the solar disc. In fact, flares are now classified as S, 1, 2, 3 and 4 depending upon the area of Hz emission. Supplementary indices f, n, b are also given to indicate faint, normal or bright. S indicates small sub-flares covering less than 100 millionths of the visible disc and the strongest category 4 indicates an area coverage exceeding 1200 millionths of the visible disc. A flare attains maximum intensities in 5–10 minutes and is associated with soft thermal and hard non-thermal X-rays. In radio region, five types of bursts characterised by different frequency-time evolutions are seen, the most prominent being the Type IV burst due to both synchrotron and plasma-oscillation emissions continuing for hours after the solar flare. A flare also
ejecits corpuscular radiation in a considerable energy range which can be classified as
(i) solar cosmic rays which thread their way to the Earth via appropriately connected
interplanetary magnetic field lines and (ii) a plasma cloud which consists of a high
density of low energy particles which may distort the interplanetary magnetic field
configurations. The precise magnetic configurations and the seats of origin and ac-
celeration and propagation processes for the various components in the solar flare
region are still a matter of controversy. Figure 11 shows one model (Piddington, 1969)
involving a neutral point over an arch-like magnetic field structure connecting two
sunspots of different polarities.

The various types of ejections from the Sun have a profound effect on the electro-
magnetic state of the interplanetary space. The most spectacular is the formation of
interplanetary shocks, which have a direct bearing on geomagnetic sudden commence-
ments. There are two types of flare-associated shock waves (Hundhausen, 1972) (i)
Blast waves for which the flare is presumed to have emitted a large burst of energy but
no mass and hence are characterised by increased values of particle densities N and
velocities V at the shock front with decreasing values of N and V behind the front and
(ii) Driven shocks having N and V increasing behind the front due to the following
helium-rich material acting as a driver gas. Most of the flare-associated shocks are
Driven shocks. Figure 12a shows a synoptic view of the same. However, not all inter-
planetary structures are flare-associated. Sometimes interplanetary streams are
encountered which may have shocks at their leading edges but are not apparently
connected with any solar flare (Figure 12b). Gosling et al. (1974) have shown that
some of these seem to be related to sudden mass ejections from the Sun (as observed
Fig. 12. Synoptic views of (a) flare-associated 'driven' shock, and (b) stream interface (Hundhausen, 1972).
by the Skylab white light coronograph from above the atmosphere) with large magnetic loops rooted on the Sun and yet expanding through the corona at about 400 km s\(^{-1}\) with no associated solar flare. Burlaga (1975) identified high speed interplanetary streams with three distinct types, (i) Simple streams having a monotonic increase in velocity \(V\) for 1–3 days, (ii) compound streams having two maxima of \(V\) separated by a day or two and (iii) variable \(V\) with no large streams. It is known that the solar wind emitted from the solar surface is not uniformly the same from all solar longitudes. The consequences of a fast solar wind stream impinging upon a slow stream were examined by Parker (1963) and Sarabhai (1963) who predicted standing shock waves at the interface. Hundhausen (1973) has developed a non-linear model of high speed solar wind streams and concludes that three types of discontinuities would be formed between 1 and 1.5 AU (1 AU = distance between Earth and Sun) characterised by (i) \(N\), \(V\) and \(T\) (temperature) increasing, (ii) \(N\) decreasing, \(T\) increasing and (iii) \(N\) and \(T\) decreasing and \(V\) increasing. Burlaga (1974) has given a model in which he identifies all these as the different parts of an impact region between two solar wind streams of different velocities, (i) and (iii) as the forward and reverse shocks and (ii) as the stream interface. It would be interesting to see how these various types of interplanetary structures affect the geomagnetic field when the Earth is engulfed by them.

Several decades ago, Bartels (1932) suggested the presence of M regions on the Sun, which were responsible for the 27-day (synoptic solar rotation period) recurrence tendencies of some geomagnetic storms. It is known that the recurrent storms are associated with high speed solar streams (Snyder et al., 1963). However, attempts at identifying the sources of these fast streams on the solar surface had proved inconclusive for a long time and it was tacitly assumed that the faster streams must be connected with very active solar regions. However, recent evidence (Hundhausen, 1972) indicated that the solar wind emanated from coronal regions of open diverging magnetic field lines which emerged from large photospheric regions of weak, unipolar magnetic fields, the fast streams emanating from the centre of such a structure and the slow streams from its edges. Complementary evidence from Krieger et al., (1973) and Neupert and Pizzo (1974) showed that high speed solar wind emanated from coronal holes or regions of low solar X-ray fluxes. Thus faster streams seem to be connected with regions of lesser solar activity (lesser densities, pressures and temperatures) rather than enhanced solar activity. This throws an entirely new light on the baffling aspect of the average characteristics of solar wind viz. that whereas many solar parameters (e.g. sunspot number) exhibit an 11-year cycle, the average yearly solar wind velocity does not increase with solar activity (Gosling et al., 1971; Diodato et al., 1974). In fact, very high as well as very low velocities are more frequent in years of low sunspot activity indicating that during solar minimum, coronal expansion is easier (less restricted by transverse fields), allowing weak streams to escape with low velocities and strong streams to attain high velocities (Roelof, 1974). On the other hand, the solar wind number density \(N\) seems to decrease with higher solar activity, which may be due to the heliographic latitude effect pointed out by Hundhausen et al. (1971).
With this background of the Earth and its near and far environment, we will now describe the various types of geomagnetic variations and discuss their possible causes.

6. Quiet Period Geomagnetic Variations

All the components of geomagnetic field show distinct periodicities ranging from a few seconds to several thousand years. Periods up to 22 years are generally connected with solar phenomena while larger periodicities are mostly related to the internal structure of the Earth and its core dynamics, though some periods of a few years could also be of internal origin.

6.1. SECULAR VARIATIONS

Regular observations of the geomagnetic components date back more than a century and are described in detail in Books I, II and III. Variations with periodicities less than three years cannot possibly be of internal origin as these are effectively screened by the Earth's mantle. For the slower field variations, data for the last two or more centuries show:

(i) The geomagnetic field has been predominantly dipolar with the dipole axis and the axis of rotation of the Earth roughly coincident.

(ii) The main dipole component has maintained an approximately constant direction over several decades. However, the magnitude of the total magnetic dipole moment has reduced from about 8.5 in 1833 to about 8.0 \((\times 10^{25} \text{ G cm}^{-3})\) in 1965, indicating a rate of change of about 5% per century. If this rate continues, the present geomagnetic field should reduce to zero in 4000 A.D.! Changes for 1964–70 are given in Hurwitz et al. (1973).

(iii) The non-dipole components show a considerable secular variation. The eccentric dipole has moved outward, northward and westward since 1835 drifting about 0.1 to 0.6° yr.⁻¹

(iv) Power spectrum analysis has revealed periodicities of about 11, 17, 22, 60 and perhaps 80 yr (Bhargava and Yacob, 1969; Currie, 1973).

The history of geomagnetism can be traced further back with the help of studies of rock magnetism for archaeological as well as geological times. Such studies have revealed the following interesting features:

(i) The present westward drift is observed only in recent times. Eastward as well as westward drifts seem to have occurred in the past.

(ii) The position of the geomagnetic pole has meandered in the past but always within about 20° of the geographic pole.

(iii) The recent rate of decrease of about 5% in a century in the total dipole moment started about 2000 yr ago when the dipole moment was about \(12 \times 10^{25} \text{ G cm}^{-3}\). However, before that at about 6000 ybp (years before present), the moment was only about \(4 \times 10^{25} \text{ G cm}^{-3}\). The variation is shown in Figure 13 based on the work of Smith (1967). Thus, a possible periodicity of about 8000 yr (half cycle 4000 yr) is indicated.
(iv) Changes in the declination (D) and inclination (I) of the geomagnetic field for the last several thousand years indicate possible periodicities of 400, 700, 1200, 1800 and 8000 yr (e.g. Banerjee et al., 1974).

A study of sea-floor spreading combined with potassium-argon dating has added considerably to our knowledge of prehistoric geomagnetic field. The most interesting finding has been the complete reversals of geomagnetic field at frequent intervals in the past. There have been at least nine reversals in the last 4 my (million years). The period is characterised by (i) polarity epochs (periods of normal or reverse polarity) having durations of about 0.7–1.8 my, (ii) polarity events which may be as short-lived as $10^3$ yr and (iii) polarity transitions which probably occur in about 1000–10000 yr. The lower limit is not yet well established and could be much lower than 1000 yr. The total field during transitions may reduce to as much as $\frac{1}{3}$th of the normal value. The spacing between successive reversals is not constant. The first reversal, established from lava studies and ocean sediments seemed to have occurred at the Brunhes-Matuyama boundary at 0.69 mybp (million years before present). However, recent studies of cores of sediments from the bottoms of lakes change this picture considerably. Because of the much faster rate of lake sedimentation (several cm per thousand years) as compared to deep sea sedimentation (few mm per thousand years), it has been possible to study the fine structure of the Brunhes normal polarity epoch (0 to 0.69...
mybp) which reveals at least three very short geomagnetic field reversal events during this epoch at about 0.11 (the so-called Blake event), 0.18 and 0.30 mybp, lasting for about 13000, 10000 and 6000 yr respectively (Smith and Foster, 1969; Kawai et al., 1972, Lake Biwa observations in Japan). In the last 100000 years (0–0.1 mybp), striking excursions of the geomagnetic poles involving declination changes exceeding ±30° have been noticed at about 18, 30 and 49 thousand ybp (Barbetti and McElhinny, 1972; Yaskawa et al., 1973) and some polarity events called ‘Laschamp event’ (about 8000–20000 ybp, Bonhommet and Zahringer, 1969) and ‘Gothenburg event’ (about 12400 ybp, Morner et al., 1971) have also been reported. However some of these need further confirmation from more copious data. There is also some indication that the reversals might occur in much less than 1000 yr (about 500 yr) and have generally a fine structure. This has an important bearing on the origin of the geomagnetic field as we will see soon.

The history of geomagnetic field reversals has been extended further back up to 160 mybp (Heirtzler et al., 1968; Larson and Pitman, 1972) and the reversal patterns are roughly similar to those observed earlier. Figure 14 shows the magnetic field reversals (black) for 0 to 160 mybp. The first column refers to 0–1 mybp on a logarithmic scale and shows changes in the total dipole strength between 0–9000 ybp, the westward and northward drift of the eccentric dipole center (dashed lines) from 5°S, 183°E in 1835 A.D. to 17°N, 148°E in 1965 (10 ybp). The Gothenburg (GOT),

![Figure 14](image-url)

Fig. 14. Magnetic field reversals in the last 160 mybp. The first column refers to 0–1 mybp on a log scale and shows changes in the total dipole moment M (full line) for 0–9000 ybp, the westward and northward drift of the eccentric dipole center (dashed line) from 5°S, 183°E in 1835 A.D. to 17°N, 148°E in 1965 A.D. and the various reversal events (black) and declination excursions (D). The second column shows reversals for the Holocene, Pleistocene and Pliocene epochs 0–10 mybp. Various known events and the so-called normal polarity (N) epochs (Brunhes and Gauss) and reversed polarity (R) epochs (Matuyama and Gilbert) are indicated. The third, fourth and fifth columns show reversals for 10–60, 60–110 and 110–160 mybp. (References given in the text.)
Laschamp (LAS), events, large declination changes (D) and Blake and other events are indicated. The second column shows changes for 0–10 mybp (Cox, 1969) and the third, fourth and fifth columns for 10–60, 60–110 and 110–160 mybp (Heirtzler et al., 1968; Larson and Pitman, 1972). There seem to be some very extended periods of normal polarity (e.g. 80–110 mybp). But these must be interpreted with caution as these could be due to lack of adequate data or due to low concentrations of Fe and Ti in some rock samples (Vogt and Johnson, 1973) or due to migration of rock samples in continental drifts. Also, better techniques have revealed recently many more short-lived field reversals and excursions (McElhinny et al., 1974) and hence Figure 14 may have to be revised often in future. Figure 15 shows the frequency of occurrence of the reversals in the Quaternary, Tertiary and the Cretaceous intervals, showing a slower rate of reversals in deeper past. However, these too are subject to revision as more and more reversals are observed.

Geomagnetic history has been studied for earlier periods too and a conspicuous feature is a prolonged 45 my interval of single (reversed) polarity from about 225 to 270 mybp termed as the 'Kiamen' magnetic interval. The studies have been extended to the Cambrian period (500 mybp) and even earlier (2000 mybp; Spall, 1973). For the whole Phanerozoic period (0–500 mybp), McElhinny (1971) has presented results in the form of percentages of normal and mixed polarity occurrences at different geological era as shown in Figure 16 which indicate a possible periodicity of about 350 my.

The phenomenon of geomagnetic reversals has obviously a profound implication for the theories of the origin of the geomagnetic field. Thus, any mechanism that creates the geomagnetic field must also be capable of turning it upside down from time to time. The estimated resistive decay time for conditions like those expected in the interior of the Earth is about $10^4$ yr. Thus, the mechanism envisaged for producing the geomagnetic field should be such that field with a particular sense of polarity is
produced and maintained for an interval of about $10^6$ yr which is long in comparison with the decay time but geomagnetic reversals must occur within about $10^3$ yr which is much shorter than the decay time. If the field is due to some sort of a dynamo action, a viable mechanism would be a dynamo in the liquid core of the Earth. This idea was introduced long ago by Larmor (1919) in connection with solar magnetic fields and envisages a motion of a conducting fluid in such a way that electromotive forces are induced which could sustain the magnetic field against a resistive decay. Bullard (1955) proposed a simple method of a self-exciting dynamo as shown in Figure 17(a) where a circular disc $D$ rotates around the axis $CC'$ parallel to a magnetic field $H$. A radial electric current $I$ is produced which, while flowing back to the axis $CC'$ and the disk $D$ through the coil $S$, produces an intensification of the original field $H$. Such a dynamo gives oscillations in the currents but does not readily give reversals. Also, in the Earth's core, the conditions are likely to be more complicated and several electric current eddies may take part in the dynamo process simultaneously. Hence, Rikitake (1958) proposed a system of two disk dynamos coupled electromagnetically to one another as shown in Figure 17(b). Allan (1962) demonstrated by numerical calculations that the currents in the two disks oscillated around a steady state for some time but the amplitudes changed with time and then suddenly switched over to another steady state of reversed current, continued therein for some time and then switched back to the earlier state. The reversal time was much shorter than the time spent in each steady state. Thus, a remarkable qualitative resemblance to the behaviour of geomagnetic field was obtained. However, idealised simple disk dynamos are far removed from fluid dynamos. Considerable theoretical work has been done in the last two decades on the formation of dynamo theories for the interior of the earth. The core dynamics is governed by Lorentz and Coriolis forces and any formulation has to consider the rotation as well as the back reaction of the magnetic field on the flow of the fluid in the core. If there is a seed dipole (poloidal) field to start with and if there is a differential rotation, the dipole field lines would be twisted to give a
toroidal field which, in principle, could be increased indefinitely by increasing the fluid motion. This field would remain in the core and would not be felt on the surface of Earth. However, the real problem is to reconvert a part of this toroidal field back into a poloidal form so that the initial dipole field could at least be sustained (against its natural ohmic decay) if not enhanced. The exact mechanism of converting the toroidal field into the poloidal field is not yet well understood. Cowling (1934) pointed
out in connection with sunspots that steady dynamos cannot exist if the field is axially symmetric. Since then, rigorous proofs of dynamo action for idealised systems have been offered by several workers and presently the belief is that given a sufficiently complicated motion inside the core, a homogeneous dynamo is in principle possible. The problem is tackled in two ways viz. by a kinematic approach where a suitable velocity field is invoked which would give the observed field variations, and by the hydromagnetic approach where a force function has to be provided by some mechanism. In the kinematic approach, both periodic as well as turbulent dynamos are studied in great mathematical detail for a conducting sphere (the core) surrounded by an insulator (the mantle). The principle difficulties are in connection with the insulating boundary. However, the recent success in developing periodic dynamos and identifying the motions which could result into a dynamo action (Childress, 1970; Roberts, 1972) has encouraged several workers (e.g. Childress and Soward, 1972) to examine the role of thermal convection (due to radioactive heating) in producing such motions in the core. A major difficulty here is that the liquid core seems to be stratified into stable layers (Higgins and Kennedy, 1971) in which case thermal convection will be strongly inhibited. However, some workers (e.g. Busse, 1972) suggest that the core may be in the form of a slurry and solidification of the liquid in the core may give convective motions.

A theory for the secular variation was given by Bullard (1949) on the assumption of a large toroidal field (several hundred gauss) in the core. The westward drift was explained by Bullard et al. (1950) as due to a slower rotation of the core with respect to the mantle. Recently, Acheson and Hide (1973) indicate that hydromagnetic waves in a rapidly rotating fluid (as in Earth’s liquid core) can have periodicities of several decades. In this connection, the observation of Roederer (1974) that the secular variations of some field coefficients are similar may be of significance.

Theories of geomagnetic dynamos have been recently reviewed by Gubbins (1974) who concludes that the core dynamics is not at all certain and questions are being raised about the very existence of a toroidal field as also about density stratifications. Thus, whereas the earlier picture of large scale overturns and differential rotation in the core are not yet ruled out, other equally plausible mechanisms such as magnetic field generation due to turbulence or instabilities due to hydromagnetic waves have to be considered. Busse (1974, 1975) has obtained a solution for a convection driven dynamo, and finds that the toroidal field need not be very much higher than the poloidal field. Cox (1968) suggested a model in which the main dipole is given by a steady oscillator (as envisaged in Rikitake’s double disk dynamo) while the non-dipole terms are due to a random element due to turbulence and the reversals occur whenever the dipole component reduces in magnitude to levels comparable to the non-dipole magnitudes. Thus, reversals would not be equally spaced but would occur randomly with some probability distribution and the steady states between reversals would have variable spans as are actually observed. However, it is not clear whether the dipole component is due to a single source. Even though Heirtzler et al. (1968) have reported that the normal and the reversed states of geomagnetic field have similar characteristics,
some recent evidence (Wilson, 1972; Dagley and Lawley, 1974) indicates that the time-averaged mean dipole positions of the normal and reversed populations are different and the reversed state is less stable than the normal state. Recently, Verosub (1975) re-analysed the IGRF 1965 model field not in the usual way of an eccentric dipole but as a combination of (i) a geocentric axial dipole and (ii) an eccentric but not necessarily axial dipole, treating the strengths of the two dipoles and the coordinates of the eccentric dipole as free parameters to be estimated statistically. He found that the best fit was not as a sum of two more or less parallel dipoles but as a sum of two large anti-parallel dipoles. The observed dipole would, therefore, be a vectorial difference of two very large dipoles envisaged to originate in the inner (solid) and outer (liquid) cores. The recent observation that the reversals can occur in intervals less than 1000 yr does perhaps indicate the presence of multiple sources. An apparent difficulty in having any source in the solid inner core seems to be that the temperatures there are near about 4000 K and hence far above the Curie point (few hundred degrees) so that no ferro-magnetism can exist. However, it must be realised that the pressures at the core are enormous (several million atmospheres) and the effect of such high pressures on the Curie point is not at all known. Also, the core seems to consist besides iron, large fractions of nickel and smaller fractions of carbon, sulphur and silicon (Higgins and Kennedy, 1971). The magnetic properties of the solid core at enormously high pressure is, therefore, anybody's guess and significant contribution of field from the solid core cannot be ruled out. This idea is of course speculative; but it is a sad commentary on the state of knowledge in this field that the most fundamental aspect of geomagnetic field viz. its origin is by far the least understood.

Data from rock samples indicate large-scale pole wanderings in the remote past some of which seem to be connected with continental drifts. For a study of the Earth's internal field this would be an added complication. On the other hand, since the phenomenon of continental drifts is related to large-scale upheavals of the Earth's surface and interior, it could be used as an additional tool to trace the evolution of the Earth. Considerable work is going on at present in studying and dating old rock samples, ocean bed spreading, deep sea and lake sediments and so on. It is hoped that these would help in solving the jigsaw puzzle of the evolution of the Earth and its magnetic field in the near future.

Since information about the geomagnetic field variations is obtained mainly from surface observations, a problem of immediate relevance is the electric conductivity structure of the interior of the Earth. Some estimates of the conductivities of particular types of rocks at particular temperature are available from laboratory experiments. However, similar values at enormously high pressures are not known. The electric conductivity of the Earth can be studied by examining the electromagnetic induction effects. For example, external current systems will produce induced currents in the Earth and the effect of both these would be included in the effects observed on the surface. By applying potential theory, the external and internal components can be separated and the conductivity of the Earth can be inferred. Detailed mathematical formulations are given by Price in Book II (pp. 235–298). The induction phenomenon
depends upon the time rate of change of the magnetic field. The longer the period, the larger is the penetration. Thus, periodicities less than about 3 years and originating inside the Earth are not seen on the surface. Similarly, the daily variation $S_q$ of geomagnetic field which is of external origin, gives induced currents confined to only a few hundred km depth from the surface. Larger periodicities (27 day, etc.) respond to larger depths. Data from these are used for estimating the conductivity profile with depth. So far these have shown somewhat divergent results. However, in general, the conductivity at the surface is as low as $10^{-14}$ emu for some land surfaces and as high as $10^{-11}$ emu for sea water. From land or ocean beds, it rises from $10^{-14}$ to $10^{-12}$ emu at about 600 km depth. Whether this increase is at a uniform rate or abrupt is controversial. Banks (1969) estimated that there might be a sharp increase by two orders of magnitude near 400 km. From about $10^{-12}$ emu at 600 km, conductivity rises to about $5 \times 10^{-9}$ emu at about 1500 km depth after which it remains almost constant up to the core-mantle boundary at 2900 km. Conductivity in the liquid core is probably as high as $5 \times 10^{-6}$ emu ($5 \times 10^5$ mho m$^{-1}$).

For fluctuations of high frequencies (periods of a few hours or less) the induced currents are from very shallow depths and their net effect is to reduce the vertical $Z$ component and enhance the horizontal $H$ component. For very high frequencies the $Z$ component is practically extinguished while the $H$ component increases in the ratio $(2n+1)/(n+1)$ where $n$ is the order of the spherical harmonic involved. Thus, the ratio would be $\frac{3}{2}$ for the first harmonic, $\frac{5}{3}$ for the second and so on, finally tending to 2. Detailed calculations of the induced effects on the $H$ and $Z$ variations at the surface of an ocean of different depths are given by Price (Book II, p. 287). These as well as the peculiar effects of a land-sea environment of an island must be taken into account while studying quantitatively the $H$ and $Z$ variations of short periods (few hours).

6.2. PERIODICITIES OF A FEW YEARS

A search for periodicities in geomagnetic elements has continued for many years. Early attempts are described in Book I. Vestine et al. (1947) reported a solar cycle variation of about $\pm 20 \gamma$ which was in opposite phase to solar cycle, i.e., the $H$ component was minimum when the solar activity was maximum. Yukutake (1965) examined whether the low values of $H$ at high solar activity were due to the well-known storm effect when $H$ values are depressed following solar flares. Using data for quiet days only, he concluded that the solar cycle effect on $H$ was genuine. Several workers have reported periodic variations in the geomagnetic activity indices ($K_p$, $A_p$ etc.). These will be discussed later. Different workers have used different techniques to obtain the residuals for studying the cyclic components (Vestine et al., 1947; Pramanik and Ganguli, 1954; Degaonkar, 1963; Yukutake, 1965; Slaučitajs and Winch, 1965). Eckhardt et al. (1963) were the first to use the method of power spectrum analysis and confirm the solar cycle variation. Currie (1966) also reported a solar cycle variation and Bhargava and Yacob (1969, 1970) reported periodicities of 11, 17, 22, 60 and possibly 80 years. Recently, Currie (1973) used the elaborate
and elegant MEM (Maximum Entropy Method) and carried out power spectrum analysis for the $H$ and $Z$ data of 49 observatories at different latitudes and showed that the 'noise' observed earlier (Currie, 1966) could be resolved clearly into several spectral bands, in particular at 10.5 yr and its first four upper harmonics at 5.2, 3.4, 2.7 and 2.15 yr and at 21.4 yr and its first nine upper harmonics at 10.5, 7.1, 5.2, 4.4, 3.7, (6th harmonic missing), 2.7, 2.4 and 2.15 yr, thus revealing a plethora of distinct frequency ranges. He also reported a cluster at 6.7 yr and another at $60 \pm 5$ yr, in agreement with similar waves at $50$–$60$ yr reported by Orlov (1965) and Slaucitajs and Winch (1965).

The 10.5 and 21.4 yr periodicities seem to be related to the wellknown 11-yr and 22-yr sunspot cycles. A possible explanation would be the varying pressure of solar wind on the geomagnetic cavity. If higher solar activity resulted in enhanced compression of the magnetopause (as happens during sudden commencements of magnetic storms), it would enhance the magnetic field, contrary to what is observed in the solar cycle variation of $H$. However, there is no evidence that solar wind pressure really increases with solar activity. The average solar wind velocity does not seem to be correlated with solar activity (Gosling et al., 1971; Diodato et al., 1974). On the other hand, the solar wind proton number density decreases with solar activity by a factor of two. Thus, the average solar wind pressure is probably lesser at higher solar activity. The effect would be to reduce the value of $H$ at high solar activity as is actually observed. Another possible explanation is in terms of the permanent quiet-time proton belt ring current which seems to encircle the Earth. For ring current protons to have a long life time, the belt will have to be at about $7 R_E$ (Swisher and Frank, 1968). Such a belt was recently inferred by Frank (1971a, b) from the observations of 10–50 keV protons on OGO-3. Whether the belt characteristics (strength as well as distance from the Earth) undergo systematic solar cycle changes has yet to be investigated fully.

Periodicities exceeding three years can be of internal origin too. Nagata and Rikitake (1963) indicated the possibility of a simple harmonic oscillation of the axial quadrupole field of a period of 77 yr. Braginskiy (1970) estimated the theoretical oscillation spectrum of the hydromagnetic dynamo as having harmonics at about 60 yr and 1000 yr with the fundamental mode at 10000 yr. Yukutake (1972) calculated the free mode of an electromagnetically coupled core-mantle Earth system as having a period of 6.7 yr. Astrophysically, the Moon causes a precession of $23^{1/2}$ in 25800 yr in the Earth’s axis of rotation. Malkus (1963) calculated the hydromagnetic torque between the rigid mantle and the liquid core due to this precession and predicted a main period of 18.6 yr and harmonics at 9.3 and 6.2 yr. Thus, the results of Currie and others seem to confirm the validity of many of these theoretical estimates. The mode of period 2.15 yr (26 months) is the quasi-biennial mode which was also observed by Yacob and Bhargava (1968). It resembles a similar period observed in stratospheric temperature, total ozone content and tropopause heights in polar, temperate and tropical zones (Angell and Korshover, 1964). All these may have the same origin.

For the spectral analysis of these periodicities, the basic data input is the annual mean values of the $H$, $D$, $Z$ components. It is not always clear, however, whether data
used are for all LT hours of a day. As will be discussed soon, all these components have a daily variation mainly confined to the sunlit hours and the range of this variation is dependent on ionospheric electron densities which are enhanced with solar activity. Thus, even if the background night-time level of these elements were to remain constant, the daily mean would show larger values (by a few gamma) for higher solar activity. This effect is reverse to the observed effect and hence, if corrected for, would enhance the amplitude of the real anti-phase solar cycle effect. Bhargava and Yacob (1969, 1970) used for their analysis, values centred around local midnight for selected quiet days and obtained solar cycle effect amplitudes of 11 to 21 γ which were higher than the values 2 to 17 γ obtained by Yukutake (1965) who probably used means involving all LT hours. This discrepancy would be large only for locations having a large daily variation (equatorial, low and polar latitudes) and would be negligible for middle latitude stations near the Sq focus.

6.3. ANNUAL AND SEMI-ANNUAL VARIATIONS

Periodicities in this category have also been studied very exhaustively a long time ago (Book I) and later by Vestine et al. (1947), Vestine (1954), Currie (1966), Bhargava et al. (1973). An annual and semi-annual wave of about 5 γ in the $H$ component and 5 and 2 γ in the $Z$ component has been noticed. For the semi-annual variation, equinoctial maxima are noticed. The earliest explanation was offered by Bartels (1932) and later by McIntosh (1959) and Bartels (1963) as an Equinoctial hypothesis based on the fact that the geographical (and also geomagnetic) axis has a varying inclination with respect to the ecliptic plane and hence the shape of the geomagnetic cavity and its pressure should show a semi-annual variation. There are of course other possibilities viz. the magnetotail configuration and/or the proton belts may have semi-annual variation. There are some indications that the electrons and protons in the geomagnetic cavity show seasonal variations. However, this needs further investigation.

Another explanation for the semi-annual wave is the Axial theory by Cortie (1912) which is based on the fact that the axis of rotation of the Sun deviates from the ecliptic plane within $\pm 7.5^\circ$, the maximum of heliographic latitudes occurring on September 7 and March 6. The observed $H$ variation shows maxima about two weeks after these dates. A part of the delay could be due to the 4–5 day transit time of slow plasma from the Sun to the Earth. However, the exact process involved does not seem to have been worked out in any detail and only coincidences are noted.

For the annual wave, Vestine (1954) gave an explanation in terms of a dynamo mechanism due to meridional ionospheric winds. The nature of the annual variation of $H$ in the northern and southern hemispheres is such that the meridional winds should blow always from the summer to the winter hemisphere with appropriate zonal flows to conserve angular momentum. For a long time, this hypothesis remained a mere speculation till Kochanski (1963) showed that such a wind pattern did actually exist at 70–100 km altitudes. Thus, the trans-equatorial flow seems to be a reasonable explanation for the annual variation.

Whereas the above workers have invoked two separate mechanisms for the annual
and semi-annual variations, Olson (1970a) has proposed that even under constant solar wind conditions, the strength and shape of the magnetopause current system and its associated magnetic field would exhibit annual and semi-annual variations, mainly because of the peculiar shape of the tilt of the magnetopause in different seasons (Olson, 1969). This explains only about 20% of the observed effect but Olson points out that other factors like seasonal changes in the magnetotail neutral sheet currents, quiet-time ring currents and field-aligned currents may also contribute in a similar way and may account for the annual and semi-annual variations completely. This needs further experimental exploration. Quantitative magnetospheric models incorporating expected magnetopause, tail and quiet-time ring current have been recently proposed by Olson (1974) and Olson and Pfitzer (1974).

For a study of the annual and semi-annual variations too, it is important to choose the proper input. If daily means are used, the seasonal variation of the strength of the ionospheric Sq current system is likely to be reflected in the results. Bhargava et al. (1973) have investigated the seasonal variations using $H$ values at different LT intervals and report that the amplitudes are larger for 0700–1000 LT and the evening-night sector values. They conclude that for low latitudes and the equatorial region, the large amplitude of the seasonal wave of the daytime component is due to the seasonal modulation of Sq and the equatorial electrojet while the large wave in the evening component is due to seasonal changes in the magnetospheric ring current.

6.4. PERIODICITY OF A FEW DAYS

A period of 27 days was reported decades ago by Chree and Stagg (1927). From the analysis of $H$ values, Eckhardt et al. (1963) reported a period of 13.5 days. Banks (1969) showed that for the range 4–180 days there was a significant continuum superposed with discrete lines at 27, 13.5 and 9 days, which could be fitted with spherical harmonics on a global scale. He attributed all these to fluctuations in the magnetospheric ring current strength. Hauska and Dyring (1972) reported periods of 13, 9 and 6 days. Currie (1972) reported a periodicity of 54 days with an amplitude of about 1.4 $\gamma$. Most of these results were obtained by using daily means. Bhargava (1973) showed that the power in the 27-day wave varied greatly with local time, being maximum near noon hours and also there was a significant forenoon-afternoon asymmetry, the afternoon power being larger. For such an analysis, data needed are for continuous intervals and hence the analysis cannot be restricted to quiet days. Bhargava concludes that the afternoon enhancement is related to the dusk-dawn asymmetry of the ring current (Cahill, 1966). The day-time enhancement must be due to a 27-day modulation of Sq. Most probably, the periodicity of 27 days and its harmonics are related to the sector structure of interplanetary magnetic field (Wilcox and Ness, 1965) through the changes of solar wind characteristics. However, quantitative estimates have yet to be made.

6.5. DAILY VARIATION

One of the most spectacular variations exhibited by all geomagnetic elements is the
daily variation (24 hourly). These have been illustrated copiously in Book I and by Vestine et al. (1947). Figure 18 shows plots of the hourly values of the $H$ component at several stations in the Indian longitudes (60–80°E) for a few consecutive days.

One notices on some days a steady night-time level followed either by a rise or a fall (depending upon whether the station is below a particular latitude or above it) starting at about 0600 LT, attaining a maximum (or minimum) at about 1100 LT, falling back (or rising) to the original level by about 1700 LT and then remaining constant till the 0600 LT of the next day. Such days are termed as quiet days and the smooth daily variation pattern is termed as $Sq$ ($S$ = solar, $q$ = quiet). However, since the quiet-day pattern varies largely from day to day, Mayaud (1965) prefers to use the term $Sq$ for the average quiet-day pattern over a long interval while patterns on individual days are termed as $S_q$.

Figure 19 shows the average quiet-day daily variation plots for components $H$, $D$, $Z$ for equinoxes (when the amplitudes are highest as compared to the other seasons) for a few stations in the American longitudes for the year 1958 (Price and Stone, 1964). For comparison, similar curves for Trivandrum at equator in the Indian longitude are shown as superposed dashed curves on the full line curves for Huancayo.
From plots like these, several characteristics of the middle and low latitude patterns of Sq are revealed and may be summarised as follows:

1. In every hemisphere (northern or southern) the low latitude Sq pattern of daytime maximum reverses above about 30–40° latitude. This latitude is termed as the Sq focus latitude. The exact latitude is different for different longitudes and seasons.

2. Very near the dip equator (±5° Dip) the amplitude of the H variation increases abnormally by almost a factor of 2. This is considered as the effect of a narrow equatorial electrojet, a nomenclature given by Chapman (1951).

3. The daily range of H increases with solar activity, being about double in the solar maximum of 1958 as compared to the solar minimum of 1964.

4. The daily range shows a semi-annual variation with maxima in equinoxes which are particularly pronounced at equator.
(5) The electrojet strength in the American longitudes (Huancayo) is higher than that in Indian longitudes (Trivandrum) (Rastogi, 1962).

(6) The $D$ variation has specific patterns in each hemisphere viz. a maximum in the morning and minimum in the evening for the northern hemisphere and a reverse pattern for the southern hemisphere.

Ever since these patterns are known, a popular and fascinating exercise has been to postulate over-head current systems which could reproduce all these details. This is because the method of magnetic potential and its spherical harmonics by Schuster, Chapman and several others (Book I) had revealed long ago that the source of this field was mainly external, only about 1/3rd being of internal origin. A recent attempt by Matsushita (1969) envisages ionospheric current patterns as shown in Figure 20(a) for Sq depicting two Sq current vortices, one in each hemisphere. The patterns change from season to season being stronger in the sunlit portion. This current system is not valid for the polar region where additional current patterns are needed (Kawasaki and Akasofu, 1967).

A major difficulty in evaluating such current systems is to choose the correct base level for obtaining the deviations. From a correlation analysis of $H$ values at different locations, Kane (1971a) showed that the pre-dawn hours (00–04 LT) were least

![Fig. 20. (a) The external Sq current systems for different seasons and for the yearly average during the IGY (1958). The current flow between two lines is $25 \times 10^8$ A; the numbers near the cross marks indicate the total current circulation, the unit being $10^3$ A. After Matsushita (1969). (b) The external L current systems at new moon during three different seasons, and the yearly average. The current intensity between two lines is $10^3$ A. After Matsushita (1969).]
affected by the daily variation and hence could form the most appropriate base-line for Sq studies.

6.5.1. Source of the Sq Current System

The atmosphere immediately above the Earth is a non-conductor. However, from about 80 km upwards, the atmospheric components are ionised by solar radiation forming the D, E, F₁ and F₂ ionospheric layers (Figure 1 inset). In the presence of a magnetic field and collisions between the electrons, positive ions and neutral particles, the ionospheric plasma exhibits three characteristic conductivities viz. \( \sigma_0 \) (direct conductivity) along the magnetic field, \( \sigma_1 \) (Pedersen conductivity) in the direction of the component \( E_1 \) of the electric field perpendicular to the magnetic field and \( \sigma_2 \) (Hall conductivity) in a direction perpendicular to both \( E \) and \( B \). From the known height distributions of the various atmospheric constituents, Maeda and Matsumoto (1962) calculated the height distributions of \( \sigma_0 \), \( \sigma_1 \) and \( \sigma_2 \) for middle latitudes at noon and midnight as shown in Figure 21. The daytime values are larger than the nighttime values as the daytime ionisation is much larger. Also \( \sigma_0 \) is larger than \( \sigma_1 \) and \( \sigma_2 \) by several orders of magnitude (upper scale) and increases with height monotonously. However, \( \sigma_1 \) and \( \sigma_2 \) seem to attain peak values near about 100–110 km, i.e., in the ionospheric E region. This is mainly because the collision frequencies there are appro-
appropriate to hold the ions tied but let the electrons move freely. The electric current intensity is given by

\[ j = \sigma_0 \cdot E_\parallel + \sigma_1 \cdot E_\perp + \sigma_2 \cdot \frac{(\vec{B} \times \vec{E})}{B}. \]

It is also known that the atmosphere is not stationary but is subjected to dynamical motions due to solar heating and the Earth's rotation. The wind system is the upper atmosphere is essentially composed of a prevailing wind and the diurnal and semi-diurnal tidal components. If the ionosphere is also subjected to these motions with velocity \( v \), an electromotive force \( v \times B \) is produced. This is the ionospheric dynamo. The dynamo theory was developed long ago by Stewart, Schuster, Chapman (Book I) assuming an irrotational velocity \( v \) for a thin shell ionosphere. Several modifications have been made since then (e.g. Chakraborty and Pratap, 1954; Pratap, 1957) and the general practice has been to infer the velocity potential in the ionosphere from the tidal wind velocity on the ground and express it in terms of a series of surface harmonics. At the ground level, the Moon produces mainly a semi-diurnal tide \( L_2 \) in the barometric pressure and the Sun produces a small diurnal \( S_1 \) and a large semi-diurnal tide \( S_2 \). All these are associated with similar harmonics of wind patterns blowing east-west and north-south. The exact mechanisms of these tides are not precisely understood. Only gravitational forces do not seem to be the main cause; otherwise
lunar effects should have been greater than the solar effects. Thermal processes are obviously contributing significantly (almost equally, see Book I) but the relative roles of ozone, water vapour etc. are not yet fully known. Further, the propagation of the various surface modes to the ionospheric levels is not yet fully understood. At the surface the diurnal \( (1, -1) \) mode (in the Hough function \((s, r)\) mode notation) is very prominent. But the calculation of tidal wave propagation by Hines (1967) seems to indicate that this wave will be greatly attenuated before it reaches the ionosphere. Instead, the \( (1, 3) \) mode could reach ionosphere easily. Hines suggested that the excitation of the \( (1, -1) \) mode in the ionosphere may require a heat source there. On the other hand, Lindzen (1967) calculated the \( (1, -1) \) mode taking into account the absorption of solar radiation by water vapour and predicted substantial velocities for this thermally driven mode even at ionospheric levels. Experimental data do not indicate substantial \( (1, -1) \) mode at ionospheric E region.

It may be noted that in all recent calculations, the space time dependence of the conductivity through the zenith angle dependence (as done by earlier workers) has been completely ignored. As emphasized by Chakraborty and Pratap (1954) and Pratap (1957), a semi-diurnal atmospheric oscillation can yield a diurnal magnetic field variation due to beating between the time-dependent conductivity and the velocity potential. Presently, a great confusion seems to exist regarding the tidal modes available in the ionospheric E region.

### 6.5.2. Three-dimensional Formulations

In the formulation mentioned above, it was assumed that the currents flow essentially horizontally in the ionospheric region and vertical currents are negligible. This was partly because it seemed reasonable to do so and partly because calculations became simple. First attempts at a three-dimensional formulation were made by Nishida and Fukushima (1959). They concluded that the difference in current strength obtained from the two-dimensional formulations is less than one-tenth of the total current estimated from the three-dimensional formulation. On the other hand, Cocks and Price (1966) found that the actual current systems may be quite different from the representative horizontal current systems derived from observed Sq field. In fact, the latter would form only one part and the vertical currents, though significant, would remain unobserved. It seems obvious by now that whereas the two-dimensional formulation gives a qualitative picture, a quantitative estimate of the electric field distribution will depend considerably upon the success of a three-dimensional formulation, which has not yet been fully achieved. Pratap et al. (1972) have formulated a three-dimensional dynamo theory for the magnetospheric region and conclude that some contribution to ground-based observations, which is not of ionospheric origin, is expected. Matsushita (1971) has indicated that plasmaspheric motions may also produce some effects. Quantitative estimates are awaited.

### 6.5.3. Equatorial Electrojet

For a location at a dip angle \( I \) when \( I \) is very small, the vertical Hall currents are great-
ly inhibited and a vertical polarisation field is formed which when crossed with the predominantly horizontal north-south magnetic field produces an additional east-west motion causing the strong electrojet. Several workers notably Baker and Martyn (1953) evolved the mathematical treatment of this problem and estimated that the half-width of this strip of enhanced conductivity would be about 3° in latitude and also predicted that the electrojet would lead the mid-latitude Sq by about 1 hr. The electrojet current was given by $j = \sigma_3 \cdot E = E (\sigma_1 + \sigma_2^2/\sigma_1)$ where $\sigma_3 = \sigma_1 + (\sigma_2^2/\sigma_1)$ is termed as the Cowling conductivity which far exceeds the Pedersen conductivity $\sigma_1$ in the equatorial $E$ region. Here again, the zenith angle dependence of the conductivity is neglected and Chakraborty and Pratap (1954) and Pratap (1957) point out that this will give only a semi-diurnal magnetic field variation and not a diurnal Sq. A survey by Forbush and Casavaode (1961) in the electrojet region of the American zone during IGY (1957-58) confirmed some of the features predicted by Baker and Martyn (1953). Ogbuehi (1964) reported a similar survey in Nigeria during September, 1962. Earlier, Chapman (1951) had suggested a uniform band model or a parabolic current distribution model for the electrojet. Onwumechilli (Book II, p. 426) formulated a new empirical model in which the possibility of return currents a few degrees away from the electrojet axis was incorporated. His analysis of all available data in the electrojet and nearby region indicated a possibility of return currents at about $\pm 5^\circ$ dip latitudes. This finding has very serious repercussions as it could imply that the electrojet may not be just a confluence of the northern and southern hemisphere Sq current systems intensified because of the peculiar high Cowling conductivity conditions at $I = 0$ but perhaps a partly independent current system having partly independent return paths.

The longitudinal difference between electrojet strengths at Huancayo and Trivandrum (about 190$\gamma$ and 140$\gamma$ respectively in 1958) is another interesting aspect (Chapman and Raja Rao, 1965). The first attempt to explain it was made by Sugiura and Cain (1966) by formulating a model for the electrojet region wherein they used a set of 48 G coefficients for the geomagnetic field and found that the Cowling conductivity was indeed highly longitude dependent. In fact, they predicted that the conductivity at Huancayo would be about twice that at Trivandrum and hence for similar east-west electric fields, the electrojet strength and hence $H$ range observed at the ground should bear the same ratio. The observed ratio is, however, only about 1.4 and Kane (1971b) has suggested that a part of the observed $H$ range at ground may be of magnetospheric origin and since this is expected to have a ratio 1.0, the net ratio observed may be diluted from 2.0 to 1.4. This is quite speculative and is only a possibility, not an evidence; but it needs to be borne in mind specially because the observed ratio changes with solar activity and was only about 1.1 for 1964 (Kane, 1972c). If the origin was purely ionospheric, the ratio should have remained constant. On the other hand, a varying proportion of ionospheric and magnetospheric contributions would give varying ratios. However, the possibility of electric field itself having a longitudinal variation opposite to that of the Cowling conductivity should also be kept in mind.
The model of Sugiura and Cain (1966) assumes a complete vertical polarisation of the electric field with \( \text{div} \ J \neq 0 \). Untiedt (1967) removed this assumption by including vertical meridional currents. Sugiura and Poros (1969) further improved upon this and have constructed new electrojet profiles for five different longitude zones. Figure 22 shows the profiles for Huancayo and Trivandrum. The predicted ratio of the current strengths at the two longitudes is still quite large. However, a new interesting feature is the possibility of return currents on either side of the electrojet at latitudes of about 7–10°. This is consistent with the empirical model of Onwumechilli, as also with a rocket flight result of Cahill (1959) where he found on 17 October 1957 a reversed (westward) current at an altitude of about 110 km, about 3.4°N of the dip equator in the Pacific region (159°W) at about 1400 LT.

Recently Schiedledge et al. (1973) and Richmond (1973) have evolved composite models for the mid-latitude \( \text{Sq} \) and the equatorial electrojet and have been able to produce some of the observed features but not all. Also, their predictions about return currents are different from those of Sugiura and Poros (1969). Kato (1973) points out that the assumption of a curl-free electric field by Untiedt (1967) and Sugiura and Poros (1969) may not be always valid in the presence of horizontal wind motions and may cause considerable errors under certain conditions. Suzuki (1973) calculated the distribution of return currents of the equatorial electrojet and concluded that the return currents decreased rather quickly with increasing distance from the equator and their contribution to the ground magnetic variations would be mostly 10% or less except in small areas just under the current vortices.

The problem of the reversed currents and their effects could be examined if conti-
nuous data were available from a closely spaced network of ground observatories. Presently, no such network exists. Since only India has a network of three stations (Trivandrum, Kodaikanal and Annamalainagar) in the electrojet region, it would be very useful to augment the same to form a closer chain. Such an augmentation would also help in studying the day-to-day changes in the electrojet strength and location (Van Sabben, 1966; Hutton, 1967a, b; Kane, 1973b).

While comparing electrojet strengths at different longitudes, it is usually assumed that the ratio of external to internal (induced) component is constant for all longitudes. However, Fambitakoye (1972) shows that the induced effect for the African region is negligibly small. If true, this would indicate a longitude dependence (or perhaps local anomalies) in the ratio of the external to the internal component and will have to be investigated further.

A new and very fascinating aspect of the electrojet is the phenomenon of counter-electrojet. This will be discussed in the section dealing with the variability of Sq and L patterns.

6.5.4. Lunar Daily Variations, L

More than a century ago, it was discovered that geomagnetic field components were affected by the Moon too. Several workers (Book I) evaluated lunar diurnal, semi-diurnal and higher order components and it was noted that the semi-diurnal term was the most prominent. It was also noted that at the equator the effect was enhanced. Rastogi (1964) and Rastogi and Trivedi (1970) showed that the latitudinal as well as the longitudinal behaviour of the L and Sq variations were similar. Using the method of spherical harmonic analysis, Matsushita and Maeda (1965) obtained the external and internal L (lunar) current systems including the equatorial electrojet. Comparison with the corresponding Sq field (of solar origin) showed that their solar activity dependences were roughly similar and their current systems flowed in the same ionospheric region. However, the intensity of the lunar (L) current system was much smaller than that of Sq, by about a factor of 30.

Rastogi and Alurkar (1966) compared the lunar daily variations at fixed lunar hours for $H$ and $f_0 F_2$ at Huancayo, and found that the variations in both these parameters were larger during solar day-time and their curves had opposite phases, indicating a close relationship between the two. Earlier, Moos (Book I) had reported similar results for geomagnetic field.

Using the same procedure as used for the Sq variations the lunar tidal wind patterns necessary for producing the observed lunar daily variations have been obtained (Matsushita, 1969). In contrast to the Sq current system which has only one focus in each hemisphere (Figure 20a), the L current system has two foci, indicating basically a semi-diurnal character (Figure 20b). Actual plots for $D$ show maxima at 0600 and 1800 (lunar time) in the northern hemisphere and minima at these hours in the southern hemisphere. $H$ variation has maxima at these hours for latitudes between $\pm 15^\circ$ (dip) but the hours are shifted at higher latitudes. Amplitudes are 2–3 $\gamma$ except at equator where values may be about 5 $\gamma$ or more (Matsushita and Maeda, 1965).
These are longitude-dependent. Recently, Tarpley (1970a, b) investigated the effect of various tidal modes using height-dependent wind fields and concluded that the lunar (2, 2) mode with wave amplitude of about 7.5 m s$^{-1}$ and a vertical wavelength of 85 km would fit the experimentally observed data very well. Rao and Sastry (1972) studied the partial lunar tides at Alibag and reported second harmonics in $H$ and $Z$.

6.5.5. **Present Status of Sq and L Current Systems**

The present status of these current systems may be summarised as follows.

(1) If it is assumed that the overhead current systems are confined to thin ionospheric layers, electric conductivities at various latitudes can be derived and the basic equations of the dynamo theory would give the electric field patterns and the associated observable geomagnetic effects for any assumed wind system. Alternatively, using the known electric conductivities and ground observations of geomagnetic field, the necessary wind patterns could be derived, for both Sq and L.

(2) If the current systems are not confined to thin layers and if three-dimensional models are formulated, the problem becomes extremely complicated and no complete solution has been obtained so far though solutions with reasonable approximations have proved instructive.

(3) Several workers have examined the effects of the presence of various tidal modes in the ionosphere (Tarpley, 1970a, b; Schieledge *et al.*, 1973; Stenning, 1973) and have concluded that the main wind field needed for explaining the ground pattern should be the (1, -1) mode for Sq and (2, 2) mode for the lunar semidiurnal pattern whereas other diurnal and semi-diurnal modes in lesser proportions are needed to account for the fine structure observed on individual days. However, the zenith angle dependence of conductivity is ignored which, if taken into account, may give a diurnal Sq from the beating with a semi-diurnal velocity mode (Chakraborty and Pratap, 1954; Pratap, 1957; Pratap *et al.*, 1972).

(4) To estimate the possible wind patterns one could extrapolate from the ground and stratospheric meteorological observations or evolve tidal theories (Siebert, 1961; Hines, 1967; Chapman and Lindzen, 1970). Presently available calculations do not favour the required (1, -1) mode in the ionosphere.

(5) Radar observations of meteor trails have supplied some information about the winds in the 80–100 km region (Greenhow and Newfield, 1961) indicating a semi-diurnal pattern for the east-west component and a diurnal pattern for the north-south component. Sodium vapour cloud experiments are confined to twilight hours only and are not of much use for this purpose. Some chemical release experiments (Tarpley, 1970a, b) have indicated the presence of the (1, 3) diurnal mode but not the (1, -1) diurnal mode. Incoherent scatter measurements (Bernard, 1974; Salah and Wand, 1974) seem to indicate semidiurnal oscillations in the mid-latitude E region. At Jamaica (low latitudes), Alleyne *et al.* (1974) and Scholefield and Alleyne (1975) report a diurnal mode in meteor winds, but with a highly variable phase and amplitude. Thus, the observational data are neither adequate nor very promising for the mainly required diurnal (1, -1) mode in the E region.
(6) In view of this confusion, some attempts have been made to examine the effect of zenith angle dependence of the conductivity (Pratap, 1957) in producing Sq variation from the semi-diurnal velocity modes, as also to investigate whether sources could be localised above the E-region where the (1, -1) mode is known to exist between 150–500 km. Mohlmann (1973) claims that this region could contribute a height integrated current density of about $10^{-1}$ A m$^{-2}$. Matsushita (1971) has proposed a possible effect due to plasmaspheric motions. Most of these need further exploration.

(7) Rocket observations of actual magnetic and electric fields (discussed later) indicate definite current systems in the equatorial regions, but evidence for middle latitudes is somewhat obscure.

6.5.6. **Variability of the Sq and L Patterns**

6.5.6.1. **Solar cycle and annual and semi-annual variations.** The quiet day daily variation range of $H$ undergoes large changes with solar activity. The amplitudes are large for higher activity, for both the solar tide Sq as well as the lunar tide L. (Matsushita and Maeda, 1965; also Book I). Most of these can be adequately explained in terms of the enhanced ionization and hence enhanced ionospheric conductivity due to higher input of solar ultraviolet and X-ray radiation during higher solar activity. The observed geomagnetic changes are sometimes used for estimating the solar cycle changes of the EUV and X-ray fluxes (Sengupta, 1970). There is however, some disagreement regarding the magnitude of the effect of solar cycle on Sq and L. Whereas Matsushita and Maeda (1965) indicate that the changes in Sq and L are similar, Chapman et al. (1971) show that if the yearly average daily range is expressed as $A(1 + MR)$ where $R =$ sunspot number, the constant $M$ (called Wulf number) for the Sq variation is about thrice that for the Lunar variation. The possible explanation is that whereas the L range is purely a gravitational effect, the Sq range is both gravitational as well as thermal and the latter may have a larger solar cycle dependence. Also, the lunar component may have a constant background of oceanic dynamo effect especially near the seacoast. Raja Rao et al. (1973) examined the $D$ component at Alibag and reported that whereas $S(D)$ was about 4.4 times $L(D)$, the principal harmonics $L_2(D)$ and $S_1(D)$ were almost equal.

Both Sq and L show strong seasonal variations. Rastogi and Trivedi (1970) studied the semi-diurnal amplitude $L_2$ at equatorial stations and reported that for Jarvis Island, Addis Ababa and Trivandrum the D-month amplitudes were about 3 times larger than the J-month amplitudes. For Huancayo, the ratio was still larger, about 5. Only for Koror, the ratio was about unity. In the early analysis, Chapman and Bartels (Book I) had reported that the seasonal variation of L was much greater than that of Sq. Matsushita and Maeda (1965) reported that the two varied similarly. Gupta and Malin (1972) reported similarity of L and Sq for one sample of data and L exceeding Sq for another sample. It is likely that the small magnitude of $L_2$ (a few gamma) may be difficult to assess correctly, leading to contradictory results.

The causes of the annual and semi-annual variations of Sq and L are still a matter
of speculation. For higher latitudes, the lesser amplitudes in winter are qualitatively consistent with lesser solar input and hence lesser ionisation. However, as proposed by Olson (1970a, b), some of these could be due to magnetospheric current systems. In this connection, it is interesting to note the seasonal variations of the Sq current foci. For the data for 1958, for the American, European and Australian zones, Gupta (1973) reported that the two foci move as a rigid system, the largest movement occurring in the American sector. Tarpley (1973) reported that in each equinox, one focus or the other was nearer to the equator and proposed this as a possible cause for the semi-annual variation (high values at equinoxes) for the equatorial electrojet strength.

6.5.6.2. Day-to-day variability of strength and position of Sq. A very striking aspect of the daily range of the geomagnetic elements, specially $H$, is its high day-to-day variability (Book I). A part of it could be due to lunar effects. However, it is observed that the range even on two consecutive days may often vary by a factor of two, specially in the electrojet region. This raises several problems. If we assume that the daily variation is caused by overhead currents, the magnitudes of these must be changing violently from one day to another. Roughly, the current $J = \sigma \cdot E$ and hence either the conductivity $\sigma$ or the electric field $E$ or both should change. The Sq dynamo is caused by solar heating and gravitational effects, their associated winds crossing with geomagnetic field lines. The solar heating depends upon the dissipation of solar radiation in the Earth’s atmosphere. For a constant influx, changes in the composition of the atmosphere can cause changes in the heating produced but this will be comparatively small and highly localised. On the other hand, ionisation is produced mostly by the solar UV and EUV (Extreme ultra-violet) radiations, some of which change appreciably from day to day. Some clue to the actual source of variability could, therefore, be obtained by comparing the variability at different geographical locations.

On a quiet day the daily ranges of $H$ at different latitudes in the same longitude zone do not correlate very well (Osborne, 1966, 1968; Schlapp, 1968). Figure 23 shows a plot of the $H$ range at Alibag (+13° Dip) vs $H$ range at Trivandrum (-1° Dip) in the Indian zone. A large scatter is obvious and the correlation (+0.39), though positive, is low. Normally this would imply that the mid-latitude Sq current system responsible for the $H$ range at Alibag is not completely identical with the electrojet current system that gives rise to the $H$ range at Trivandrum (equator). Kane (1971c) investigated this critically by examining the days in groups A and E in Figure 23 which represent extremely low and high ratios respectively for the ranges at the two locations. It was noticed that on many of these days, the latitudinal variation of $H$ pattern in this longitude region was such that the northern Sq focus was either too near or too far from Alibag. As mentioned earlier, the position of the Sq focus is indicated by the change-over of the $H$ daily variation pattern from a day-time maximum to a day-time minimum while passing from low latitudes to high latitudes. In Figure 18 we have already shown for a few days a plot of $H$ at Trivandrum (geomagnetic latitude -1.1), Alibag (+9.5), Sabhawala (+20.5), Tashkent (+32.6) and Sverdlovsk (+48.5) all in the 60°-80°E longitudes. The day-to-day variability in amplitudes is
seen at almost all locations though predominantly so at Trivandrum (equator). Also, the changes are not completely parallel at Trivandrum and Alibag. The ratios fall into wide-ranging categories A to E. It is interesting to note that whereas normally the Sq focus i.e., change-over from a day-time maximum to day-time minimum is expected to be between Sabhawala and Tashkent, the focus position also changes from day to day. On E type days (Alibag to Trivandrum ratio very low), the focus is nearer to Alibag than normal and on A type days it is farther away. For any day, the position (latitude $\bar{\phi}$) of the focus can be obtained as $\bar{\phi} = (H_2\phi_1 - H_1\phi_2)/(H_2 - H_1)$ where $\phi_1$ and $\phi_2$ are the geomagnetic latitudes and $H_1$ and $H_2$ are the $H$ ranges at Sabhawala and Tashkent respectively (Osborne, 1968). If amplitudes were normalised to correspond to an average focus position assuming direct proportionality with angular distance from the focus, it was observed that the correlation coefficients improved from about $+0.40$ to $+0.80$. Thus, a considerable part of the lack of correlation is
because of day-to-day changes in the focus position. However, as pointed out by Kane (1971c), not all discrepancies can be thus explained.

A possible connection between the day-to-day variability of equatorial $H$ and changes in ionospheric parameters was first indicated by Dunford (1967) and later by Akasofu et al. (1969) and McDougall (1969). A detailed analysis exclusively for quiet days (Kane, 1972a) showed that on an average, the strength of the equatorial electrojet was:

1. not correlated with direct solar radiation parameters viz. 2800 Me s$^{-1}$ flux or X-ray (44–60 A) flux or sunspot number,
2. well correlated with non-time E region drifts at equator, and
3. associated with changes in $h'F_2$ and the bite-out of $f_0F_2$ at the equator.

Thus, an association between the changes of equatorial electrojet strength and the equatorial F region dynamics is clearly indicated. The actual cause of these dynamical upheavals is not quite clear but the upheavals do not seem to extend to high latitudes and thus some changes at the equator may not be reflected completely at middle latitudes.

A detailed study of the seasonal changes as well as day-to-day variability of equatorial electrojet in the American zone was reported by Hutton (1967a, b) who found that the relative influence of the northern and southern Sq foci on the equatorial electrojet was also changing from day to day.

The day-to-day shifts in the position of Sq foci have been reported earlier (Hasegawa, 1936, 1960). An interesting aspect of the day-to-day variability of the electrojet was investigated recently by Kane (1974b) who showed that on the average, for days when the Sq current strength was higher (as revealed by larger daily ranges of the D component near the Sq focus), the Sq focus shifted equatorward and the equatorial electrojet strength was higher. As pointed out by Hasegawa, these changes are related more to the changing wind patterns rather than changing ionospheric conductivities. Hence, the exact mechanism causing day-to-day changes of the strength of Sq and/or equatorial electrojet should be sought in parameters causing changes in the wind patterns. It was shown by Matsushita (1960) that the unusually high or low latitude of the Sq focus position in one longitude zone need not have a corresponding high or low in other zones. Also, the overhead current loop patterns were never ideally circular but showed large deformations with considerable longitudinal as well as hemispherical inequalities (Matsushita, 1965). As pointed out by Mayaud (1967), there may be essentially two current systems, one the $C_M$ system causing the Sq foci at middle latitudes and another $C_P$ system having centres in the polar regions. For locations beyond the Sq focus, an encroachment of the $C_P$ system into the $C_M$ system would cause considerable distortions of an ideal symmetric Sq pattern. For middle and low latitudes, the $C_P$ encroachment would be negligible but the invasion of the $C_M$ system of one hemisphere into the $C_M$ system of the other hemisphere would be important. These encroachments as well as the forms and strengths of these current systems are dependent upon wind patterns and thus are subject to its vagaries. The current systems depicted in Figure 20 are not adequate to represent the polar regions.
On the other hand, the polar region is the most dynamic part of our globe where solar wind intrusions seem to occur, so to say, at the slightest excuse. It is conceivable, therefore, that encroachments of a highly variable $C_p$ system into the comparative calm of the midlatitude $C_M$ system is more frequent than is usually believed. In this connection, the observations of Brown and Williams (1969) assume added significance. From the $H$ data of locations near Greenwich (U.K.) they noticed that whereas the usual quiet-day pattern of daily variation was a noon-time minimum (the station being poleward of the Sq focus), on some apparently quiet days, the minimum occurred outside the 0830–1330 LT range. They termed such days as AQD (Abnormal Quiet Days) and reported that these occurred more often in years of sunspot minimum and during winter, i.e., when solar intensity would be minimum. This could imply an encroachment of the $C_p$ system on the $C_M$ system when the latter had weakened. Recently, Brown (1975) has reported that the phase of the AQD was generally late when stratospheric isobaric levels were rising and the electron content of the $E$ region was less than normal. It would thus seem that the variability in the dynamo region was related to an upward propagation of planetary waves from the troposphere and stratosphere in winter. Thus, a possible meteorological origin is also indicated, though it is likely that both these had a common origin in some of the polar phenomena. It would be interesting to see whether any such relation is obtained in lower latitudes also. Abnormal Sq phases at low latitudes (Alibag) were reported by Arora (1973) who studied data for 37 years and found about 7% AQD when daily maxima occurred outside the usual 1000–1300 LT range. He also found that AQD occurred more in summer and winter than in equinoxes and were inversely related to sunspot activity. Day-to-day changes in the electrojet strength, width as well as deviations from the east-west direction have been demonstrated by Van Sabben (1966), Hutton (1967a, b), Kane (1973b). The exact causes of these are still obscure. Partial currents along the magnetic field lines might be playing a significant role (Van Sabben, 1966).

6.5.6.3. Day-to-day variability of profiles: Counter-electrojet. The magnitude of the daily range may change from day to day as described above; but that is not the whole story. The pattern of rise and fall may have changing gradients even from hour to hour (Schlapp, 1973), showing that the wind patterns may undergo a qualitative change during the course of a day. In the equatorial region, Onwumechilli (Book II, pp. 425–507) reported three types of quiet-day daily variation patterns of $H$. One pattern rose steadily from midnight to an early maximum about 1000 LT, later decreasing to a minimum about sunset. Another (symmetrical) pattern had a minimum at sunrise and sunset and a maximum at about 1100 LT. The third had a minimum about sunrise, a maximum about 1200 LT and a slow decrease up to midnight. Taken on their face value, these patterns would imply that on some days appreciable overhead currents existed in pre-dawn or post-dusk hours also besides the usual sunlit hours. However, it is known that the ionospheric $E$ region electron densities fall sharply after sunset and are very low before sunrise. It is obvious, therefore, that the pre-dawn and post-dusk currents could not possibly be of ionospheric origin. It is also known now
(as we shall discuss later) that even on apparently quiet days, the magnetospheric effects may not be negligible and these have an isotropic component ($D_{st}$) as well as LT dependent component ($DS$) (Sugiura and Chapman, 1960). To correct for both these simultaneously, we proposed a parameter $Sd_1$ of equatorial electrojet strength (Kane, 1973e) defined as:

$$Sd_1(\text{equator}) = H(\text{equator}) - H(\text{low lat.}) + S_q(\text{low lat.}).$$

Thus, hourly $Sd_1$ at Trivandrum (Indian equator) would be obtained by subtracting hourly $H$ at Alibag (Indian low latitude) from hourly $H$ at Trivandrum and adding the average $S_q$ at Alibag for the month for which $Sd_1$ hourly values are being calculated. Figure 24 (Kane, 1973f) illustrates this procedure for 8 consecutive days 1–8 January 1964 and shows that irrespective of whether the days are quiet or geomagnetically disturbed (Ap values high), the parameter $Sd_1$ shows a constant level for consecutive nights and the variations are confined only to sunlit hours. Thus, the pre-dawn and post-dusk currents noted in the three patterns mentioned by Onwumechilli are mostly magnetospheric effects ($D_{st}$ and/or $DS$) which can be eliminated by subtracting the $H$ values of a low latitude station just outside the electrojet region from the $H$ values in the electrojet region. A similar method was used by Cohen and Bowles (1963).

A critical appraisal of the parameter $Sd_1$ is given in Kane (1973f). We believe that the deviations $\Delta Sd_1$ from night-time values of $Sd_1$ as defined above represent the electrojet strength within an accuracy of $\pm 10 \gamma$.

Using the $Sd_1$ values so obtained Kane (1973b) studied the profiles of the electro-
jet strength and identified even for quiet days fourteen types of abnormal profiles characterised by very weak or very strong electrojet strengths at the usual 1100 LT as also abnormally large and/or abnormally small currents in the morning and/or afternoon hours. These are illustrated in Figure 25 (Kane, 1975c). Particularly fascinating is the phenomenon when on some quiet days the $H$ values in the equatorial

![Image](https://example.com/image.png)

Fig. 25. Abnormal daily variation profiles (full lines) of $Sd_I$ at Trivandrum on selected days (dates and $Ap$ values indicated). Dashed lines show the average quiet day variations for the respective months (Kane, 1975c).

region seem to drop below the night-level at some day-time hours. The phenomenon was first observed by Gouin and Mayaud (1967, 1969) and was christened 'counter-electrojet' implying thereby that during these intervals, the overhead electrojet current reversed its direction of flow temporarily. Hutton and Oyinloye (1970) studied further details. The phenomenon occurs predominantly around 0630, 1200 and 1500 LT, more frequently during quite sun years and has no relation with either solar flares or lunar age though the latter may cause some modifications in magnitudes of the effect. Onwumechilli and Akasofu (1972) report days when the counter-electrojet has a strong lunar influence but sometimes in phase and sometimes anti-phase. In the equatorial region, the ionospheric E region is characterised by the presence of irregularities giving rise to equatorial sporadic E ($E_{sq}$), almost throughout the day-time (0600-1800 LT) so that $f_0 E_s$ is several MHz. However, during the occurrence of counter-electrojets $f_0 E_s$ drops to very low, mostly undiscernable values. Thus, counter-electrojets are strongly associated with disappearances of equatorial sporadic $E$.

The temporary reversal of an electrojet would be, to say the least, baffling as the
associated dynamics would be quite confusing. Balsley and Woodman (1971) who reported measurements of the ionospheric drift velocities at Jicamarca, showed instances when the E region drifts reduced to zero when $H$ values showed counter-electrojets; but reversals of E-region drift directions were not observed by them. Their data were obtained by determining the mean Doppler shift of oblique radar returns from a certain type of electron density irregularities. On the other hand, using the three spaced receiver method, Rastogi et al. (1971) measured the E and F region drifts at Thumba (equator, India) and found a clear reversal during counter-electrojets, from the usual westward flow to a temporary eastward flow. Another test would be to observe the magnetic fields at heights above the ionosphere. From traverses of POGO satellite over the equatorial electrojet, Cain and Sweeney (1973) obtained the signatures of the electrojet at several longitudes. Comparing with ground observations in Indian longitudes, Kane (1973d) could identify at least one traverse, that on 13 September 1967 at about 1400 LT when the POGO observed a reverse pattern, which was associated with a counterelectrojet on ground. The correlation between ground observations and POGO signatures is not perfect. Nevertheless, it seems beyond doubt that the counter-electrojet is really a reversal of the usual electrojet.

For quiet days, identification of a counter-electrojet is a simple matter. However, for disturbed days when $H$ changes of non-ionospheric (magnetospheric) origin occur, the identification is difficult. Hutton and Oyinloye (1970) showed that for some days the afternoon counter-electrojet observed in $H$ values persisted even after $D_{st}$ corrections were applied. However, as pointed out by them, $D_{st}$ represents only the symmetric ring current and hence local-time dependent $D_S$ effects remain uncorrected. Hence, the persistence does not invariably indicate an ionospheric origin.

Using the parameter $S_{di}$, we studied the phenomenon of counter-electrojet. Figure 26 shows a plot of $H$, $S_d$ and $S_{di}$ at Huancayo, Addis Ababa and Trivandrum for the period 12–19 January 1964 when prominent counter-electrojet effects (shown by black patches for $S_{di}$) occurred. Besides showing the appropriateness of $S_{di}$ as a measure of electrojet strength, the figure shows that:

1) The counter-electrojet phenomenon is restricted to very narrow longitude zones though it may persist in that zone for several days, continuously or intermittently (Kane, 1973c; Rastogi, 1973b, 1974a, b),

2) There is no obvious connection between the occurrence of the electrojet and the interplanetary plasma parameters (Kane, 1973c).

We feel that the counter-electrojet phenomenon is caused by very local stormy conditions in the ionospheric regions. These may be connected with similar stormy conditions in stratopause regions. Webb (1971) indicated that the wind circulation systems generated by the heat wave of the stratopause region and turbulent transport processes interacted through the geomagnetic field with ionospheric plasma.

Recently, Fambitakoye et al. (1973) suggested as a possible cause of the counter-electrojet an additional belt of current underlying the normal electrojet and flowing in the opposite direction. They showed that whenever the factor $AH$(equator)–$AH$(low lat.) became negative, the $E_{eq}$ disappeared. In Kane (1973a) it was shown
that on some occasions $E_{sq}$ disappeared even when $\Delta Sd_1$ was positive. Recently, we examined several events to check whether it was $\Delta Sd_1$ or the factor $\Delta H$ (equator) -- $\Delta H$ (low lat.) which needed to be zero or negative for $E_{sq}$ to disappear. The latter factor is equivalent to $\Delta (Sd_1 - S_{q1})$ by our notation where $S_{q1}$ is the average $S_{eq}$ at low latitude. In Figure 27, (Kane, 1975c) we show samples of days when $E_{sq}$ disappearances (marked as black flags) were associated with reversals of $\Delta Sd_1$ rather than $\Delta (Sd_1 - S_{q1})$ as shown in columns (a) and (b) and with perhaps $\Delta (Sd_1 - S_{q1})$ but not with $\Delta Sd_1$ as

Fig. 26. Counter-electrojet effect during 12–19 January 1964 (Kane, 1973c).
Fig. 27. Daily variation of $\Delta Sd_1$ (full lines) and $\Delta (Sd_1 - Sq)$ (dashed lines) for selected days. In (a) and (b) $\Delta Sd_1$ reversals coincided with $E_{sq}$ disappearances (black flags). In (c), $E_{sq}$ disappeared when $\Delta Sd_1$ was still positive (Kane, 1975c).

shown in column (c). The latter cases pose a serious dilemma viz. since the ground $H$ is positive, the net electrojet current must have the usual direction. On the other hand, since $E_{sq}$ has disappeared, the currents in the layer where $E_{sq}$ is normally formed must have either stopped or reversed. Thus, two unequal electrojet current systems flowing within a few kilometers and opposite to each other are implied. The counter-electrojet is itself a baffling phenomenon as it is difficult to imagine such a reverse current at equator amidst normal Sq current systems in both the hemispheres on either side. To have two opposite current systems in nearly the same (electrojet) region is still more difficult to imagine. On the other hand, there seems no other plausible way of explaining the occurrences of positive H deviations observed on ground associated with $E_{sq}$ disappearances in the E region. In situ observations of currents, fields and irregularities in the electrojet region should throw some light on this aspect. The problem is perhaps connected with the exact nature of the instabilities and irregularities present in the electrojet region. Basically, two types of irregularities have been envisaged and observed viz. Type I (two-stream) which occur when electron velocities exceed the sound speed (as at the peak of the electrojet at noon) and have short wavelengths (Farley, 1963) and Type II (cross-field) which need electric fields and electron density gradients in the same direction and have very low thresholds and normally favour
long wavelengths (Reid, 1968; Register and D'Angelo, 1970) in the horizontal
direction which in turn may produce short wavelength vertically propagating instabilities (McDonald et al., 1974). These have been actually observed in rocket flights (Prakash et al., 1971). Another possibility due to electromagnetic effects has been recently proposed by Kaw et al. (1974). Recent studies of the instabilities by radar techniques (Farley and Balsley, 1973; Cohen, 1973) indicate that the electrojet is highly turbulent over scales of 1000 m and may have two or more strata having non-two-stream irregularities moving at different velocities.

6.5.6.4. Sidereal effects. There have been some attempts recently to investigate whether the geomagnetic daily variation has any sidereal component. Campbell (1972) reported the presence of such a component which though small in magnitude was statistically significant. Malin (1973) suggested that such changes could be due to purely terrestrial factors such as conductor movements in the interior of the earth. However, Murty and Yacob (1974) found depressions in $H$ at Alibag corresponding to the transit of galactic X-ray sources. The topic needs more investigation.

6.5.7. Polar Daily Variation $S_q^\beta$

It was pointed out long ago by Nagata and Kokubun (1962) that the $S_q$ current patterns like those shown in Figure 20(a) do not represent adequately the daily variation patterns actually observed in the polar cap. They showed that an additional current system would be needed having two vortex-like currents, one vortex shifted towards the dawn side and the other towards the dusk side of the pole at about 75° latitude and termed it as $S_q^\beta$. This was re-examined later by Kawasaki and Akasofu (1967) and Feldstein and Zaitsev (1967) who showed that the pattern for very quiet days was not as proposed by Nagata and Kokubun but was considerably different and was mainly confined to the 06-12 and 12-18 LT quadrants with a single predominant vortex in the sunlit portion. It seems this current system is connected with a convective motion of the magnetospheric plasma and the associated electric field which is shown in Figure 9 and seems to be a permanent feature of the polar region even on quiet days in accordance with the models of Axford and Hines (1961) and Dungey (1961) though Dungey envisaged it only when interplanetary magnetic field has a southward component. Its permanent existence could imply that the magnetosphere is permanently open. Recently Kawasaki and Akasofu (1973) proposed that the $S_q^\beta$ is not entirely due to the ionospheric current system mentioned above but is also due to field-aligned currents flowing from the dawn magnetosphere to the forenoon polar ionosphere and from afternoon ionosphere to dusk magnetosphere, the whole pattern being a manifestation of convection. Even with moderate geomagnetic activity, the $S_q^\beta$ current strength seems to increase indicating enhanced convection effects and some of these seem to be connected with what are known as DP current systems (Disturbance, Polar) as we will see later.

6.5.8. Non-ionospheric Sources

Since the ionospheric E region wind systems are shrouded with mystery, alternative
sources for producing the ground patterns of $H$ were sought. Van Sabben (1966) examined the possibility of magnetospheric currents associated with the north-south asymmetry of Sq. Sarabhai and Nair (1969a, b; 1971) proposed that the daily variation of $H$ at a low latitude station away from the influence of the equatorial electrojet was dominated by current systems outside the ionosphere. As evidence, they showed plots of $\Delta H$ (daily range of $H$) vs the daily minimum $H_{\text{min}}$ as shown in Figure 28 which indicated a strong negative correlation. Since larger ranges of daily variation are associated with lower $H_{\text{min}}$, they concluded that the daily variation is caused not by a daytime increase of $H$ (as is envisaged in the usual ionospheric source of Sq) but mainly by a night-time decrease of $H$. However, as pointed out by Hutton (1970) and Kane

![SCATTER PLOT OF $H_{\text{MIN}}^*$, $\Delta H^*$
HONOLULU (1963-1967)](image)

**Fig. 28.** Relation between $H_{\text{min}}$ and $\Delta H$ for Honolulu for period 1963 to 1967 (Sarabhai and Nair, 1971).
(1971 d), the parameter $\Delta H$ (defined as $H_{\text{max}} - H_{\text{min}}$) is not an appropriate indicator of the daily variation specially on disturbed days. This is obvious from Figure 28 where $\Delta H$ values as high as 480 $\gamma$ are shown to occur which could not possibly be due to a daily variation and must be largely polluted by the storm time effects. If the analysis is confined to quiet days, the correlation between $\Delta H$ and $H_{\text{min}}$ is very low and $\Delta H$ then shows a good positive correlation with $H_{\text{max}}$, indicating a daytime increase as the main source of $\Delta H$ on quiet days. Nevertheless, the suggestion of Sarabhai and Nair seems to have stimulated a great interest in the search and estimation of non-ionospheric sources. Olson (1970a, b) estimated that magnetopause currents could give a daily variation range of a few gamma and an hour of maximum at about 1130 LT mainly because the solar wind does not flow exactly along the Earth-Sun direction but at an angle of about $8^\circ$ to the west of that direction (Hundhausen, 1972). In his later model (Olson, 1974) which includes effects due to tail currents and quiet-time ring currents, the net daily range is expected to be about 9–14 $\gamma$ which is still only about 1/3rd of the $H$ range observed at a low latitude station like Alibag. Matsushita (1971) examined the possibility of producing Sq type currents in the dynamo region by the magnetospheric electric fields caused by motions in the plasmasphere and hinted that this mechanism may produce Sq ranges larger than the other effects due to magnetopause, tail and quiet-time ring currents. Pratap et al. (1972) solved the three-dimensional dynamo equation for the magnetospheric region assuming conductivities as that for a fully ionized but highly rarefied gas in a magnetic field, with the velocity field based on the convection patterns as observed by satellites. Quantitative estimates have not been possible due to lack of information about all relevant parameters. Purely from comparison of ground observations at equatorial and low latitudes Kane (1970, 1971b, c) estimated possible magnetospheric contributions of about 15 $\gamma$ in winter and about 40 $\gamma$ in summer. However, these should be considered as tentative. It would be very useful indeed if accurate magnetic field measurements could be made by satellites flying above but not too far from the ionospheric E region.

6.5.9. Relationship with Interplanetary Plasma Parameters

It would be of interest to examine whether the day-to-day variability of $S_q$ is related to the changes in interplanetary plasma parameters. Sarabhai and Nair (1969a, b) correlated $(\Delta H)^2$ with kinetic energy $(N V^2)$ of the solar wind for the IMP-1 period (November 1963 to February 1964) and obtained a positive correlation. However, as shown in Hutton (1970) and Kane (1970, 1971s), the parameter $\Delta H = H_{\text{max}} - H_{\text{min}}$ used by Sarabhai and Nair does not represent the daily variation properly on disturbed days. Instead, it would represent the storm-time $D$st change and hence the positive correlation obtained by them is similar to the result obtained by Hirshberg and Colburn (1969).

Restricting the analysis to quiet days only, Kane (1971e, f) reported for the IMP-1 period a positive correlation of equatorial daily $H$ range with interplanetary magnetic field southward component $B_z$ and of low latitude daily $H$ range with $B_x$ and $B_y$. However, these data were very scanty. The analysis was recently extended (Kane,
1975a) to the period 1965-68 using $H$ data at Trivandrum and Alibag and inter-
planetary data from Explorer 28, 33 and Vela-3. It was noticed that on the average
the normal electrojet weakened and the counter-electrojet intensified when $B_x$
(towards Sun) attained large values, or when $B_z$ (southward) attained large values
or when the Archimedes spiral deviated considerably from the usual 45° orientation
relative to the Sun-Earth line or when the plasma density increased. Southward $B_z$
attaining large values usually leads to disturbed conditions due to field-line merging
(Dungey, 1961) resulting in an enhanced dawn-dusk electric field and a host of storm-
time phenomena as will be discussed soon. However, the orientations of $B_x$ and $B_y$
too, though not resulting into the conventional storm effects, modify considerably
the polar environment. The $S^p_0$ patterns are such that the ionospheric daytime currents
circle the magnetic poles and are *counter-clockwise* for interplanetary fields away
from the sun (Svalgaard, 1973). The average electric field pattern shown in Figure 9
also changes considerably with the interplanetary magnetic field structure (Heppner,
1972b). It is not quite clear how these polar configurations affect equatorial and low
latitude region dynamo currents. But there is enough evidence that the two are related.
On moderately disturbed days, Onwumechilli et al. (1973) found that the $S^p_0$ was en-
hanced and the equatorial electrojet was either enhanced or suppressed and showed
short-term fluctuations called DP2. There is perhaps only a hair-breadth distinction
between quiet periods and disturbed periods. Most probably the polar situation is
dynamic all the time due to frequent changes in interplanetary magnetic components,
though the conventional storms are associated preferentially with large southward $B_z$.
Afanasyeva (1973) also reported changes in the form of $S^q$ connected with $B_x$, $B_y$,
$B_z$. It needs to be investigated further whether this connection is necessarily through
polar current systems encroaching upon the low latitude dynamo currents or the
latter can somehow respond independently to the interplanetary plasma parameter
changes.

During disturbed days, the equatorial electrojet strength can be studied only
through the parameter $S_d$. Large southward $B_z$ seems to be associated with a weakening
of the electrojet as shown by a reduction of the daily range of $S_d$ (Kane, 1971f) as also reduced east-west drift velocities in the ionospheric E region at equator
(Rastogi and Chandra, 1974). This will be discussed later.

6.6. **TRANSIENT FLUCTUATIONS: SOLAR FLARE AND ECLIPSE EFFECTS**

Solar flares usually have two distinct effects on geomagnetic field. Firstly, the en-
hanced UV, EUV and X-ray fluxes in the solar flare reach the Earth within a few
minutes and produce extra ionisation in the D and E region of the sunlit part of the
Earth mostly in the vicinity of the subsolar point. Secondly, the corpuscular radiation
spreads into the interplanetary space, forms shock waves which may engulf the Earth
in due course (in a matter of hours or days depending upon the suitability of transit
paths) and may produce peculiar storm-time changes in the geomagnetic field. These
will be discussed later. Here we emphasise the first aspect viz. the enhancement of
ionospheric conductivities within a few minutes of the occurrence of the optical flare, which though not strictly speaking a quiet time phenomenon, is a transient phenomenon which may or may not produce a subsequent storm.

Since the immediate effect is enhanced conductivity, the result would be an augmentation of the overhead Sq current system existing at that time. However, this is not the whole story. As the solar flare spectrum is more penetrating than the normal solar spectrum, the seat of the new currents is shifted towards lower altitudes and could even be interpreted as an additional current. Since the ionospheric winds are expected to be height-dependent, the additional current may not be exactly like the normal Sq currents. It may sometimes flow even in the night side with intensities about 10–20% of its intensity at the subsolar point. On the ground magnetograms, the solar flare effect (sfe) looks like a kink in the H pattern and is called a Crochet. Between equator and Sq focus, the normal Sq pattern is an increase of H above the night level and the crochet looks like an additional increase. For stations poleward of the Sq focus, the normal H pattern is a decrease below the night level and the crochet looks like an additional decrease.

Equivalent current systems for sfe have been obtained by several workers. Earlier works (Book I) proposed current systems simply augmenting the Sq. Later works (see Book III, p. 564; also Richmond and Venkateswaran, 1971 and references therein) brought out significant differences which were explained on the basis of larger penetration into the D region. A study of the time evolution of crochet currents for different flare epochs has revealed that the changes in the current patterns are mostly due to a time-varying spectrum of the flare radiation incident on an ionosphere with winds varying with height (Greenfield and Venkateswaran, 1967). Also, the crochet often manifests a composite structure consisting of a fast component and a slow component caused probably by EUV (100–1000 Å) and X-rays (1–100 Å) respectively.

The amplitude of the sfe (H) is sometimes larger in the equatorial region but roughly in the same proportion as the ratio of midlatitude and equatorial Sq. A study of 15 well-recorded sfe’s in the Indian longitudes during 1957–59 (Pisharoty and Joseph, 1963; Raja Rao and Rao, 1963) revealed a definite positive deflection of H for 0700–1400 LT with maximum effects seen near about 1030 LT in contrast to an hour of maximum at about 1200 LT for normal Sq. However, for sfe occurring before 0700 LT or after 1500 LT, H deflections were negative. In a sfe which occurred on 3 May 1973 at 0830 UT, Srivastava (1974) observed positive sfe amplitudes of H of about 60 µ at the middle and low latitude stations Sabhawala, Alibag and Hyderabad but only about 30 µ (positive) for the equatorial stations Annamalainagar, Kodaikanal and Trivandrum all in the Indian zone at about 1500 LT. The lower values at the equatorial region are surprising indeed and Srivastava proposes that this could be due to a possible counter-electrojet occurring at that time. Some of the negative H deflections of sfe observed by Pisharoty and Joseph for the pre-0700 LT and post-1500 LT intervals could also be due to a presence of counter-electrojets. Recently, Rastogi (1975b) studied a few events when the counter-electrojet and sfe occurred simultane-
ously in the afternoon and the $H$ deflections were found to be negative at Trivandrum and positive at Alibag. It would be very interesting indeed to check whether sfe's occurring during clear counter-electrojets and partial counter-electrojets (when $\Delta H$ was still positive but $E_{sq}$ disappeared) showed any distinct characteristics which could throw some light on the conjecture that there might coexist in the electrojet region current systems in opposing directions as suggested by Fambitakoye et al. (1973). However, one thing is certain. These current systems are in the ionospheric regions and hence support the conclusion that Sq current systems are also mainly in the ionospheric $E$ region. The contribution from magnetospheric sources must be rather small.

The effect of solar eclipses would be of a nature opposite to that of the solar flares. The solar radiation is temporarily cut-off over a region of the earth. A very well-known example was that of the total eclipse of 12 October 1958 when Kato (1960) observed a clear decrease $f_0$ about 12 $\gamma$ at about 0900 LT in the $H$ value at Suwarrow Island ($13^\circ S$, $163^\circ W$). This leaves little doubt that the seat of the Sq variation is mainly in the ionosphere.

6.7. MICROPULSATIONS

Sensitive magnetometers on Earth as well as on satellite often record quasi-sinusoidal disturbance patterns which have been attributed to hydromagnetic waves in the magnetosphere (Campbell, Book II, p. 822; Campbell, 1973b; Orr, 1973 and references therein). Periodicities as small as $\frac{1}{2}$ s with amplitudes about 10 $\gamma$ and as high as 5 min with amplitudes about 100 $\gamma$ are noticed with rapid-run magnetometers, induction coils and potential measuring devices buried in the earth. The General Assembly of IUGG (Jacobs et al., 1964) has recommended a standard nomenclature as follows:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Period range (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular patterns</td>
<td>Pc1</td>
</tr>
<tr>
<td></td>
<td>Pc2</td>
</tr>
<tr>
<td></td>
<td>Pc3</td>
</tr>
<tr>
<td></td>
<td>Pc4</td>
</tr>
<tr>
<td></td>
<td>Pc5</td>
</tr>
<tr>
<td>Irregular patterns</td>
<td>Pi1</td>
</tr>
<tr>
<td></td>
<td>Pi2</td>
</tr>
</tbody>
</table>

All these are termed generally as Micropulsations. Periodicities less than 0.2 s are also noted and are mainly due to atmospheric lightning discharges and cavity resonances excited between the Earth and the lower ionosphere. The Pci pulsations give a bead-on-a-string appearance on an amplitude versus time trace and hence are known as pearls. Figure 29 shows samples of Pc1 and Pc3 events. The large amplitude Pc5 events are humorously called giant micropulsations!

The micropulsation activity at any location depends upon the solar cycle phase,
seasons, time of the day, ionospheric and magnetospheric conditions and geomagnetic activity, besides the geographical latitude and longitude. Several characteristics of the various Pc and Pi have been listed by Orr (1973). Pc1 are most frequent in the morning hours at middle latitudes but occur all through the daylight hours above 65° latitude. Pc2–5 occur at mid-latitudes also; but their variety and amplitudes increase in high latitudes. All these can be explained on the basis of excitation of hydromagnetic (Alfvén) waves at the magnetopause and in the magnetosphere and their propagation to the Earth after undergoing absorption and partial reflection. Their speed is given by $B(4\pi m)^{-1/2}$ where $B =$ the magnetic field and $m =$ the mass density of charged particles. Hence, in the equatorial plane, the velocities would be about 150 km s$^{-1}$ at the Earth’s surface rising rapidly to as high 4000 km s$^{-1}$ at about 1.5 $R_E$ (Earth radii), drop again to about 1200 km s$^{-1}$ at about 3 $R_E$, rise again to about 2500 km s$^{-1}$ at about 4 $R_E$ (plasmapause) and then fall rapidly at larger distances. It is surmised that hydromagnetic waves are preferentially produced in these regions and are guided by the magnetic field lines to reach the Earth giving the observed micropulsations. Several generation mechanisms are theoretically possible, e.g. Kelvin-Helmholtz instabilities at the dawn and dusk meridians of the magnetopause, solar wind fluctuations, wave particle interactions giving cyclotron and bounce resonances, transient magnetospheric current sheets, reconnection of field lines in the geomagnetic tail
and so on. The magnetospheric pulsations cause precipitation of electrons in the ionosphere which results in additional ionospheric currents giving micropulsations on the ground. It is also known that hydromagnetic waves dissipate their energy in the ionosphere and cause heating. Satellite drag has shown large temperature increases at times of geomagnetic disturbances. Thus excitation of hydromagnetic waves in the magnetosphere and their subsequent guided arrival at Earth particularly at middle and high latitudes, their absorption in the ionosphere producing heating and additional ionospheric currents, their excitation of magnetospheric particle fluxes which later bombard the ionosphere, their interaction with lower ionosphere to get converted into electromagnetic waves and duct around the Earth in an ELF mode are all distinct possibilities giving the complex phenomena that micropulsations seem to be. Conjugate point studies have indicated clearly that micropulsations are often guided by the geomagnetic field lines.

A study of the amplitude, frequency and polarisation of the micropulsation activity obtained simultaneously from a global surface network as also from satellites is helpful in studying the Earth’s space environment, in particular changes in the interplanetary plasma parameters, movement of low energy plasma and energetic charge particles within the magnetosphere, position and variation of induced ionospheric current systems, plasma density variations with solar cycle, pitch angle distribution and energy spectra and fluxes of energetic particles and so on. Presently, effort is made not only to pinpoint the exact location in the magnetosphere of the generation of the various types of micropulsation but also to identify the exact mechanisms of generation. Fukunishi and Lanzeroti (1974a, b) have recently shown that Pc3 and Pc4 are produced in narrow latitude ranges, Pc3 outside and Pc4 inside the plasmapause. Also both represent the odd modes of standing Alfvén waves. Chen and Hasegawa (1974) have produced additional evidence for the steady state field line resonance model.

6.8. MEASUREMENTS OF FIELDS

Information about the currents, magnetic and electric fields and irregularities in the upper regions can be obtained from ground-based whistler studies, micropulsation studies, back-scatter radar techniques, drift measurements by 3-receiver techniques as also by actual in situ measurements in space by balloons, rockets and satellites.

6.8.1. Magnetic Field Measurements as Indicators of Currents

Since balloons reach heights of about 30 km where the atmosphere is mainly neutral and non-conducting, measurements with these are not of any great geomagnetic interest. For rocket and satellite measurements, magnetometers of the flux-gate type (measuring one component per fluxgate and hence needing three sensors for a complete vector estimation), spinning coil type, proton precession type and rubidium vapour type are generally used, the latter two giving the total scalar field. Several rocket flights have been conducted so far, many of these in middle latitudes. Burrows and Hall (1965) flew a proton magnetometer at Woomera (41°S) and Davis et al.
(1965) flew a Rubidium vapour magnetometer at Wallops Island (49° N) and reported field changes of 10–30 γ between 100–120 km. Recently, Yabuzaki and Ogawa (1974) used a cesium magnetometer at Kagashima (20° N) and observed a major current sheet at 104 km and a minor sheet at about 116 km at 1542 LT. Several satellites have been put into a variety of orbits yielding valuable information on magnetospheric and interplanetary fields. The equatorial region is also investigated by both these types of vehicles. The rocket measurements refer mostly to the total field $F$. From the observed field the expected field on the basis of any standard model can be subtracted and the residual $\Delta F$ can be studied. Specially, its height gradient gives the local current density $J$. The pioneer effort in this field was made by Singer et al. (1951a, b) who observed with flux-gate magnetometers a $400 \pm 50$ γ change when their Aerobee rocket attained a peak altitude of 105 km at 0° dip latitude in the Pacific region (89° W) at about 1120 LT. The next attempt was by Cahill (1959) who obtained with proton precession magnetometers sent with Aerobee rockets the vertical profile up to an altitude of 120 km in the Pacific region (161° W) and reported a maximum electrojet strength at 105–107 km and a north-south width of more than 300 km. A second current layer at a height of about 125 km was also indicated. In 1963, the Thumba Equatorial Rocket Launching Station (TERLS) was commissioned at Thumba near Trivandrum (India) and Maynard et al. (1965) reported results from Nike-Apache rockets carrying Proton Precession magnetometers and electron density probes which reached as high as 160 km. An electrojet centred at about 107 km with a half-thickness (vertical) of about 18 km was indicated. Also, a second layer at about 140 km was again indicated.

The next series of Nike-Apache rocket launching was reported by Davis et al. (1967) and Maynard (1967) who investigated the structure and latitudinal spread of the equatorial electrojet near Peru from the ship USNS Croatan using total field magnetometers. They found the lower boundary of the electrojet at an altitude of about 87 km, a current density $J$ of about 10 A km$^{-2}$ at its centre at about 107 km, and a half-width (north-south) of about 600 km. Every overhead current would have an induced current in the interior of the conducting earth. They estimated the internal/external ratio ranging from 0.23 to 0.33 in this region. Whereas the day-time electrojet current (conventional) is from west to east, they found in a night-time flight a small opposite current (east to west), indicating that the electric field reversed during the night. The current intensity of the electrojet in the American longitudes was found to be higher than that in the Indian longitudes. In one of the flights by Maynard, a small reverse current was observed to the north of the electrojet region.

In the last few years Sastry (1968, 1970, 1973) conducted several rocket flights at Thumba (TERLS, Equator, India, 77° E) using proton precession and rubidium vapour magnetometers. He found that the height of the centre of the electrojet did not vary appreciably during the day or from one day to another; but the nature of the vertical profile of current density changed with time and solar activity. On an average, the vertical distribution closely followed similar distribution of the calculated Cowling conductivity. This would imply that the horizontal electric field was constant in the 100–150 km
height region. Sastry also found that the electrojet width varied from time to time and the internal/external ratio was about 0.39 in contrast to about 0.28 for the Pacific zone. A secondary peak at about 140 km was also indicated, which could be in consonance with the weak secondary peak at about 130–140 km predicted for the equatorial conductivity profile by Maeda (1965).

In some of the flights carried out by Sastry at Thumba, several other parameters like electron density and temperature, electric fields etc. were also studied simultaneously. Sastry found that the electrojet current density and the variation of $H$ at ground (equator) were well correlated. This would imply that $H$ variations represent mainly an ionospheric electrojet effect. No definite evidence was available for any reversal of the current either during sun-set, sun-rise or night hours in the flights conducted so far by him. On the other hand, in one instance, appreciable currents continued to flow till late in the night in the same direction as the day time electrojet. This was unusual indeed.

At equator, the E region is characterised by a perpetual equatorial sporadic E ($E_{eq}$) during sunlit hours. However, no fine structure in the electrojet was ever observed by Sastry which could be attributed to sporadic E. In one flight where the electron temperature was simultaneously measured, the excess over corresponding ion temperature ($T_e - T_i$) showed good correlation with the current density $J$ indicating that joule heating occurred due to the strong flow of currents (Sampath et al., 1974).

One of the flights by Sastry was on 7 July 1966 at 1345 LT and happened to be preceded by a proton flare by about 7.5 hr. The day was still quiet ($Ap = 4$) and the flight showed the main electrojet layer extending from 90 to 118 km and a second layer between 130 and 150 km. In the period 1–7 July 1966 the solar activity showed a general increase and this was accompanied by an increase in the amplitude of the $H$ variation at ground. Sastry suggests, therefore, that changes in the solar EUV radiation may be responsible for the day-to-day variability of equatorial electrojet strength, specially through the formation and dissolution of the second (higher) current layer in the electrojet region. However, this cannot explain the day-to-day variability during quiet sun years (Kane, 1972a) when solar flares are rare.

Some of the magnetic variations observed by eight separate low altitude satellites during 1964–1971 have been described in the ‘Symposium on Low Level Satellite Surveys’ held at the second general scientific assembly of IUGG at Kyoto (Cain, 1973). The vector field experiment aboard TRIAD satellite revealed field-aligned currents as a permanent feature of the auroral-ionosphere-magnetosphere coupled system with the patterns showing diurnal and seasonal variations as also modifications with geomagnetic activity (Zmuda and Armstrong, 1974). As we shall see soon, these currents form an integral part of the storm time behaviour of the magnetosphere. Langel (1974) investigated the $\Delta B$ patterns in the polar regions as measured by OGO-2, 4, 6 satellites and found positive $\Delta B$ between 2200–1000 MLT and negative $\Delta B$ from 1000–2200 MLT with modifications related to the nature of the interplanetary field (away from or towards the Sun) and also connected with latitudinally narrow auroral electrojet currents. Cain and Sweeney (1973) showed from the POGO data that the
dayside passes indicated electrojet and counter-electrojet and to some extent even the weak Sq effects.

At much higher altitudes, the ATS satellites at about 6.6 $R_E$ indicated a daily range of about 30–40 $\gamma$ (Cummings et al., 1971) with a maximum at local noon and minimum near local midnight which would be explained in terms of magnetopause, tail and quiet-time ring currents. The effects of these on the ground could be about 10 $\gamma$.

6.8.2. Electric Field Measurements

Measurement of ionospheric electric fields through probes has always been a difficult task because of the very small magnitudes (few mV/metre) as compared to the much larger sheath effects which occur when the detectors enter a plasma. Fields can, however, be measured more accurately by release of barium clouds where the ion diffusion gives the electric fields. There are also indirect measurement techniques such as measuring drift velocities and studying particle pitch angle and energy spectra, the latter more useful in the magnetosphere.

Measurements by probes have been conducted copiously in the auroral regions and have yielded field magnitudes in a wide range 10–130 mV/m, though typical values are between 30 and 50 mV/m. However, in the equatorial region and middle latitudes, there have been very few measurements. Earlier results were not conclusive (Aggson et al., 1967). Recently a noon-time rocket measurement at Thumba (India) on 13 October 1972 indicated a vertical field increasing from zero at 90 km to about 25 mV/m at 120 km (Sartiel, 1972) and remaining stationary for higher altitudes up to about 130 km. This is very mysterious indeed as a magnetometer payload sent up by Sastry within 30 min of the above flight showed a maximum current of 10.5 A km$^{-2}$ near 108 km reducing rapidly to 2.0 A km$^{-2}$ at about 120 km.

The technique of barium vapour release involves optical observations when the vapour cloud is illuminated by solar rays in twilight conditions. Hence, observations are confined to twilight hours only. Rieger (1970) used the technique for equatorial regions also and obtained horizontal fields of about 0.45 to 2.6 mV/m$^{-1}$, westward in the morning (0530 LT) and eastward in the evening (1800 LT) and vertical fields of still higher magnitudes.

The drift measurement technique (Balsley and Woodman, 1971) involves the detection of motions of ionospheric irregularities by determining the mean Doppler shift of oblique VHF back-scatter radar signals received at ground. The technique is good for velocities in the range 50–360 m s$^{-1}$ and the east-west electric field $E_y$ equals $(5.9 \times 10^{-6} u_e V m^{-1})$ where $u_e$ = the electron drift velocity. Observed velocities did reach the 360 m s$^{-1}$ value indicating an electric field of about 2 mV m$^{-1}$, mostly east-west in the day and west-east in the night, the reversals occurring at about 0630 and 2030 LT. An increase in the magnitude of the field around dawn and dusk was also seen. A similar technique gives also the F-region vertical drifts. They reported a very good correlation between the vertical F-region drifts and the horizontal E-region drifts indicating an intimate dynamical connection between the two. In particular, they reported that during counter-electrojets, the horizontal E-region drifts and vertical
F-region drifts seem to be about zero. In contrast, the ionospheric drift measurements by the ground-based three receiver technique show a reversal of the normal E-region horizontal drifts (Rastogi et al., 1971). It seems, therefore, that the irregularities observed by these two techniques are not of the same type. Those observed by Balsley and Woodman are most probably cross-field instabilities which occur only when a vertically upward electric field occurs simultaneously with a positive electron density gradient ($N_e$ increasing with height).

Balsley and Woodman (1972) and Balsley (1973) presented several details such as seasonal changes of the drift velocities (and hence electric field) as also peculiar day and night effects (layered structure during night in contrast to a smooth field during day). They also reported that the vertical drift was essentially constant from about 120 km to more than 200 km altitude.

Using probe measurements at balloon heights, Mozer and Manka (1971) detected ionospheric horizontal electric fields as mapped at balloon altitudes. The technique is not yet tested in the equatorial regions.

Reiger (1970) measured the electric fields with the help of barium release for a large range of latitudes, from $+53^\circ$ to $-43^\circ$ (including equator) and concluded that there was strong evidence for dynamo-generated Sq fields at evening twilight at mid-latitudes, while for the equator he concluded that the current was from polarisation fields. It is realised, however, that a quantitative formulation of the complete process involving the F-region dynamics at equator and the regular Sq current system at middle latitudes is difficult, firstly because all the parameters (e.g. variation of electron and ion densities, temperatures and compositions with height and latitude) are not always available simultaneously and secondly, a complete three-dimensional formulation poses mathematical problems. In particular, the problem whether the whole process is purely electro-magnetic or whether neutral winds play any significant role, specially during odd events like the counter-electrojet, is still open. Effects of neutral winds on the ionisation distribution in the low latitude F-region and the Appleton anomaly have been recently studied (Rush, 1972; Rush and Richmond, 1973) analytically. It is hoped that more precise data from rocket measurements will help in resolving this problem. Some recent results from the Indian equatorial region may be of great interest. Muralikrishna (1975) reports from rocket measurements of the current density and electron density and from backscatter radar studies that the East-West field which is usually assumed to be constant with height in the electrojet region shows an upward gradient. Also, just before the start of the counter-electrojet, the field is stronger and at higher altitudes. Another interesting feature is the dissimilar evolution of the magnetic field component H and the backscatter signal strength S during the course of the day. From their study of VHF scatter in the American zone, Cohen and Bowles (1963) had earlier noticed that the scatter dominated in the day time, its source was located in the electrojet region and the intensity of the signal was imperceptible until a certain threshold of electrojet current was reached. The signal increased rapidly thereafter until about noon but then lingered along at a considerable strength even though the magnetic field decreased in the afternoon-hours. Thus,
a sort of \textit{hysteresis} effect was observed. Cohen and Bowles attributed this to additional changes due to non-ionospheric causes (magnetospheric ring currents) since the hysteresis seemed to disappear in some cases when $H$ (Huancayo) minus $H$ (Bogota) were used in place of $H$ (Huancayo). In Figure 30, are shown sample daily variation plots for two quiet days 9 January 1972 and 17 January 1973 (Muralikrishna, 1975) for the signal strength $S$ and the parameters $H$ (Trivandrum) and $H$ (Triv.) minus $H$ (Alibag). On 9 January 1972, $H_T$ and $(H_T - H_A)$ started increasing much earlier than $S$ while on 17 January 1973 all started almost simultaneously. Thus, no threshold seems to be involved. Also, even though Farley and Balsley (1973) mention that the signal strength from Type II irregularities is linearly proportional to $H$, it seems from the data for these two days that the ratio $S/H$ may vary from day to day and may be different in the morning and afternoon hours. Figure 31 shows a plot of $S$ vs $\Delta H_T$ and $\Delta(H_T - H_A)$ for morning hours (full circles) and afternoon hours (open circles) for 8 and 9 January 1972, both quiet days. Plots using $H_T$ only show the hysteresis 

Fig. 30. Daily variation of the radar back-scatter signal strength $S$ and the $H$ component at Trivandrum as also $H$ (Trivandrum) minus $H$ (Alibag) for (a) (Upper) 9 January 1972 and (b) (Lower) 17 January 1973 both quiet days (based on Muralikrishna, 1975).
loops. Using $\Delta (H_T - H_A)$, the loop disappears for 8 January but not for 9 January. A study for several such days revealed that the afternoon values of $S$ were generally larger. However, this could also be interpreted as an excess of $H$ values in the morning hours and Muralikrishna suggested that the morning $H$ values have a part contribution from sources above the electrojet region. Thus, multiple current sheets in the E and lower F region (and perhaps even above) are hinted. It was also pointed out that the ratio of the horizontal electric fields in the F-region to E-region exceeded unity throughout the 24 hr except for short intervals near the morning and evening reversal times and the ratio was larger during forenoon hours than afternoon hours.

For the E and F regions, the main solar component of electric field has been reported to be diurnal and the main lunar component semi-diurnal (Tarpley and Balsley, 1972). However, it would seem from the above and many other evidences that the patterns may have other harmonics of varying proportions specially on days of counter-electrojets. These must have been produced by abnormal wind patterns.
For the F region, the wind patterns are known to be basically diurnal. However, information regarding winds in the E region specially at equator is very inadequate indeed and needs further exploration.

For the polar region, the electric field patterns are known much more precisely, as shown in Figure 9, mainly because the magnitudes of fields are much higher there. Magnetospheric field patterns have also been copiously studied with satellite data and show basically a dawn-dusk field, greatly enhanced during storms. The quiet-day current systems are already mentioned earlier. The disturbed day patterns will be discussed later.

6.8.3. Ionospheric Irregularities

In the last few years, considerable information about ionospheric irregularities has been obtained, mainly with ionosondes, back-scatter radar, ionospheric drifts and rocket-borne probes. Detailed properties of phenomena like sporadic E and spread F are studied at all latitudes. The motions of the irregularities are directly connected with ionospheric currents specially in the equatorial region and hence have an immediate implication for geomagnetic field variations. Excellent reviews are available (e.g. Cohen, Book II, p. 561; Prakash et al., 1973) and we summarize here only the salient points and latest information. Several types of ionospheric irregularities are noticed as follows:

(a) **Large scale irregularities** of horizontal sizes of few tens of km and vertical sizes of a few km, mainly between 85-120 km altitude mostly during daytime with density varying by a factor of 25.

(b) **Cross-field instabilities** of scale sizes 1-300 m, above 85 km at all times of the day with fluctuations in density of about 2% for 1-15 m sizes and about 30% for larger sizes (the 3 m sizes termed as Type II) with a size spectral index of $-2$ to $-3$.

(c) **Two stream instabilities** of sizes 1-15 m near the peak of the electrojet (around 106 km) near noon hours with density changes of about 2% (3 m sizes termed as type I) with a spectral index zero.

(d) **Irregularities due to neutral turbulences** of sizes 1-300 usually in the lower D region (85 km) occurring occasionally during daytime with density changes of 2% for 1-15 m size and about 30% for larger sizes.

(e) **Other irregularities** of sizes 30-300 m at about 95 km with density changes of about 25%, observed during a counter-electrojet.

Because of their different properties, the presence or absence of these irregularities provides information about the environment where these are noticed. In particular, the cross-field irregularities (responsible for $E_{sq}$) occur only when the electron density gradient and the electric field are vertically upward. Earlier results from ground-based studies have been reported by Farley and Balsley (1973) and Cohen (1973) and rocket results by Prakash et al. (1971). Of particular interest would be the in situ measurements during a counter-electrojet. The only such successful attempt so far was made by Prakash et al. (1975) in the rocket flight No. CO 5.16 on 17 August 1972 (quiet day, Ap=6) at 1532 LT at Thumba (Indian equator). Figure 32 shows a comparison
of $N-h$ profiles obtained from rocket flights conducted at different times of the day on different days. The pattern during counter-electrojet (1532 LT) (dashed line) showed significant deviations from the usual day-time pattern (thick line). Figure 33 shows the actual plots of $H$ at Trivandrum, Alibag and the difference $(H_T - H_A)$. The rocket flight time is marked by the arrow at 1532 LT when the $H$ at Trivandrum had just touched the zero line (night level) while $(H_T - H_A)$ was far below the night level. Usually, in the region 90–100 km, the electron density gradient is upward and hence during daytime when the electric field $E$ is also upward, cross-field instabilities (Type II irregularities) are seen copiously in this region ($E_{sq}$ as seen on ionograms). On 17 August 1972, the gradient was upward right up to 94 km (point B on dashed curve in Figure 32) but no irregularities of Type II were noticed. Instead, an altogether different type of irregularities was noticed between 92–94 km (region AB in Figure 32). Thus,

Fig. 32. $N-h$ profiles from rocket flights conducted at Thumba on various dates at various local times. The dashed curve refers to a counter-electrojet period on 17 August 1972 at 1532 LT (based on Prakash et al., 1975).
Fig. 33. Plots of $H$ at Trivandrum and Alibag and the difference ($H_T - H_A$) on 17 August 1972. A rocket flight was conducted at 1532 LT (indicated by the arrow) during a possible counter-electrojet (based on Prakash et al., 1975).
the vertical Hall electric field in the region up to B was either non-existent or reverse (pointed downwards) during the counter-electrojet. In the region BC (94-97 km, Figure 32), the density gradient was temporarily reversed and some weak irregularities of Type II were noticed. Thus, in the whole region 85-95 km, the vertical electric field must have pointed downwards. In the region 95-106 km, no Type II irregularities were observed even though the gradient was upwards immediately above C. However, in the region 106-110 km, two stream instabilities (Type I) were noticed indicating very high drift speeds as are usually observed at the peak of the normal electrojet. Since the gradients are negligible in this region, no irregularities of Type II are expected here and hence no clue is available for the direction of the Hall field. If it was vertically downwards as in the lower region (85-105 km), it would result in a very large counter-electrojet giving negative $\Delta H$ at ground which was not observed. If the Hall field was upwards, one would get a normal electrojet effect from the 105-110 km region and to get a null $H$ at ground, one would need a strong negative current in the 85-95 km region and/or above 110 km. In situ magnetic field data or drift data from ground measurements were not available for this event. It seems that the counter-electrojet phenomenon is very complicated indeed and needs a much more thorough investigation.

7. Disturbed Day Geomagnetic Variations

The quiet-day patterns of geomagnetic field and its periodic variations are occasionally violently disturbed, producing what are known as geomagnetic storms. The anatomy of such storms and their relationship with extraordinary events on the Sun has been a matter of study for almost a century. The storm-time patterns show an amazing variety and their study would have perhaps remained in the same category as the proverbial elephant and the five blind men but for the tireless and persistent efforts of eminent visionaries like the late Prof. Sydney Chapman and his band of brilliant colleagues and students like Ferraro, Sugiura, Akasofu and several others. The subject matter has received detailed exposition in the earlier literature (Books I, II, III) and hence only the salient well-established features and recent developments will be discussed here.

7.1. Geomagnetic indices

Apart from the fine structure of a geomagnetic storm, an assessment of the general level of storm activity is made by formulating what are known as geomagnetic indices. The assessment is first made locally by several participating observatories and the results from all are combined to give international or planetary indices.

7.1.1. $C$ and $Ci$ Indices

Each observatory inspects its own daily records and assigns a daily character figure $C=0, 1, 2$. These are combined to give international daily character figure $Ci$ ranging from 0.0 to 2.0 in 21 steps of ascending degrees of disturbances.
7.1.2. K, Kp and Ap Indices

Each observatory compares its H, D, Z records for a given 3-hourly interval with the standard patterns for that time of the day, month and solar activity phase and chooses the maximum deviation to assign a number K which ranges from 0 for negligible deviations to 9 for a maximum deviation, the limit for which is different for different locations, being as low as 300-500 γ at low latitudes and about 2500 γ at high latitudes. The K values from 12 selected observatories in moderately high northern and southern latitudes up to dipole latitudes of about 63° are collected at Göttingen and the international Planetary Kp index for every 3-hourly UT interval is produced, ranging as 0o, 0+, 1−, 1o, 1+, 2−, ..., 9−, 9o in 28 steps. From the sum of Kp of eight consecutive 3-hourly UT intervals, the daily index \( \sum Kp \) is obtained. Also successive 3-hourly Kp can be represented for every day of a 27-day solar rotation period as a sequence of vertical bars of lengths proportional to Kp on what are known as Kp musical diagrams which are very useful for locating 27-day recurring events. The Kp index is not linearly proportional to the storm effect but has a semi-logarithmic relationship. To obtain a linear scale, Bartels gave a conversion table from Kp to ap, where the latter has a unit equivalent to 2 γ. From the 3-hourly ap values, the daily index Ap is obtained by summing eight consecutive values. Other indices called Cp and C9 are obtained from Ap from suitable conversion tables. Cp ranges from 0.0 to 2.5 and C9 ranges from 0 to 9. Cp is almost equal to Ci referred to earlier.

7.1.3. Kn, Ks and Km Indices

For obtaining Kp, the 12 observatories are mostly in the northern hemisphere (only Amberley is in the south). Mayaud (1968) introduced separate indices Kn and Ks for the northern and southern hemispheres and showed that their behaviour was not always similar, mainly because of seasonal variations in K. The mean of Kn and Ks would be Km. There are the corresponding A indices AN, AS and AM just as Ap corresponds to Kp.

7.1.4. Auroral Electrojet Indices AE, AL, AU

For obtaining Kp, only latitudes up to 63° are used. To give specific representation to the auroral region, Davis and Sugiura (1966) superposed H data from several auroral stations (at different longitudes) on the same UT scale. On quiet days, all would show roughly horizontal traces. On disturbed days, strong auroral electrojets develop and the traces deviate from the zero line differently at different longitudes (at the same UT). The deviations indicated by the upper envelopes are termed as AU and represent the effect due to an eastward electrojet. Those of the lower envelope are termed as AL and represent the westward electrojet. The separation (AU - AL) is the AE index for any given UT. Hourly as well as 2.5 min values for these are now available at the various WDC (World Data Centers).

7.1.5. Dst, DS, DR, DP

A typical geomagnetic storm is characterised by a sharp initial increase (SSC) fol-
followed by a sudden drop in H values of a few hundred gamma within a few hours, followed by a slow recovery. These features are different at different longitudes, indicating a UT component called storm-time variation \( Dst \) and a LT component called disturbance local-time inequality \( DS \). If data from several (at least three) midlatitude stations spaced roughly equally in longitude are first corrected for \( Sq \) effects and then averaged for the same UT, the LT effects would be cancelled and an estimate of \( Dst \) would be obtained. Since \( Dst \) decreases with latitude roughly as \( \cos \theta \), the H values are to be multiplied by \( \sec \theta \) before combining. Vestine et al. (1947) used this method first. Using data from Hermanus, San Juan, Honolulu, Kakioka and Tashkent, Sugiura and Poros (1971) have given hourly equatorial \( Dst \) values for 1957–1970 and in later publications for 1971 and 1972.

If the \( Dst \) is eliminated from the storm-time variations, the residuals would represent the LT dependent component \( DS \). No continuous series of \( DS \) indices are published. Individual workers have evaluated \( DS \) in different ways for specific storms. Separation has also been made of DR (ring current) and PC (polar cap) fields (Kamide and Fukushima, 1971) and plots of values for January 1971 are shown in Kamide and Fukushima (1973).

7.1.6. Time Variation of Geomagnetic Indices

The planetary indices \( Kp \) and \( Ap \) are known to show long-term and short-term variations (Virginia Lincoln, Book II, p. 84). Since the geomagnetic activity depends upon solar emissions, it is understandable that the two should show parallelism. Whereas a 11-year cycle was reported earlier (Book I), Cheronsky (1966) reported a 22-year cycle which was interpreted by Russell and McPherron (1973) as due to the heliographic latitude dependence of interplanetary magnetic field. Russell (1974) interpreted these as indicative of long-term changes in magnitude and sign of solar polar fields. Gnevyshev and OI (1966) reported a two-humped sunspot cycle variation, the two humps occurring within a year or two on either side of the main hump of sunspot numbers and similar to the two-humped solar cycle variation of coronal \( \lambda \) 5303. The connection is most probably through the solar wind velocity which seems to be related to both coronal emission and \( Kp \) (Snyder et al., 1963; Krieger et al., 1973); but the solar wind velocity does not show any clear solar cycle variation while the plasma number density shows a reduction with higher solar activity (Diadato, 1974).

Stolov and Cameron (1964) and Bell and Defouw (1966) reported a lunar effect where \( Kp \) was low before full moon and high after full moon and attributed it to the disturbance of the neutral sheet by the moon.

The planetary indices also show annual, semi-annual and diurnal variations. From his study of \( a_\alpha \) and \( a_\varphi \) in the two hemispheres, Mayaud (1970) reported besides annual and semi-annual effects, a UT component and two UT pseudo-components which could be explained partly on the basis of the McIntosh (1959) effect which relates to the varying inclination of the dipole axis with the Earth-Sun line both during the course of a day as also from season to season. Recently, Russell and McPherron (1973) offered another explanation for the semi-annual effect of \( Ap \) in terms of
changes in the $B_z$ component of the interplanetary field mainly because $B_z$ is ordered in the solar equatorial coordinates while the geomagnetic effects would be ordered by the solar magnetospheric coordinates and the two have a semi-annual motion with respect to each other. Murayama (1974) suggested that besides the Russell-McPherron mechanism, there was an additional effect due to the heliographic latitude dependence of some of the solar wind parameters controlling polar storms. However, as pointed out by Mayaud (1974), the diurnal variation of $K_m$ still remained unexplained and the McIntosh effect was still a plausible explanation.

A 27-day recurrence tendency in $K_p$ and its relation to solar cycle was reported by Shapley (1947). Using power spectrum analysis for $A_p$ values, Fraser-Smith (1973) obtained besides the annual wave two distinct peaks at 27.2 and 27.6 days which he attributed to a possible 27.37 day wave modulated by solar activity. Abdel Wahab and Gonad (1974) also reported 27 and 13.5 day periods showing solar cycle modulations. Possible relations with the interplanetary sector structure have also been studied. Siebert (1968) reported that the ratio $K_n/K_s$ was higher when the interplanetary field component $B_x$ pointed away from the Sun. Burch (1973) showed that the auroral indices $A_U$ and $A_L$ had a seasonal effect as also a sector structure effect and concluded that whereas for $A_U$ the solar radiation (affecting the ionospheric conductivity) was important, for $A_L$ the particle precipitation was more important. Wilcox and Colburn (1972) reported that in the days before a sector boundary crossed the earth, the $K_p$ index had a monotonic decline to a minimum about one day before the boundary. Hirshberg and Colburn (1973) reported significant step-like changes at the sector boundary for the $A_E$ index as also for southward $B_z$ and Shapiro (1974) showed similar changes for $K_p$ while Fougere (1974) showed differences in the behaviour of $(+ \rightarrow -)$ and $(- \rightarrow +)$ boundaries. Recently, Kane (1975b) examined the behaviour of $K_p$, $A_E$, solar wind parameters and geomagnetic $D_{st}$ vis-à-vis the well established sector boundaries and found that the above-mentioned patterns, though true on the average and in a small way, showed very divergent behaviours for the various boundaries, occasionally showing no variations or patterns opposite to those mentioned above. Thus, not all sector boundaries are connected with geomagnetic storm activity. Gulbrandsen (1973) has reported that coronal $\lambda 5303$ has some relation with the sector structure. It is likely that only those sector boundaries which have a relation with $\lambda 5303$ affect geomagnetic activity. A good correlation between coronal holes and recurring geomagnetic storms seems to be well established (Gulbrandsen, 1973; Krieger et al., 1973; Neupert and Pizzo, 1974). The sector structure itself seems to have a semi-annual and solar cycle variation (Sawyer, 1974).

During geomagnetic storms, $K_p$ would naturally be high. Bobrov (1973) studied the behaviour of $K_p$ during recurrent storms and found that in the first stage when $B$ was high, $K_p$ correlated well with $B$, $B_z$ and $\sigma_B$ while in the second stage when $B$ weakened, $K_p$ correlated well mainly with $\sigma_B$ and weakly with $B_z$.

7.2. SOLAR STORM AS A SOURCE OF GEOMAGNETIC STORM

There is enough evidence to conclude that the geomagnetic storm is caused by inter-
planetary shocks or stream interfaces which in turn are caused by occurrences on the Sun. The geomagnetic storm is in short a sequence of varying magnetospheric response to the varying conditions in interplanetary space which are caused by a variety of emissions from the Sun. The magnetospheric response (or the magnetospheric storm) has generally four major phases viz. (i) Storm Sudden Commencement (SSC), (ii) Initial Phase, (iii) Main Phase and (iv) Recovery. Different components of the solar emissions viz. solar radiations, energetic particles and slow and fast plasma have different effects on the interplanetary space and/or the Earth’s environment (ionosphere, plasmasphere and magnetosphere) and have different implications for the various storm phases as discussed below.

7.2.1. Solar Radiations
During solar flares, solar radiations of a wide variety (X-rays, EUV, Hz, white light and radio emissions) are emitted. The X-rays and EUV give the solar flare effects (sfe) within a few minutes of the flare and affect the ionospheric D and E regions to give geomagnetic ‘crochets’. The geomagnetic storms occur (if at all) several hours later and hence the crochets, apart from their use for studying the transient ionospheric current systems, serve as a vanguard for the geomagnetic storm and as a warning signal and alert to the ground observers to prepare for special observations (rocket or balloon flights etc.).

7.2.2. Energetic Protons and Electrons
A few solar flares produce very energetic protons (1 to 15 GeV) and are termed as proton flares. These protons produce no geomagnetic effects but give a lot of information about the interplanetary field structure and its irregularities. In fact, an asymptotic direction of arrival preferentially along a line about 55° to the west of the Earth-Sun line was perhaps the first clue to the Archimedes spiral structure of interplanetary field lines.

Of geomagnetic interest is the solar flare particle flux in the energy range of a 100 keV to a few MeV which serves as a useful probe for tracing of high latitude field lines. As shown in a recent review (Paulikas, 1974), these particles cannot reach the Earth at low or middle latitudes due to the geomagnetic cut-off but may enter through the flanks of the magnetosphere and nearby neutral sheet from as near as 30 $R_E$. A large fraction of the auroral particles seem to originate on field lines connected with interplanetary space indicating an open magnetospheric configuration.

On entering deep into the polar atmosphere, these particles produce high ionisation causing the well-known polar cap absorption (PCA) events.

7.2.3. Low Energy Plasma
The low energy (about a keV) plasma cloud from the flare causes shock or blast waves in the interplanetary space. As soon as the Earth encounters the shock front, a geomagnetic sudden commencement is signalled. In fact, this is the first, proper beginning of a magnetospheric storm. Soon, the Earth is engulfed into the post-shock wind adn
this is most probably the initial phase of the geomagnetic storm which may last from a few minutes to several hours. Later follows the impact of the shock-driving plasma which is turbulent and may cause frequent changes of the interplanetary $B_z$ component direction from north to south. At every such southward excursion, the field merging envisaged in the Dungey (1961) model occurs and a magnetospheric substorm is produced. The total storm may be a succession of such explosive processes.

7.2.4. Large-scale Magnetic Field Distribution

Whereas every solar flare produces an interplanetary shock wave, every shock wave need not be connected with a flare. In fact, many shock waves are created at the interfaces of a high speed solar stream encountering a slow speed solar stream (Gosling et al., 1974). When the Earth encounters such interfaces a storm can be produced. Many of the storms showing 27-day recurrence tendency are of this category. The initial and main phases may follow the same patterns as in the case of solar-flare initiated shock waves, provided the southward $B_z$ component is substantial which will happen if these M streams are turbulent.

7.3. Transfer of Energy from the Solar Wind to the Magnetosphere

Even the average solar wind has a kinetic energy flux of about $5 \times 10^{-4}$ W m$^{-2}$ which impinges constantly upon the geomagnetic dipole and is large enough to sustain even the largest known geomagnetic disturbances continuously. However, what actually happens is that the flux is largely diverted to the back side causing in the process the geomagnetic cavity called magnetosphere. Due to the partly open nature of the magnetosphere, quiet-time convection patterns are established in the magnetosphere. However, these are much more complicated than the solar wind which drives them mainly because of the strong magnetospheric magnetic field gradients, wave-particle interactions, field-aligned electric fields (causing field-aligned currents), particle shielding phenomena, dissipation in the ionospheric regions below 300 km due to collisions and so on. Nevertheless, the quiet day magnetic field and electric field patterns in polar regions do show a strong dependence upon the direction of the interplanetary magnetic field component $B_y$ and sometimes even $B_x$. Thus, even though the viscous interaction of solar wind (irrespective of its magnetic state) with the magnetosphere causing tangential stresses on the magnetopause and causing magnetospheric convection (Axford and Hines, 1961) is always a plausible process, the Dungey (1961) reconnection model evolved mainly for a southward $B_z$ component is likely to be valid for the $B_x$ and $B_y$ components too. However, the real catastrophic changes seem to occur only when the interplanetary $B_z$ component turns southward and merges with the geomagnetic field on the day side. The field lines are convected rapidly to the magnetotail resulting in (a) an inward motion of the magnetopause, (b) an equatorward motion of the dayside aurora by a few degrees, and (c) an increase of magnetic field in the lobes of the magnetotail.

In the tail, the field lines reconnect across the neutral sheet and the magnetospheric plasma can convect back towards the day side. However, the tail reconnection is an
impulsive process connected with macroscopic tail instabilities. Also, the convective flow is choked by magnetic field gradients and ionospheric dissipation. As a result, a considerable amount of magnetic energy is built up in the lobes of the magnetotail. The spasmodic dissipation of this energy in the various regions of the magnetosphere and ionosphere gives the variety of phenomena known as storms.

7.3.1. Phenomenological Model

The phenomenon of magnetospheric substorms is quite complicated and some aspects are still controversial. The topic is discussed in many recent publications (Book III, McPherron et al., 1973; Russell and McPherron, 1973; Burch, 1974) and a few models have been proposed (Coroniti and Kennel, 1973; Kan and Akasofu, 1974; Heikkila, 1974; Schindler, 1974). The basic processes and their sequences may be summarised as follows:

1. **Growth phase**: As soon as the interplanetary discontinuity carrying southward $B_z$ encounters the subsolar magnetopause, the interplanetary and geomagnetic field lines merge and the growth phase begins. The field lines get convected to the magnetotail increasing the field in the lobes. The $S_0$ which was small at quiet-times shows considerable enhancements and electric field and magnetic perturbations appear in the polar cap. In the auroral zone, weak magnetic bays and westward electric fields start appearing and weak electron precipitation begins. At synchronous altitudes ($6.6 \, R_E$)

![Diagram illustrating the major changes in magnetic field configuration during substorm growth phase.](image)

Fig. 34. Schematic diagram illustrating the major changes in magnetic field configuration that occur during the substorm growth phase. Erosion on the dayside moves the magnetopause earthward, reducing the front side cross-section and moving the feet of the polar cusp field lines equatorward. Flux eroded from the dayside is convected to the tail, increasing the field magnitude in the near-earth region, because of the increased flux in a smaller cross section. Electric fields resulting from convection cause the plasma sheet to thin and the inner edge of the tail current to move earthward, projecting as an equatorward motion of nightside auroral arcs. (McPherron et al., 1973.)
the field decreases in the pre-midnight sector and a similar effect is noticed on the ground at midlatitudes. In the near tail region, the plasma sheet starts thinning and plasma moves earthward. Figure 34 shows a schematic of the various processes. Figure 35 shows details of the thinning of the plasma sheet in about $\frac{1}{2}$ to 1 hr, before the expansion phase.

\textbf{GROWTH PHASE}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{growth_phase.png}
\caption{Three stages of the substorm growth phase in the near tail region, the lowermost signalling the beginning of expansion phase (McPherron et al., 1973).}
\end{figure}

\begin{enumerate}
\item \textit{Expansion phase:} This phase begins when the near-Earth plasma sheet reaches almost zero thickness (Figure 35 bottom). An intense negative bay appears in the midnight sector in the auroral zone indicating an overhead \textit{westward} electrojet which expands northwards and westward with intense electron precipitation. A positive (magnetic) bay appears in low latitudes at midnight (Ijima and Nagata, 1972). In the evening sector auroral zone, an \textit{eastward} electrojet may appear which slowly shifts equatorward. The plasma sheet expands rapidly and large amplitude magnetic fluctuations and energetic particles appear in the plasma sheet.

\item \textit{Recovery phase:} After about half an hour the westward auroral electrojet starts decaying and the magnetosphere returns to its quiet time configuration. With a slight timelag, the eastward electrojet also follows the same pattern.
\end{enumerate}

In the above and all similar models, a coupling between the ionosphere and magnetosphere is envisaged and leads to field-aligned currents, and particle acceleration (Bostrom, 1964; Atkinson, 1967; Bonnevier et al., 1970). Such currents are also envisaged in the models for partial ring currents. Figure 36 (a), (b) show the models proposed by Akasofu and Meng (1969) and McPherron \textit{et al.} (1973). In these, field-
aligned currents from the magnetosphere towards the ionosphere in the dawn sector and from the ionosphere to the magnetosphere in the dusk sector are envisaged. Recently, Rostoker (1974) has suggested a different model in which the current flows only one way, from the auroral ionosphere to the equatorial magnetosphere and mixes with the main stream of the dawn-dusk tail current (Figure 37a). The point in the ionosphere is the Harang discontinuity where the auroral westward and eastward electrojet meet and its position shifts with the evolution of the substorm. Sugiura (1974) has proposed another model (Figure 37b) which is different in that whereas a
Fig. 37(a). Field-aligned current models. Changes in the magnetospheric current flow associated with a substorm expansion phase intensification. The current flow in the magnetospheric equatorial plane is not necessarily along a constant L shell and probably tends to flow at higher L values as one progresses into the evening sector from midnight (Rostoker, 1974).

Fig. 37(b). Field-aligned current systems $C_{fa}^{-1}$ and $C_{fa}^{-2}$ where $C_{fa}^{-1}$ flows in the polar cap boundary which coincides with the high latitude boundary of the plasma sheet and $C_{fa}^{-2}$ flows in the low latitude side of the auroral belt (Sugiura, 1974).
single auroral belt is taken as the ionospheric base in all the other models, Sugiura envisages two circuits that have ionospheric bases at two different latitudes.

The onset of the expansion phase is also associated with positive bays (increases in $H$) in the equatorial midnight region on the surface of the Earth, and sometimes later with negative bays (decreases in $H$) in the equatorial dusk-midnight sector.

Another important process associated with the substorm is the injection of plasma from the magnetotail to the trapping region from the midnight sector. The electrons enhance the population of the outer Van Allen (radiation) belt while the protons enhance the quiet-time proton belt and lead to the ring currents responsible for the equatorial storm effects. A comprehensive diagram summarising the various effects of a substorm is given by Akasofu and Chapman (Book III, p. 613) and is reproduced in Figure 38.

![Diagram of Magnetospheric Substorm](image)

**Fig. 38. Effects of a magnetospheric substorm.**

7.3.2. Morphology of Storms

The various processes described above give distinct patterns of geomagnetic storm variations, which are different at different latitudes and longitudes, the longitudinal
variation occurring mainly because of the day-night asymmetry of the magnetosphere. The storm can be divided into distinct phases, viz. sudden commencement, initial phase, main phase and recovery. Almost all of these show differences of behaviour during day and night. The storm starts when the interplanetary shock-front encounters the magnetopause giving the first phase of sudden commencement. Figure 39 illustrates the storm-time behaviour for the period 28 October to 13 November 1968 characterised by a fascinating variety of a succession of events (Kane, 1974c).

7.3.2.1. *Sudden commencements and sudden impulses.* The first impact of an interplanetary irregularity is to cause a sudden change in the geomagnetic components,
called storm sudden commencement (ssc) or sudden impulse (si). There is no basic
difference between the two except that impulses which are followed by a storm are
termed as ssc. In Figure 39, the full triangles at the top indicate occurrences of ssc and
open triangles indicate si. Since a major storm developed in this case, it is obvious
that all the si's could have been termed as ssc's.

The ssc is usually a positive change. Sometimes, it is preceded and/or followed by a
sharp negative impulse (ssc*). The si also can be positive or negative. The negative
impulses are more frequent at high latitudes.

From satellite studies it has been possible to correlate occurrences of ssc and si in
space and on Earth and the following facts seem to be well established (Book III,
p. 582 for early references).

1) The ssc's and si are caused by hydromagnetic shock waves and discontinuities
in the solar wind. Chao and Lepping (1974) examined 93 events and found that 81
were flare associated.

2) The events occur about a few to several minutes earlier in higher latitudes.
Patel (1972) studied correlated events on Earth, in the tail and in the magnetosheath
and estimated propagation velocities of 550–1200 km s⁻¹. Also, some si seemed to
originate in the perturbations of the tail and magnetosheath field rather than in the
solar wind.

3) The ssc change is not instantaneous. The H value may attain a maximum in a
few to several minutes. The rise is quicker at noon (about 2 min) than at midnight
(about 5 min). The rise-time seems to be negatively correlated with ssc amplitudes
at middle latitudes (Pisharoty and Srivastava, 1962; Srivastava and Abbas, 1973) but
poorly correlated at the equator (Natarajan, 1969).

4) The magnitudes are larger in the equatorial electrojet region, indicating some
ionospheric contribution too (Sugiura, 1953).

5) Some positive-negative impulse pairs have a 27-day recurrence tendency
(Razdan et al., 1965) indicating association with recurring streams (M regions).

6) ssc* events are observed both during day and night hours at high latitudes, only
during daytime in the electrojet region and very rarely at middle latitudes (Rastogi

7) Strong ssc and positive si are associated with electron precipitation in the
auroral zone while some negative si seem to inhibit this precipitation (Brown, 1974).

8) Some ssc and positive si seem to trigger negative bays in the mid-night sector
of the auroral zone (Burch, 1972; Brown and Driatsky, 1973) specially when inter-
planetary Bz is already southward when impact occurs.

Whereas it is accepted that the impact of the interplanetary irregularity on the
magnetopause causes hydromagnetic waves which travel through the magnetosphere
towards the Earth as also into the tail and their isotropic modes give the ssc and si,
some aspects are not well understood. Thus, the amplitudes are proportional to the
pressure jump across the interplanetary shock but the constant of proportionality is
wrong by a factor of 2. Recently, Kane (1974a) found that the constant varied widely
from event to event indicating that much more than an ordinary pressure balance was
involved. The rise-times of one to several minutes are explained as due to arrivals from different points on the boundary but the validity of the necessary ray-path theory in the magnetospheric plasma is doubtful. For the enhancement in the equatorial electrojet region Jacobs and Watanabe (1963) proposed that the electric field associated with the isotropic hydromagnetic wave causes a downward drift of the ionisation in the upper ionosphere, thus increasing the ionospheric E region electron densities and hence the electrojet strength. However, Schutz (1974) measured the electric field in the ionospheric E region during an $si$ event and noticed an increase in the electric field. Thus, it is not clear whether the $si$ is due to an increase in the electron density or electric field or both. It would be interesting to see what happens to the $si$ if it occurs during a counter-electrojet when the ionospheric electric field is expected to be reverse. Would the $si$ at the equator be negative when that at low latitudes is positive? Occurrence of $ssc^*$ at the dip equator (negative impulse) is also not yet understood. Another baffling feature is the occurrence of $ssc$ sometimes after the main phase has started (Akasofu and Yoshida, 1965) indicating that the compression field causing $ssc$ may operate independently of the ring current field causing the main phase.

For the $sse^*$ at high latitudes (also called primary reverse impulse PRI) equivalent current systems in the polar ionosphere have been computed and have the form of two ovals. Explanations for these are sought in terms of mixed transverse hydromagnetic waves, dynamo action in the polar ionosphere and twist transverse waves, with some success. Some of the negative $si$'s seem to be directly related to the density reductions across some interplanetary tangential discontinuities. Also, some $si$ (positive as well as negative) seem to occur all over the world simultaneously and these and many other similar short term world wide changes (Nishida and Jacobs, 1962) seem to be correlated with similar changes in the field strength everywhere within the magnetosphere and are due to inward and outward motions of the magnetopause (Nishida and Cahill, 1964).

During storms, micropulsation activity is enhanced (Campbell, 1966). Recently, Degaonkar and Dhanju (1974) observed prominent peaks in the range 60–300 s, immediately after an $ssc$ in the low latitude region.

7.3.2.2. Initial phase. At the initial impact, the $H$ values at low and middle latitudes show a rise in a few minutes which may be of several tens of gamma. The rise may persist for anything from a few minutes to several hours before it drops back to the pre-impact level. This interval is termed as the initial phase. After encountering the shock front, the Earth would now be sampling the plasma immediately behind the front. In low and middle latitudes this may be regarded as a new steady state though such a picture may not be completely valid (Kane, 1974a). However, in the polar regions specially in the sunlit noon sector, this phase is characterised by a considerable activity. It is known that the quiet-time polar $S_q^p$ which is due to the convection of magnetospheric plasma in the polar regions as shown earlier in Figure 9, enhances considerably during storms. However, this enhancement is generally associated with
7.3.2.3. **Main phase.** The most spectacular part of a geomagnetic storm is the main phase. In low latitudes, the $H$ value which had increased during the ssc, drops back to the initial level and then dips down far below it by several hundred gamma in a few hours. The depression has two components. One is the isotropic component Dst which is common to all longitudes and the other is the DS component which is LT dependent. If data from stations at roughly similar latitudes and equally spaced longitudes are combined for the same UT, the LT effects would cancel. The Dst so obtained (Sugiura and Poros, 1971) is shown in Figure 39. It shows a large negative swing exceeding 200 $\gamma$ on 31 October. Normally the negative values recover smoothly to the original level. However, this was a particularly complicated storm in which a second and larger swing occurred on 1 November and a minor one on 2 November after which the intensity recovered by 6 November. The auroral electrojet index AE is shown below Dst and shows a succession of increases from 28 October to 4 November, particularly large on 31 October and 1 and 2 November. It is now believed that the injection of energy into the ring currents which are responsible for the Dst change is spasmodic. Davis and Parthasarathy (1967) introduced a measure for the energy input in the form of a rate of change of Dst with due compensation for the natural decay of the ring current. The energy input EDst so obtained is shown in Figure 39 as black patches on the positive side of the zero line of the Dst scale. The EDst and AE are expected to show good correlation indicating that simultaneously when the magnetospheric tail is unloading energy in the polar and auroral regions, some energy is being pumped into the ring current belts in the form of high energy protons. The correlation between EDst and AE is not perfect (Davis, 1969), the former being more narrow-peaked. This could mean that the ring current injection is more selective and stringent. Also, the AE index may not be fully satisfactory as the present network of stations in the auroral region does not cover all longitudes properly. Nevertheless, it is usually found that large Dst changes exceeding 100 $\gamma$ occur only when the AE index exceeds 1000 very frequently, while AE values of 500 $\gamma$ or less (no matter how frequent) produce Dst changes of only 50–70 $\gamma$.

It is usually noticed that the growth and decay of the AE index follow variations of the interplanetary $B_z$ component with an average time delay of about 40 min (Arnoldy, 1971; Meng et al., 1973). However, considerable variations in this delay interval may occur from event to event, depending upon the favourability of actual magnetospheric configurations (Burch, 1972). The variance of the interplanetary field also seems to play an important role (Garrett, 1974), though only when $B_z$ is southwards. The effect of southward $B_z$ on Dst is not so straightforward as that on AE. (Kane, 1974a;
Russell et al., 1974). Whereas Russell et al. indicated a threshold for southward $B_z$ as the only necessary element in the growth of the main phase, Kane indicates that this may not be sufficient.

If from the actually observed $H$ variation at any location, the average $Sq$ as well as storm-time $Dst$ are removed, the residue would represent $DS$. For a given UT, the $DS$ at different longitudes would correspond to different LT. Combining data from several stations, the evolution of $DS$ at various LT can be obtained separately. In Figure 39, $DS(0),...,DS(21)$ represent $DS$ at LT sectors centred at 00, 03, ..., 21 LT. Thus, $DS(18)$ would represent evolution of $DS$ in the dusk sector and $DS(6)$ in the dawn sector. From a study of several storms, Sugiura and Chapman (1960) obtained the average characteristics (called $SD$) of $DS$ for weak, moderate and great storms for the first, second and third day of the storms as shown in Figure 40. For the low latitudes,

![Diagram](image)

Fig. 40. $Sq$ and $SD$ in the horizontal force $H$ (not the geomagnetic north component $Hgm$). The first panel illustrates $Sq$; the following three sets (of three panels each) refer to the three intensity sets, in the order weak, moderate and great; each set gives $SD^n$ ($n=1, 2, 3$) for the first three storm days. The force scale is uniform except where otherwise indicated by a number (the scale contraction factor) enclosed in a circle. The abscissae for $Sq$ refer to standard local time; those for $SD$ refer to gm local time (Sugiura and Chapman, 1960).

$DS$ has a sinusoidal variation with a maximum in the morning (dawn sector) and a minimum in the evening (dusk sector). Accordingly, in our notation, $DS(6)$ should show large positive values and $DS(18)$ large negative values during the storm. Similar results were reported by Kane (1971d) who studied $SD$ for $Ap$ ranges 8–15, 16–26, 27–45 and exceeding 45, using the group $Ap=0$–7 as quiet period. However, Bhargava
and Yacob (1971) using $Ap=0$ as the quiet period, found that $Ap=5$, 10 etc. showed only larger and larger decreases in the dusk and no increases in the dawn sector. Kane (1972b) showed that whereas the dusk decrease seems to be mainly magnetospheric, the dawn increase may have a partly ionospheric origin. In Kane (1973g), it was shown that whereas in general the pattern of a dawn increase and a dusk decrease was observed, DS at other LT (besides morning and evening) showed considerable fluctuations during the different phases of a storm. In Kane (1974a), a part of which is depicted in Figure 39, one can observe large fluctuations (mostly decreases) in DS(0) and DS(12), i.e., DS at midnight and noon during 31 October to 2 November. The DS is usually explained as due to an asymmetry in the ring current belt due to the dawn-dusk electric field which develops during storms. The fluctuations of DS at other LT besides 06 and 18 LT may be possibly due to distortions of the dawn-dusk electric field and the associated plasma flow in the trapping region. Crooker and Siscoe (1971) studied the evolution of the amplitude and phase of DS during storms and demonstrated that these do not correlate well with auroral indices. It seems almost certain that a major part of the DS variation is due to asymmetries in the ring currents in the magnetosphere due to partial ring currents for which Kamide and Fukushima (1971) have evolved DR indices. Campbell (1973a) indicated a possibility of estimating the nightside magnetospheric currents from a study of the H, D, Z variations near the midnight hours at different latitudes.

The auroral manifestations of a storm are equally fascinating (details given in Book III). The variety of displays of visual aurora have to be seen to be believed. Within an hour of the interplanetary field turning south (start of growth phase) the plasma sheet in the magnetotail moves earthward and the equatorward edge of the auroral oval suddenly brightens. This is stage 1 of the expansive phase of an auroral substorm. In stage 2, there is a poleward motion of the region of distorted auroral forms. In stage 3 westward travelling surges develop. Then starts the recovery phase in which in stage 1, weak loops and folds near the northern border of the auroral oval appear. In stage 2, the auroral forms shift equatorward and in stage 3 the auroral arcs return to the presubstorm configuration. The changes in ground magnetometer records (Kisabeth and Rostoker, 1974) show very intense negative bays in the midnight sector and indicate that during the expansive phase there must have developed an overhead westward electrojet which increases in width northwards (polewards) in a steplike fashion in stage 1 and maintains its strength for a while with variations in the northern border in stage 2. Weak positive bays in the evening sector are also seen. In stage 3 the northern border moves equatorward and subsequently the southern border decays. The auroral displays are due to particle precipitation from the magnetospheric region and are associated with field aligned currents coupling the magnetospheric current system with the polar ionosphere. These currents form a small diversion of the normal dawn-dusk magnetotail current flowing in the neutral sheet, and their circuit in the ionosphere is the cause of the electrojet as illustrated in the models in Figures 36 and 37 which is responsible for the polar magnetic substorm. Figure 41 (a) and (b) show typical records of storm-time negative and positive bays in polar and auroral regions.
as also the associated changes at midlatitudes. Generally, a negative bay in the polar region (caused by the westward electrojet in the midnight and early morning sector) is associated with a positive bay in the low latitude midnight while a positive bay in the polar region (caused by the eastward electrojet in the afternoon-evening sector) is associated with a negative bay in the low latitudes. Even though the auroral negative and positive bays may appear simultaneously during a substorm, the growth and decay of the two is not simultaneous. The maximum development of the positive bay occurs during the recovery stage of the negative bay (Kamide and Fukushima, 1972).

Besides the polar bays and midlatitude Dst and DS patterns, there are some dis-
turbulence variations which seem to be similar on a world-wide scale. Figure 42 shows an example of such changes on 14 August 1965 occurring at high and low latitude stations. Nishida (1971) termed these as DP2 magnetic variations to distinguish these from other disturbances (DP1) localised in the polar regions and caused by auroral electrojets. The DP2 variations are very closely related to the southward turning of the interplanetary $B_z$ and are short-lived (about an hour). Because of their effects in high and low latitudes simultaneously, the equivalent overhead current system is supposed to be different from that for the auroral electrojet system (DP1). During the initial and main phase, large oscillations of periods of $\frac{1}{2}$ to 1 hr are often observed. It is not clear whether all these are Nishida's DP2 variation. Perhaps those during the main phase are DP2 while those in the initial phase (when $B_z$ is not yet southward) are of a different type. Dessler and Parker (1959) attributed these to hydromagnetic waves due to instabilities at the magnetopause, due to the storm-time compression of its subsolar region (from about 10 $R_E$ to 7–8 $R_E$) and its oscillating back and forth or due to irregularities in the solar wind post-shock-front plasma. Pai and Sarabhai (1964) used the latter concept and estimated that the scale size of the irregularities was about 0.02 AU. However, these oscillations must have a partly ionospheric
origin as Bhargava and Sastry (1969) reported that their amplitudes were significantly larger in the equatorial electrojet region.

The auroral electrojets are ionospheric phenomena developing essentially during stormy periods and produce intense joule heating and associated neutral winds which spread equatorward and may be the main cause of storm time variations of the low

![Typical Train of DP2 Fluctuations](image)

Fig. 42. The DP2 magnetic variations at Alert, Kiruna, Tixie Bay, College, S. Fernando, Fredericksburg, Fuquene and Huancayo, together with the corresponding interplanetary magnetic variations (Nishida, 1971). Dashed curves are quiet day patterns.
latitude ionosphere. The equatorial electrojet is, however, a permanent feature even during quiet days. Does it get modified during storms? Osborne (1963) and Kane (1971d) reported that $H$ values in the equatorial region sometimes showed day-time depressions (electrojet weakening) during storms. Onwumechilli et al. (1973) showed that on moderately disturbed days, the polar $S_p$ was enhanced and the equatorial electrojet showed abnormal variations. A major difficulty in studying the equatorial electrojet on stormy days is that the $H$ pattern is largely distorted due to the magnetospheric Dst and DS and it is sometimes impossible to discern the exclusively ionospheric electrojet effect. This difficulty is largely removed by using the parameter $S_d$ already discussed which is obtained by subtracting the $H$ values at a low latitude non-electrojet station from the $H$ values at the electrojet station in the same longitude. Some suitable pairs are Huancayo and Fuquene, Trivandrum and Alibag, Davao and Baguio. In Figure 39, the $S_d$ so obtained are expressed as deviations from the mid-

![Diagram showing the behavior of the equatorial electrojet strength $S_d$ during selected disturbed days (Ap exceeding 20) (Kane, 1973f).](image)

Fig. 43. Examples of the odd behaviour of the equatorial electrojet strength $S_d$ during selected disturbed days (Ap exceeding 20) (Kane, 1973f).
night values and plotted at the bottom. At all longitudes, the Sd1 patterns were greatly
distorted on 31 October, 1 November, and 2 November when the Dst storm was most
intense. In Figure 43 the diurnal behaviour of Sd1 for selected stormy days in 1964
obtained from the pair Trivandrum-Alibag and in 1958 from the pair Huancayo-
Fuquene are depicted (Kane, 1973f). Violent changes at noon as also at the daytime
hours are noticed indicating considerable reductions of the electrojet strength.
Whether these are due to return paths of storm-time polar currents or due to a super-
position of the magnetospheric dawn-dusk electric field on the normal Sq system is a
matter for further investigation.

During storms, the plasmasphere is also affected. The plasmapause is considered
as the boundary of two regions, the inner region (plasmasphere) where the magnetic
flux tubes corotate with the earth and the outer region dominated by convection.
Since convection gets intensified during storms, the corotating region shrinks and the
plasmapause shifts towards the Earth. Also, some plasma is peeled off from the
plasmasphere and detached cold plasma clouds are formed immediately outside the
plasmapause near the dusk sector and somewhat farther away in the afternoon sector
(Chappell, 1974).

7.3.2.4. Recovery phase. After the main phase drop at midlatitudes, the H values
gradually recover to the pre-storm level in a few tens of hours unless a fresh storm
intervenes as happened in the case illustrated in Figure 39 where the final recovery
started only on 3 November and might have been completed by 7 November but for
minor storms on 6 and 8 November which kept the H level slightly depressed almost
up to 13 November. Surprisingly, the DS effects which are very strong during the
main phase, seem to linger on into the recovery phase, more so for the noon-time
DS(12) component. This is true for many other simpler storms described in Kane
(1974c). The recovery profiles of several storms during 1947–59 were studied in detail
by Kane (1963) who noticed an amazing variety of profiles. Besides the usual pattern
of an initially fast recovery followed by a slower recovery, the recovery was initially
slow and later faster on several occasions. Sometimes much more complicated patterns
were noticed. All these are most probably connected with a varying input energy,
varying radii of the ring currents and the variations in the decay processes during the
course of the peak of the main phase and the subsequent recovery.

7.3.3. Equivalent Current Systems

The various morphological features described above can be represented by overhead
current systems. Birkeland (1913) suggested that the currents responsible for the
auroral electrojet are located well beyond the Earth. Since there is considerable evi-
dence now for field-aligned currents in the polar region (Armstrong and Zmuda, 1970;
Zmuda and Armstrong, 1974), these currents are now called Birkeland currents in his
honour. Chapman (Book I) suggested an ionospheric origin for the auroral electrojet
and proposed a system of two current cells, each cell consisting of a concentrated
current along the auroral zone with return paths in the polar cap to the north as also
in the middle and low latitudes to the south. Thus, one cell gave the westward electro-
jet in the morning sector and the other gave an eastward electrojet in the evening 
sector of the northern polar region, with a duplicate two cell system for the southern 
pole. Such a current system would explain not only the polar bays (negative in the 
morning and positive in the afternoon) due to the two auroral electrojets but would 
also give a morning maximum and evening minimum as envisaged in the average SD 
variation (Figure 40). However, it was pointed out by both Birkeland and Chapman 
that groundbased observations are not likely to give a clue as to whether the currents 
originated in the ionosphere or at higher latitudes. Silsbee and Vestine (1942) recon-
structed the current systems for polar bays and midlatitude DS and found that the 
two were similar (Figure 44). However, from studies of extensive records of IGY data, 
Akasofu et al. (1965) and Feldstein and Zaitzev (1967) showed that the westward 
electrojet was not really confined to the dawn sector but flowed westward most

Fig. 44. Equivalent current system for polar magnetic substorms 
(Silsbee and Vestine, 1942).
probably all along the oval but definitely at least in the dark sector. The equivalent DP1 current system is shown in Figure 45 and shows basically a single strong cell in the dawn sector. It was soon realised (Bostrom, 1964; Atkinson, 1967; Bonnevier et al., 1970) that none of these equivalent current systems could be the correct current systems as the latter have to be basically three dimensional with provision for field-aligned currents for which models proposed by Akasofu and Meng (1969), McPherron et al. (1973), Rostoker (1974) and Sugiura (1974) are already shown in Figures 36 and 37.

The equivalent current system for $S^p_0$ (Feldstein and Zaitzev, 1967) is shown in Figure 46(a) and that for the DP2 current system (Nishida, 1968) is shown in Figure 46(b). Thus, basically there seem to be three storm-time currents systems in the polar region (i) the DP1 system (Figure 45) characterised essentially by a major single but uneven cell having a strong westward electrojet in the pre-dawn sector and a minor cell giving the weak eastward electrojet in the dusk sector, (ii) the $S^p_0$ system (Figure 46a) which is a single cell in the sunlit sector, weak during quiet days but enhancing considerably during disturbed periods perhaps independently of the DP1 system, and (iii) DP2 system (Figure 46b) having basically two cells not connected with the
electrojet or the auroral oval and developing with southward $B_z$ as short-term fluctuations. However, this classification seems to be a subject of great controversy in recent years. Firstly, Nishida assumed that the DP2 fluctuations (shaded portions

Fig. 46. Equivalent current systems for (a) $S_\theta$ (Feldstein and Zaitzev, 1967), (b) DP2 (Nishida, 1968).
in Figure 42) are world-wide *increases* above a base level and the current system (Figure 46b) is calculated accordingly. However, there are some indications that these fluctuations may actually be *decreases* (Onwumechilli *et al.*, 1973; Kawasaki and Akasofu, 1973) below a normal level. Rastogi (1973a, 1975a) found that the equatorial *H* *depressions* during DP2 storms were associated with the disappearance of $E_{sg}$ within a few minutes. Nishida feels that the storm-time $S_p$ may not be an independent system but an accumulated effect of successive DP2 fluctuations and the DP2 system is quite distinct from and largely independent of the DP1 system; Kawasaki and Akasofu (1972, 1973) feel that the DP1 and DP2 are mostly coherent and hence there is no need to assume a separate DP2 current system. On the other hand, the $S_p$ is claimed by them to be a distinct current system which enhances *as a whole* on disturbed days due to *field-aligned currents*. From a study of several storms, Troschichev *et al.* (1974) described the substorm evolution in terms of 3 basic types of current systems as follows:

DP2 = a two vortex current system with no electrojets

DP11 = a single vortex current system with one westward electrojet at midnight auroral zone

DP12 = a two vortex current system with two electrojets, one westward in the pre-dawn sector and another eastward in the pre-dusk sector

and found that the sequences in which these occurred during the growth, expansion and recovery phases of weak disturbances, sudden substorms and ‘prepared’ substorms were as shown in Table I.

<table>
<thead>
<tr>
<th>Type of disturbance</th>
<th>Growth phase</th>
<th>Explosive or expansive phase</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak disturbances</td>
<td>DP2→DP12</td>
<td>×</td>
<td>DP12→DP12</td>
</tr>
<tr>
<td>Sudden substorms</td>
<td>×</td>
<td>DP11→DP11+DP12</td>
<td>DP12→DP2</td>
</tr>
<tr>
<td>Prepared substorms</td>
<td>DP2→DP12</td>
<td>DP12+DP11</td>
<td>DP12→DP2</td>
</tr>
</tbody>
</table>

It was also pointed out by them that according to Hartz and Brice (1967) auroral precipitation seems to occur as *discrete bursts* of high intensity at midnight and as a *diffuse drizzle* uniformly in the auroral zone. Also, there is probably a wind flux in the polar cap blowing along the 3.5 hr–15.5 hr LT meridians. Thus, the drizzle would give enhanced conductivity and hence the DP12 system of two electrojets at about 0300 and 1500 LT. The bursts would cause the DP11 system of a single strong electrojet at midnight. DP2 was the Nishida system of two cells unconnected with the electrojet and related to the polar convection connected with interplanetary southward $B_z$. It seems, however, that all these sound like descriptions of the proverbial elephant by the five blind men while the real current pattern would be a comprehensive one including polar convection, field-aligned currents and the magnetotail current systems.

The Dst and DS effects observed at low and middle latitudes are also due to current systems. During storms, plasma is injected from a narrow region of the midnight
sector of the magnetotail into the trapping region and stormtime ring current belts are formed consisting mainly of protons which are also responsible for the proton aurora in the dusk sector. The isotropic (symmetric) ring current is the main cause of Dst. The asymmetric part DS was earlier thought to be due to ionospheric return currents from an extended westward electrojet. However, the spacecraft observations (Cahill, 1966; Langel and Cain, 1968) indicated that whereas the auroral electrojets were of ionospheric origin, the DS variations were of non-ionospheric (magnetospheric) origin. The latest model seems to be in terms of magnetospheric partial ring currents (Kamide and Fukushima, 1972) shown in Figure 47. The westward electrojet along the auroral oval is connected with the tail current in a way similar to the model of McPherron et al. (1973) (Figure 36b) while the eastward electrojet is connected to the partial ring current in the afternoon sector. The model explains the dusk depression of H, i.e., negative bays at low latitudes (with magnitudes same in the electrojet region and nearby outside, see Figure 41b) associated with positive days at high latitudes, while the gap in the midnight sector explains the low-latitude positive bays (magnitudes same in electrojet region and nearby outside) associated with the high latitude negative bays. For the observed H variation, the major contribution seems to be from the field-aligned Birkeland currents (Fukushima and Kamide, 1973) rather than from the strip of partial ring current. In the model of Rostoker (1974) (Figure

![Model Current System for Polar Magnetic Substorm](image)

Fig. 47. Three-dimensional current configuration for the substorm associated current flow with a partial equatorial ring current (Kamide and Fukushima, 1972).
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37), the eastward auroral electrojet is indicated but the partial ring current is not specifically indicated though perhaps implied.

7.3.4. Relationship with Interplanetary Plasma Parameters during Disturbed Periods

During the last few years, copious data from spacecrafts have been available for interplanetary plasma parameters like solar wind velocities \( V \), plasma densities \( N \), interplanetary magnetic fields \( B \) and their components in the solar ecliptic plane \((B_x, B_y)\) and perpendicular to it \((B_z)\) and their standard deviations \( \sigma_{B_x}, \sigma_{B_y}, \sigma_{B_z} \) (revealing essentially a state of turbulence). Many of these seem to be intimately connected with the geomagnetic phenomena. \( K_p \) (or \( A_p \)) which is an index of storminess on Earth is well correlated with solar wind velocity and plasma density as also with \( B_z \) and \( \sigma_{B_x}, \sigma_{B_y}, \sigma_{B_z} \) (see review by Hirshberg and Colburn, 1969). Arnoldy (1971) showed that \( A_E \), an index of auroral disturbance, had a high correlation with \( B_z \) while Garrett et al. (1974) emphasized the additional role of \( \sigma_B \). Kane (1972d) showed that the indices \( A_p, A_E \) and \( Dst \) were related differently with different interplanetary plasma parameters indicating that interplanetary parameters responsible for polar and mid-latitude or equatorial phenomena may not be the same. For the DS (local time dependent) variation, Kane (1971f) separated the same into two parts \( \Delta Sd^+ \) (representing essentially the morning time increase) and \( \Delta Sd^- \) (dusk time decrease) and found for the IMP-1 period that \( \Delta Sd^+ \) at equator was related negatively to solar wind velocity while \( \Delta Sd^+ \) at mid-latitude was related positively to plasma number density. In contrast, \( \Delta Sd^- \) was negatively correlated with \( \sigma_{B_z} \) but only slightly.

The analysis was extended recently (Kane, 1975a) to 1965–68 and it was noticed that the noontime electrojet weakened and counterelectrojets intensified when \( B_x \) was large towards the Sun or when \( B_z \) was large southward or when the interplanetary field deviated considerably from the usual garden-hose direction or when plasma density increased. Rastogi and Chandra (1974) noticed that the equatorial electrojet region drift velocities decreased when \( B_z \) turned southwards. The role of southward \( B_z \) in initiating polar substorms is already discussed. Nishida’s DP2 storms are correlated with fluctuation in southward \( B_z \) (Nishida, 1968). Midlatitude \( Dst \) is also related to southward \( B_z \) in a general way though thresholds seem to be somewhat controversial (Kane, 1974; Russell et al., 1974). The full and partial ring current indices \( DR \) and \( DRP \) (Kamide, 1974) are also better related to southward \( B_z \).

Since Siebert (1968) and Mansurov (1969) showed that the \( B_x \) and \( B_y \) components influenced considerably the relative geomagnetic activities in the northern and southern polar region, this aspect has received considerable attention. Svalgaard (1973) showed that ionospheric daytime current \( (S_0^o) \) encircling the northern magnetic poles were strongest at about 80° magnetic latitude and flew clockwise when the interplanetary field was pointing towards the Sun and anti-clockwise when the field pointed away from the Sun. In the southern polar region, a reverse pattern was obtained. Kawasaki et al. (1973) reported that the solar vertical component \( Z \) was related to interplanetary \( B_y \) even on an hour to hour basis and changed independently of the \( H \) component which was more dependent on changes of \( B_z \).
The relationship between interplanetary sector boundary and geomagnetic indices has already been discussed in connection with the time variation of geomagnetic indices. Whereas significant average patterns have been reported (Wilcox and Colburn, 1972; Hirshberg and Colburn, 1973; Shapiro, 1974; Fougere, 1974) a detailed inspection of the behaviour of geomagnetic parameters around well-established sector boundaries (Kane, 1975b) revealed considerable deviations from the average patterns. In particular, some sector boundaries seemed to have no discernable effect on geomagnetic activity. It would thus seem that not all sector boundaries have a geomagnetic impact. What is relevant perhaps is the southward $B_z$ and its associated $\sigma_B$ which may be present in the wake of some streams but not all.

The relationship between the kinetic energy of interplanetary shockwave sand geomagnetic parameters was studied by Sarabhai and Nair (1969a, b) for IMP-1 period by using the parameter $\Delta H = H_{\text{max}} - H_{\text{min}}$ which, though meant to represent the daily variation range, would represent the storm effect Dst and DS on highly disturbed days. Thus, the positive correlation obtained by them represents the close relationship between dense shock-fronts and geomagnetic activity but mostly through southwards $B_z$ which must have been associated with many of the shock fronts. Comparing inter-
planetary plasma density and velocity with the initial phase changes of geomagnetic Dst, Verzarieu et al. (1972) concluded that the initial phase increases could be reasonably well explained by a relation of the type \( \text{Dst} = K_0(NV^2)^{1/2} - K_1 \) where \( K_0 = 0.025 \pm 0.009 \) and \( K_1 = 13.1 \pm 12.3 \), \( K_1 \) representing changes due to quiet-time ring currents. Kane (1974a) re-examined this aspect and found that the constants \( K_0 \) and \( K_1 \) varied considerably from event to event indicating that the positive initial phase was not due to a simple pressure balance. This aspect needs further investigation.

7.3.5. Theoretical Models

Since the solar wind is impinging upon the magnetosphere even during quiet times, Piddington (1960) and Axford and Hines (1961) proposed that the friction or viscous-like interaction involved would lead to a large scale convective motion of plasma in the magnetosphere such that \( \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \) giving \( \mathbf{v} = \mathbf{E} \times \mathbf{B} / B^2 \). This \( \mathbf{E} \times \mathbf{B} \) convective motion is interpreted as convection of 'frozen in' magnetic field lines (Gold, 1959) and ions and electrons drift with the same speed in a direction perpendicular to both \( \mathbf{E} \) and \( \mathbf{B} \), yielding no net current. In the equatorial plane, the convective...
motion would be as shown in Figure 48(a) which would be modified as shown in Figure 48(b) when the corotation of the plasma with the Earth is taken into consideration. The driving force, as mentioned above is the viscous-like interaction (Axford, 1964). However, a similar convection pattern is produced due to Maxwell stress when a southward $B_z$ causes merging and erosion on the sunward side of the magnetosphere (Dungey model, 1961) as shown in Figure 49. The most interesting feature here is the formation of the macroscopic X-type neutral lines in the tail from which plasma rushes in towards the Earth. In either case, a positive space charge is built on the dawn side and a negative space charge on the dusk side, giving a dawn-dusk electric field. Such a field generates current systems in the tail regions as shown in Figure 50(a) and a

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**Fig. 49.** Interaction between interplanetary southward $B_z$ and geomagnetic field lines and the resulting plasma motions (open arrows) (Levy et al., 1964).

**Fig. 50(a).** The cross-section of the magnetotail (view from the Earth) and the distribution of the normal component of the magnetic field and of the magnetotail current.
convection flow in the polar ionospheric region as shown in Figure 50(b). Since the electrons are essentially collision-free while protons suffer collisions in the ionospheric E region, the flow pattern of Figure 50(b) results into a net Hall current anti-parallel to the convective flow. The overhead current systems of DP2 and disturbed day $S_p$ are of this type.

![Diagram of circulation at ionospheric levels in the northern polar region](image)

**Fig. 50(b).** A sketch of the circulation at ionospheric levels in the northern polar region corresponding to the convective motion shown in Figure 48(a) (Axford, 1964).

During geomagnetic storms when solar wind parameters have enhanced values, both the viscous interaction and the field-merging mechanism will be strengthened. However, the fact that storms are caused more readily when $B_z$ turns southwards seems to indicate that the field-merging mechanism is more crucial. For the evolution of a polar substorm, observational data need current flow models as envisaged in Figures 36, 37 and 47 in which the magnetotail currents are disrupted near midnight and plasma is injected into the trapping region. Coroniti and Kennel (1973) have proposed a theoretical model for magnetospheric substorms in which the onset of the expansion phase is the result of turbulent resistivity. The field-aligned sheets of current flowing on the equatorward edge of the auroral oval develop instability which creates a large potential drop along the field lines allowing ionospheric Hall currents to build up on the boundary of the auroral oval. A strong polarisation electric field developing in a portion of the auroral oval drives a strong westward Hall current giving the midnight westward auroral electrojet. The model would result in current systems as envisaged in the model of MacPherron *et al.* (1973) shown in Figure 36(b). Kan and Akasofu (1974) have proposed a model of the open magnetosphere (based on the Chapman-Ferraro image method, Book I) wherein the magnetopause currents close exclusively in the magnetopause surface in contrast to the ionospheric closure envisaged by Coroniti and Kennel (1973). A new phenomenological magnetospheric theory has been proposed by Heikkila (1974) wherein the energy creation is envisaged through an MHD generator in front of the magnetopause, deriving its energy from the slowing solar wind. Schindler (1974) has proposed that the thinning of the plasma
sheet or reduction of the normal magnetic field below critical levels is conducive for
the setting in of the ion-tearing mode abruptly to start the expansion phase of a sub-
storm.

For the mid-latitude storm-time patterns, the storm sudden commencement (ssc) stage is qualitatively understood in terms of generation of hydromagnetic waves at the magnetopause. Chapman (1960) and Dessler et al. (1960) envisaged a negative correlation between rise-times and amplitudes which is observed (Srivastava and Abbas, 1973). However, quantitative estimates of the expected results do not tally with observations completely nor is the interaction of these waves with the ionospheric regions fully understood. For the initial phase, the mechanisms causing the instabilities at the magnetopause were investigated earlier (Talwar, 1964). Boller and Stolov (1973) demonstrated that the Kelvin-Helmholtz instability was an adequate mechanism.

The onset of the main phase is supposed to be associated with the arrival of the shock-driving plasma for which a ready entry into the magnetosphere is facilitated when the turbulent field inside the shock has a southward \( B_z \) component. However, the experimental evidence on this point is rather obscure. On some occasions, the alpha particle to proton ratio increased considerably at the onset of the main phase showing that the magnetosphere was sampling the core of the shock. On other occasions, no significant changes in interplanetary plasma parameters were noticed except changes in \( B_z \). It is likely that \( B_z \) acts as a trigger and the later evolution needs only a small flux of extra external protons for gradually building up the ring current. A succession of \( B_z \) changes would give successive injections and a formidable ring current even from a comparatively mildly populated shock core. Russell et al. (1974) and Garrett et al. (1974) showed that the build up of Dst was dependent upon the dawn-dusk electric field component \( (v \times B_z) \) of the interplanetary plasma as also on \( \sigma_B \). However, as pointed out by Burch (1974), a direct penetration of this interplanetary electric field into the magnetosphere must be ruled out as the major source of the cross-tail dawn-dusk electric field because, if this was so, then a normal northward \( B_z \) would imply an opposite, i.e., sunward convection over the polar caps which is not observed. However, Stern (1973) and Gonzalez (1973) proposed open magnetospheric models in which the \( B_y \) component combined with the interplanetary northward or southward electric field would always produce magnetospheric fields in the dawn-dusk direction.

Amongst the various geomagnetic storms, some start with a ssc but many others (gradual storms) do not have a sudden commencement. The reason for this absence of the initial shock-front encounter is not quite clear; but since such storms have a 27-day recurrence tendency, they are expected to be related to interplanetary streams associated with M regions from coronal holes (Kreiger et al., 1973; Neupert and Pizzo, 1974).

Once the plasma drifts inside from the magnetotail in the midnight sector, it encounters the dawn-dusk electric field and the associated gradient drifts which would push electrons towards the dawn sector and the protons towards the dusk sector.
Simultaneously, corotation is also encountered and electrons of all energies follow eastward trajectories towards the dawn sector. For low energy protons the gradient drift is westward but corotation is more predominant and hence these too are pushed eastward. For high energy protons, the gradient drift exceeds the corotation effect and the protons drift westward. Figure 51 shows a schematic of (a) the direct injection of electrons after being accelerated along the field lines and (b) the motions of elec-

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Fig. 51 (a). The precipitation area of electrons which are directly injected after being accelerated along geomagnetic field lines. (b) The motions of the electrons and protons which are injected in the midnight sector and the course of events which leads to their precipitation in the polar region (Book III, p. 694).
trons and protons after injection from the midnight sector. These processes have been studied in detail and described by Kavanagh et al. (1968), Axford (1970) and Vasyliunas (1972). Recent observations from Explorer 45 confirm this pattern (Smith and Hoffman, 1974). Some of the protons bounce from one hemisphere to the other in the trapped region and also drift around the Earth producing a symmetric ring current belt (Singer, 1957) for which detailed models have been worked out by several workers (Book III, p. 621). Sozou and Windle (1969) obtained self-consistent ring current fields for a ring radius of $3 R_E$ which would result in a depression of several gamma in the surface field. Akasofu et al. (1963) inferred the possible existence of two concentric belts, a short-lived DR1 belt at about $2-3 R_E$ and a long-lived DR2 belt at about $4 R_E$. Recent studies by Sugiura (1972) of the topology of magnetospheric fields do indicate the possibility of quiet-time equatorial current sheets due to particles of various energies entering through the tail, particles of several hundred keV energy giving the inner ring current at $2-3 R_E$ and particles of about 50 keV giving an outer ring current at $5-6 R_E$. During storms, these currents get enhanced. Cahill (1966) was the first to detect a storm-time belt at about $3-4 R_E$ from Explorer 26 data during the storm of 17–18 April 1965. Frank (1967, 1970) identified the particles responsible for the storm-time belt as 10–50 keV protons with fluxes about five-fold during the main phase as compared to the pre-storm level. These observations also indicated significant asymmetries in the ring current development as also a decrease in the radius of the ring with enhanced activity. Frank (1970) noticed that the proton fluxes maximised in the dusk-midnight sector. However, he also noticed much fewer protons in the noon sector and concluded that these had a limited lifetime of about one hour. De Forest and McIlwain (1971) reported that this was not true for all protons. The protons and electrons appeared in the form of discrete clouds and whereas some protons developed a sharp and long-lived energy structure, others had energy-dependent pitch-angle anisotropies. Also, a significant part of protons injected during sub-storms may leave the magnetosphere before making the complete revolution round the Earth (McIlwain, 1972). It would thus seem that the asymmetric component DS of the ring current belt is a predominantly magnetospheric phenomenon and is an inevitable consequence firstly of the asymmetric and spasmodic injection (from a restricted portion of the midnight sector) and secondly of the limited lifetimes of some of the protons. The spasmodic injection and further acceleration cannot be explained by a static dawn-dusk field. A time-dependent electric field model involving an additional component localised near midnight is investigated by Roederer and Hones (1974). To account for the limited lifetimes, Cornwall et al. (1970) envisage that the protons undergo strong turbulent diffusion just inside the plasmapause due to ion-cyclotron turbulence and hence are lost before reaching the noon meridian. In this model, the main phase is almost completely asymmetric with a large negative DS in the dusk-midnight sector while at the peak of the main phase DS and Dst may be comparable and later in the recovery DS would be negligible. The model does not explain adequately the large negative noontime DS(12) we illustrated in Figure 39 but this could be because of the differential behaviour of protons depicted by DeForest
and McIlwain (1971). It could also be connected with the possible turbulent diffusion of protons in the isolated cold plasma clouds which are peeled away from the plasmasphere and drift away from it towards the noon sector (Chappell, 1974). The DS variations may also be related to shifting patterns of field-aligned currents during the course of the storm. Crooker and Siscoe (1974) did model calculations for partial ring currents and found that most of the observed field at the surface would be due to field aligned currents very near the Earth.

For the recovery phase of the storm, charge exchange processes are envisaged in which protons give their energies to neutral hydrogen atoms which escape freely from the belt (Dessler et al., 1961). Since the inner ring particles would be lost more quickly, an initial rapid recovery followed by a slower recovery is expected and is generally observed. The reverse pattern (slower initial recovery) may be due to a diffused peak of the main phase due to successive injections of variable strengths. During years of high sunspot activity, the density of neutral hydrogen is lower and hence recovery should be slower. In a crude way, this seems to be true (Matsushita, 1962; Kane, 1963).

The negative relationship between the bay activity at polar and equatorial regions (positive bays in polar region related to negative bays at equator and vice versa) seems to be connected with the electrojets in the auroral ionosphere and partial ring current loops or tail current gaps in the equatorial magnetosphere via field-aligned currents. Considerable evidence has accumulated recently for such currents. Zmuda and Armstrong (1974) report that the field-aligned currents as observed at about 800 km altitude in the auroral zone show a diurnal flow pattern almost as a permanent feature. For 1400–2300 DLT (Dipole local time), there seems to be a downward flow on equatorward side and an upward flow (out of ionosphere) on the poleward side in the auroral zone. Near 2300–2400 DLT, there is a transition and for 2400–1000 DLT, the pattern is reversed. For 1000–1400 DLT, the pattern is irregular. Their earlier results for a storm-time observation (Armstrong and Zmuda, 1970) indicated a pair of field-aligned current sheets which would be consistent with the model proposed by Sugiura (1974).

For the world-wide DP2 events of Nishida (1971) shown in Figure 42, the effects at Huancayo seem to be larger than those at Fuquene by a factor of 4 indicating a large enhancement in the electrojet region and hence a predominantly ionospheric source. The simultaneous disappearance of electrojet $E_{eq}$ (Rastogi, 1973a) substantiates this conclusion. This is in sharp contrast to the positive and negative bays which show the same magnitudes at the equator and nearby low latitudes. The $ssc$ effects are enhanced at the equator but to a lesser extent than the DP2 effects.

The reason for the weakening and/or considerable distortion of the equatorial electrojet during some storms is not yet known. It could be due to the superposition of the magnetospheric dawn-dusk electric field on the normal $Sq$ field. However, Wolf and Jaggi (1973), point out that this is not possible as the Alfvén layer at the plasmasphere acts as an effective shield. Also, if such a penetration was possible, it cannot affect the electrojet region selectivity. It would affect the $Sq$ everywhere, which does not seem to be true. However, this needs further investigation.
7.3.6. Some Recent Results

Recently, several interesting results have appeared in the literature and have a direct bearing on the various aspects of geomagnetic variations, as follows:

(a) Internal field. Amongst the torroidal and poloidal components in the core of the Earth, the poloidal component, though smaller in magnitude, is of more vital interest, as it has a radial component. Busse (1975) derived a necessary condition involving the radial component for the operation of a geodynamo and concluded that the radial component required is sizable, far beyond the capability of mechanisms involving only oscillations in the core. Thus, convection in a limited portion of the core, perhaps within 800 km as outlined in the ‘core paradox’ by Kennedy and Higgins (1973), seems to be the only acceptable mechanism to operate the geodynamo. Metchnik et al. (1974) examined the core convection as a power source for the geodynamo but without the dimensional restrictions implied by Kennedy and Higgins (1973).

From the early theories of continental drifts and seafloor spreading, which have a vital bearing on pre-historic geomagnetic field, the new science of Plate Tectonics has emerged and the relative motions of major plates in the earth’s crust are fairly well-known now. Liu (1974) investigated the fracture pattern of plastic deformation in the outer shell of the Earth due to the shift of poles. His theoretical prediction regarding the break-up of tectonic plates by polar wandering correlates very well with the observed tectonic plate boundaries. It is surmised that these motions are caused by thermal motions of the Earth’s mantle. Elaborate two-dimensional numerical models incorporating convection cells in the Earth’s mantle have been recently developed by Houston and Bremaecker (1975) incorporating variable viscosity, viscous dissipation, internal heating, heat flow through the bottom and the adiabatic gradient. Several parameters had to be chosen somewhat arbitrarily; but the attempt is noteworthy.

(b) Field variations. It is generally believed (Cox 1968, 1969) that geomagnetic field reversals in prehistoric times are random. A recent analysis by Naidu (1975) seems to indicate that the spacing between the reversals may not be completely random; and the duration of the current reversal may depend upon the duration of the previous reversal to some extent. This will have important implications for the mechanisms responsible for the geomagnetic reversals.

Sudden changes (called impulses) in the rate of geomagnetic secular variations are often observed; and since these are of periodicities of a few years, the conductivity models of the earth’s crust and mantle need modifications if the source is considered internal. However, Alldredge (1975) has recently showed that these changes are well-correlated with sunspot cycles and hence should be considered as of external origin – perhaps through the solar cycle variation of the geomagnetic ring current.

The Gauss coefficients for the geomagnetic dipole field are known to be decreasing in recent years. For the period 1880–1970, Petersons (1974) reported a regression equation comprising of (i) a constant term (ii) a term giving a constant rate of yearly
change and (iii) a sinusoidal term of periodicities 60, 100 and 80 yr for $g_0^l$, $g_1^l$ and $h_1^l$ respectively.

Using the sophisticated Maximum Entropy method, Currie (1974) showed that the geomagnetic annual variation had harmonics of periods $365/(n + 1)$ days where $n = 1, \ldots, 6$ i.e. up to 52 days. Also, the 27-day peak was not a single, sharp peak but had a broad band at 24-31 days.

Global conductivity models are based on the complex ratio of external to internal diurnal variation fields. Parkinson (1974) examined this aspect critically and found that results for both the 12 hr and the 24 hr wave could be explained only if the conductivity had one sharp increase near 160 km depth and another near 400 km depth. Also, since some observatories were located on or near conductivity anomalies, the results were very sensitive to the choice of observatories.

In a comparative study of geomagnetic micropulsations and interplanetary magnetic field, Dhanju (1974) noticed that pulsations in the ranges 30-140 cph and 130-180 cph showed different relations and suggested that these two categories should be considered as having different origins. This needs further detailed exploration.

Rastogi and Sastri (1974) observed that amongst the SSC occurring at the equator, about 50% had a preliminary negative excursion (SSC*) and its magnitude decreased with latitude much faster than the amplitude of the main positive excursion. They suggested that SSC* originated mainly in the ionosphere slightly below the Sq current system.

Sastri and Murthy (1975) studied Solar Flare Effects (SFE) at night at equator and reported characteristics different from day-time SFE.

(c) Electric fields. Using the incoherent scatter technique, Carpenter and Kirochoff (1975) found that the electric fields measured at middle and high latitudes correlated very well. Since the high latitude fields are of mainly magnetospheric origin, the implication would be that the mid-latitude electric fields in the ionosphere were not just dynamo fields but had a substantial magnetospheric contribution as envisaged by Matsushita (1971).

(d) Magnetospheric changes. McDiarmid et al. (1974) noticed that whereas magnetosheath particles seemed to enter the closed field magnetospheric region at all LT with some energisation, entries at LT before noon were less probable and energisation was more for entry just before midnight. They suggested that both convection and diffusion are involved.

Mauk and McIlwain (1974) suggested a model for substorms in which, besides the usual static dawn–dusk convection electric field, there was a narrow injection boundary defined between the dusk and the midnight meridian. In the equatorial plane, the boundary was in the form of a spiral line closest to the earth at midnight and moving farther away with decreasing (and perhaps increasing too?) local time. The boundary may be coincident with the plasmapause and/or the inner edge of the plasma sheet and during substorms, particles are injected in the magnetosphere along or above this boundary, whose distance from the Earth varies with Kp. From Explorer 45 observations, Konradi et al. (1975) found that both electrons and protons showed strong dispersion effects in energy and pitch angle during substorms and interpreted
this as indicative of almost instantaneous injection along and above an injection boundary as envisaged by Mauk and McIlwain (1974).

Holzer and Reid (1975) gave a theoretical storm-time model for the day-time erosion of magnetic field lines and their sweeping into the tail region (and also the reverse process), as an electric circuit analogy with the ionosphere acting as a resistance, with a voltage generator connected in parallel and the closed magnetosphere as a set of inductance and capacitance. Apart from giving a quantitative estimate of the rate of erosion the model gives the mean position of the magnetopause and predicts oscillations of few minutes periodicities, which are observed.

(e) Phenomena in auroral and polar regions. Akasofu et al. (1973b) reported that during periods when $B_z$ is northward (low Kp), the auroral oval was contracted. Substorms did occur even in this condition, but the stations at present used for noting auroral substorms did not observe these substorms. It was only when $B_z$ turned southwards and the auroral oval expanded that the present stations observed the effect and recorded enhanced AE. Kamide (1974) arrived at a similar conclusion from the study of DP and DR and pointed out the inadequacy of the present network of auroral stations. Kamide and Akasofu (1974) reported from a chain of Alaskan observatories that a northward or a very small southward $B_z$ gave auroral electrojets which were weak and confined to narrow latitudes near 70° geomagnetic latitude and the associated mid-latitude bays were also small (less than 10 γ). In this case, the total electrojet intensity across the chain of stations was not necessarily proportional to AE but was well correlated to H increases at low latitudes.

Hoffman (1974) reported some evidence for the existence of polar wind. Further details are awaited. In one substorm, Sharp et al. (1974) observed helium ions of solar wind origin.

From a study of OGO 2, 4, 6 data, Langel (1974) reported patterns of polar total magnetic field $B$ which needed broad ionospheric current systems as also non-ionospheric sources for explanation. Positive deviations $B_p$ occurred generally from 2200 to 1000 MLT and negative deviations $B_n$ from 1000 to 2200 MLT. For negative $B_z$ (southward), $B_p$ varied linearly with $B_z$ while for northward $B_z$, $B_p$ was relatively constant. $B_n$ was also well correlated with $B_z$. However, neither $B_p$ nor $B_n$ were well correlated with DP2 fluctuations (Langel, 1975).

Gurnett and Akasofu (1974) reported for a particular substorm an enhanced plasma flow over the polar cap 30 min after $B_z$ changed southward; but no changes occurred in the electric field. On the other hand, Mozer et al. (1974) reported that the major field in the polar region had a dawn–dusk orientation (about 55 kV across the polar cap), responded to southward $B_z$ in less than an hour, increasing by about 3 mV min$^{-1}$ for every one gamma change of $B_z$; and had a two-cell convection pattern which shifted considerably towards dawn or dusk depending upon the orientation of $B_y$. Maynard (1974)) reported that the Harang discontinuity (area separating the westward and eastward auroral electrojets in the midnight sector, see Figure 9b) was present during quiet as well as disturbed periods; and was narrower and shifted equatorward with increased storm activity.
Venkatrangan et al. (1975) studied the 1–10 keV electrons in the 'inverted V' auroral substructures and concluded that at least some of these should be accelerated in processes other than that due to parallel (field-aligned) electric fields. Berko et al. (1975) studied the electron precipitation and magnetic field variations in the aurora simultaneously and classified the field-aligned currents as purely temporal or purely spatial. They found that whereas electrons having energies exceeding 1 keV were detected mainly in the nightside, those with energies less than one keV were the prime charge carriers in high-latitude dayside field-aligned currents.

Murayama and Hakamada (1975) studied the effects of interplanetary plasma parameters on substorms and noted that the strength of the auroral electrojet current was proportional to $B_z \times t$; where $t =$ duration of $B_z$, and the currents were twice as large when the interplanetary magnetic field was pointing duskward than when it was pointing downward. Also, the current was proportional to the square of the solar wind velocity, when $B_z$ was southward.

Friis-Christensen and Wilhelmin (1975) studied the polar cap currents for different directions of the interplanetary magnetic field and found that the well-known two-cell current system (Heppner, 1972a, b; 1973) was sometimes totally absent when $B_z$ was northwards. They suggested that the polar disturbance should be considered as composed of (i) a single-celled current system DPY related to the $B_y$ component of interplanetary magnetic field (ii) the usual two-cell current system DPZ related to $B_z$, and (iii) $S_0$ which is just a polar cap continuation of the mid-latitude Sq current system. They claim that this is not just another way of classification like DP1, DP2 etc; the DPY and DPZ current systems have magnitudes dependent on $B_y$ and $B_z$. DPY has a strong seasonal variation and is probably a Hall current varying according to ionospheric photo-ionisations; it may be caused by a merging process at the front of the magnetosphere where magnetospheric field lines of the northern polar cap are dragged by the interplanetary magnetic field towards the dawn or dusk depending upon the sign of $B_y$ (Jorgensen et al. 1972). DPZ has only a moderate reduction in winter, vanishes when $B_z$ is northward and is partly of nonionospheric origin. It comprises of the familiar DP2 system but is probably influenced by storm related DP1 also.

Wien and Rostoker (1975) compared the magnetograms at high, middle and low latitudes and noticed that the westward motion of the westward electrojet during substorms is not a continuous process but occurs as a succession of events at about 10 min intervals with each new westward electrojet developing to the North-West of the previous electrojet, in association with changes in the growth rate of the ring current.

The nature of polar cap magnetograms is strongly dependent upon the nature of the interplanetary magnetic field. Svalgaard (1972) utilised this property for predicting the interplanetary magnetic field sector structure (away from or toward the Sun) by introducing the A/C index even for the presatellite era. However, Russell et al. (1975) recently pointed out that the Svalgaard index had a strong bias to assigning a ‘toward’ classification on geomagnetically active days and have cautioned against its use for critical studies.
(f) **Mid-latitude changes as substorm indicators.** Clauer and McPherron (1974) used mid-latitude changes in the E–W and N–S components as precursors of polar substorms. They prepared contour maps to study (i) the meridian of onset, (ii) meridian of maximum bay development, (iii) magnitude and (iv) extent of several substorms. They found considerable fluctuations from event to event and concluded that for each event, a restricted longitudinal sector of the tail may be involved, which was at varying positions across the tail. Kamide and McIlwain (1974) reported that substorms of great intensities were synchronous at ground and ATS heights within 10 min, while for some weak ground substorms there was no particle injection at ATS heights, though it could have been at greater geocentric distances.

(g) **Magnetotail phenomena.** Akasofu et al. (1973a) studied the tail region from the Vela 5A, 5B, 6A and 6B satellites at about 18 $R_E$. They reported that the plasma sheet was uniform and cool (about 1 keV) after very low Kp; uniform but hot (20–30 keV) after a substorm; and hot at the center and cool towards the edges at other times. The high latitude tail lobes had a uniform low density plasma; while the tail boundary layer was less dense and less speedy than the magnetosheath. They concluded that the boundary layer is a magnetic projection of the dayside cusps and may be a suitable site for injection of magnetosheath plasma into the plasma sheet.

Cann et al. (1973) reported that the lobes of the magnetotail showed increases of magnetic energy density due to both a southward $B_z$ and an increase in solar wind dynamic pressure; but not all of these had a connection with localised auroral substorms. Thus, all auroral substorms may not have a magnetospheric origin.

Hones et al. (1973) reported from a study of Vela 4A and 4B data for 6–60 $R_E$ in the tail, that even during the so-called Stage 1 of the recovery phase of a substorm, when weak loops and folds are observed near the northern border of the auroral oval, energy input from the tail still continued to some extent.

Nishida and Hones (1974) compared the low energy electrons, observed by Vela satellites at about 18 $R_E$ in the tail, with the magnetic fields measured by Explorer 34 at 25–33 $R_E$. They found that during a substorm a neutral line was formed at distances less than 18 $R_E$ and an auroral magnetic bay at about 22 LT. When $B_z$ turned southwards, the neutral line appeared after about 1–2 hr. However, if $B_z$ was southwards for several hours, the neutral line and the associated plasma thinning did not persist all the while, but occurred almost every hour, with a duration of about $\frac{1}{2}$ hr, indicating a clear energy build-up state (growth phase), followed by an energy release through reconnection at the newly formed neutral line (beginning of expansion phase).

Liu et al. (1975) reported that $B_z$ turning negative did not result invariably in a substorm initiation. In some cases, only a slight decrease in plasma pressure at 18 $R_E$ was observed lasting for only about 20 min or even less.

Meng and Colburn (1974) reported that the high latitude magnetotail field increased by about 10–20% within about 10 min of the southward turning of $B_z$ and the increase was observed throughout the tail (outside the plasma sheet) from 5–40 $R_E$. A statistical analysis by Cann et al. (1975) showed that the lobe field increased on the average by about 14% in association with a southward $B_z$ and, coincident with the expansion
onset, the lobe field recovered rapidly and $B_z$ turned from southwards to northwards. Rich et al. (1974) reported that whereas the plasma sheet thinning at the onset of a substorm, and expansion during recovery, was observed even up to lunar distances ($60 \, R_E$), the thinning did not occur simultaneously throughout the region but propagated as a thinning wave as plasma was ejected from the near-earth region of the tail.

Chase et al. (1974) reported from particle measurements made by the lunar-orbiting Apollo subsatellites that the energy spectra of electrons in the magnetosheath and the high-latitude magnetotail were similar; and the plasma sheet, though often showing thinning with substorm onset, occasionally showed expansion at onset. They concluded that a magnetospheric model having closed magnetic field lines in the plasma sheet and a source of plasma sheet particles between the Earth and the Moon would explain their observations best.

From 3 years of magnetometer data from the lunar orbiting Explorer 35, Meng and Anderson (1974) reported that near $60 \, R_E$, the magnetic field lines in the high-latitude tail lobes (outside the plasma sheet) diverged gradually away from the tail axis, more so in the dusk side and in the northern tail. The divergence angle was more in the $Y$ direction than in the $Z$ direction indicating an elliptical rather than a circular cross-section for the tail. Several other details were reported for the plasma sheet also but variations with Kp (storm-time variations) were not as spectacular as reported by other workers. Bowling (1974) reported a significant diurnal motion of the neutral sheet at $30 \, R_E$ due to the diurnal wobble of the geomagnetic dipole.

We have mentioned here only some of the recent observations which have some bearing on geomagnetic variations. There are perhaps many more which we have missed or which are about to be published. There are also others which do not have a direct bearing on geomagnetic variations but are nevertheless important for an understanding of the Earth's environment and its changes. Whistler studies give information about the plasmasphere densities. Particle precipitation at different geographical locations gives important clues to the magnetospheric processes involved. There is an indication that there might be a third (innermost) radiation belt at thermospheric altitudes (Heikkila, 1971; Goldberg, 1974). Airglow and Lyman $\alpha$ observations and mass-spectrometer studies give important clues to the distribution of atmospheric constituents (including Hydrogen) around the earth (geocorona) and their storm-time changes. Ionospheric changes, especially during storms, have provided useful information about the dynamics of the ionospheric regions. Direct measurements of neutral winds have helped to obtain a clearer picture. All these are complementary to each other and need to be studied, preferably simultaneously, to give us a better understanding of the variety of complicated processes involved in solar-terrestrial relationships and magnetosphere-ionospheric coupling. The above results indicate that a considerable effort is being made to obtain detailed fine structure of the magnetospheric processes from satellite data. The era of the five blind men assessing the elephant is coming to an end; and slowly but steadily, the real nature of the complex magnetospheric processes is being divulged.
7.3.7. Geomagnetism and Other Disciplines

There are several phenomena which are intimately related to geomagnetic variations. Visual aurora is, of course, one of them. Ionospheric changes are another. In recent years, some remarkable similarities have been observed between Geomagnetism and Climatology. Over the northern hemisphere, the isoliths of magnetic intensity and the mean height contours of the surfaces of constant atmospheric pressure have similar patterns (King, 1974). Several other similarities are suspected, e.g. long-term climatic patterns associated with the secular changes of the non-dipole part of the geomagnetic field. Wilcox et al. (1974) have reported a relationship between interplanetary magnetic field sector structure and vorticity at 300 mb atmospheric level. Whereas most of these need much further investigation, their importance can hardly be overemphasised. Every tool that could help us in understanding, predicting and perhaps controlling weather would be a boon to humanity.

Biological consequences of geomagnetic storms are also often hinted at (e.g. Srivastava and Bhaskar Rao, 1974). These need further critical examination.

The size and shape of the magnetosphere, as also its permanent constituents, are strongly dependent upon the absolute value of the geomagnetic dipole moment. The sufficiently energetic inner zone protons have probably resided in the magnetosphere for hundreds of years. If the dipole moment has changed significantly in the past, it must have caused violent changes in the geomagnetic cavity. Siscoe (1974) introduced the term paleomagnetosphere to describe such changes and Schulz (1975) has investigated the paleomagnetospheric modulation of radial diffusion.

8. Concluding Remarks: Unsolved Problems

Ever since the auroral and the geomagnetic storms were observed, Man has wondered whether these are related phenomena. And ever since he observed that these are enhanced when the sun occasionally flares up, he has wondered whether the sun is not the villain of the piece, blasphemy notwithstanding. Pioneer efforts by Birkeland, Chapman, Chapman and Ferraro, Alfvén and many other helped to pose the problem in its proper perspective. A lot of water has flowed under the bridge since then. Or, to be more realistic, a lot of solar wind has blown away. Invaluable contributions by Chapman, Alfvén, Parker, Axford, Dungey, Dessler, Akasofu and many, many others have added to our knowledge of the Earth’s environment and the basic processes of interaction between solar wind plasma and the earth’s magnetosphere.

And yet, much more remains to be known. To take a stock of where we stand:

(1) We know that the terrestrial storm-time variations are caused by an impact of interplanetary shocks and stream interfaces with the magnetopause. However, many details are missing. Many phenomena are broadly understood; but the exact role of each of the interplanetary plasma and field parameters in causing various changes is not satisfactorily worked out. Even basic phenomena are open to question. Is the magnetosphere closed or open? Or does it have a dual personality? Is the southward
$B_z$ component of interplanetary field the Almighty God which dictates all storm processes, or is it only a trigger? What roles do the other components play? In what capacity? Independently, or in conjunction with each other? If so, which combinations are important for what processes and to what extent?

(2) What exactly is the nature of the reconnection at the subsolar point? How exactly are the field lines swept back? What happens to them at the neutral sheet? Why does the plasma sheet go through thinning and expansion processes? Why its spasmodic nature?

(3) How does subsequent injection and/or field-aligned precipitation occur? Is acceleration involved? Is it by electrostatic processes or by adiabatic processes? Or are both involved? To what extent?

(4) What is the precise structure of the field-aligned currents? Are these always two parallel and oppositely flowing current sheets at different nearby auroral latitudes, or are there occasionally single sheets? What decides where the equatorial magnetotail current should rupture to get diverted along the field lines to the auroral regions and back to the magnetotail? What decides the longitudinal breadth of the ruptured region and its mean longitude? Or is there no rupture at all and is the field-aligned current a tributary? What about the field-aligned currents responsible for the partial ring currents? What decides the longitudes where these occur and their longitudinal breadths?

(5) What is the precise fate of the particles injected into the trapping region? Why do some manage to reach the noon sector? What are the processes which act as sinks?

Not that all these questions have remained unanswered. In fact, many have found satisfactory solutions. But in many cases, more than one mechanism has been suggested. Which is the correct one? Or are all operative to a greater or lesser extent? What decides the extent? These are the questions which are bothering the scientific community and the hope is that more and more data from well planned experiments would help in solving this jigsaw puzzle.

Restricting ourselves to geomagnetic variations only, the following problems need further investigation:

(a) What are the exact overhead current systems which seem to cause the multiplicity of patterns of $S'_q$, DP1, DP2 etc.? What fraction of these flows in the ionospheric polar region? Are there any return currents through the low latitude ionospheric regions or is the connection only through the magnetosphere?

(b) Are there any trans-hemispherical (north-south) current systems? If so, how are they distributed in altitude?

(c) How about the midlatitude $S_q$? Is it completely in the ionospheric E region? Or is there an integrated contribution from the F region too? Is there any from the plasmasphere or the magnetosphere? If so, how much?

(d) What about the equatorial electrojet? Is it just one strip at about 105 km or are there other minor strips? Would they be above or below? Or is there an integrated contribution from higher layers? Are there any return currents independent of the $S_q$ current systems on either side?
(e) What about the counter-electrojet? What makes the main electrojet go crazy (reverse) for a few hours in the afternoon when the Sq in the nearby low latitude regions does not even show a tendency of decrease, leave aside reversal? What exactly is happening up there when the ground H shows zero in the afternoon? Does it imply no electrojet current or two equal and opposite electrojets at slightly different altitudes, or sandwiches of opposing current systems?

(f) Why do the Sq and the equatorial electrojet change violently in form and strength from day to day even during quiet periods? Why are the changes in the two not always parallel? What is the contribution, if any, of non-ionospheric currents to this variability? Since the changes are not related to solar flux changes which could have altered the conductivities, the cause must be sought in the changing wind patterns. Why do the winds change so radically from day to day? Are ground meteorological or tidal effects involved?

(g) Why are the electrojet, counter-electrojet and Sq changes restricted in longitudes too? Abnormalities seem to remain in a particular longitude zone (of a few hours breadth) for days together without affecting the nearby longitudes. Why?

(h) Why does the equatorial electrojet weaken and/or get distorted during storms? Can non-ionospheric (magnetospheric) electric fields penetrate to the equatorial E region?

(i) What are the precise causes for the 27-day and semi-annual, annual and solar cycle variations of H as well as Sq and I? Quantitative estimates are either missing or do not make complete sense: Why?

(j) And finally, the million-dollar question. What is the source of the internal field? Is there a solid core? Is it definitely incapable of sustaining ferromagnetism? Is the liquid core stably stratified? What are the relative roles of the various mechanisms thought to be possible in the liquid core?

In many ways, the terrestrial dynamo mechanism and storm processes are strikingly similar to those occurring on the sun. Magnetic field configurations, neutral points, and explosive phases of solar storms are familiar from terrestrial observations of the magnetosphere and auroral phenomena. The solar storms involve far more energy and offer manifestations which are amenable to ground or satellite observations. On the other hand, terrestrial phenomena are nearer at home and suitable for intensive long-term studies. If the similarities are kept in mind, the information obtained from these two diverse natural laboratories can be combined with advantage to understand both the basic processes and their multitude of varied effects. Geomagnetic variations form only a part of the whole – an important part, no doubt, but not sufficient. A variety of supplementary and complementary information must be pooled to get a picture which is as true as possible. It is hoped that the variety of space probes still up there, and those likely to be launched in future, will enrich our knowledge of the environment of our beautiful planet.

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