SPATIAL AND TEMPORAL VARIATIONS OF THE GEOMAGNETIC FIELD

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More than 98% of the observed geomagnetic field, referred to as the main field, *has its origin in the deep interior of the Earth, due to currents flowing in the electrically conducting liquid outer core of the Earth, while the remainder arises from currents flowing in the ionized part of Earth's upper atmosphere: the ionosphere, and magnetosphere. The main field creates a cavity in interplanetary space, which is the magnetosphere that defines the region of influence of the Earth's magnetic field. Variability of the geomagnetic field over a large range of spatial and temporal scales is linked with a wide variety of physical phenomena, occurring in the interior of the earth, in Earth's atmosphere, ionosphere, magnetosphere, and on the Sun and in interplanetary space. Hence geomagnetic observations contain fundamental information about the solid Earth as well as geospace - the region of space that stretches from Earth's upper atmosphere to the outermost reaches of the Earth's magnetic field, and its relationship with the Sun. This article describes some facets of geomagnetic field variability.*

Introduction

In the year 1600, William Gilbert presented the results of his many years of investigation of the geomagnetic field in the treatise 'De Magnete', which led him to conclude that *'the Earth itself is a great magnet'*. During the 17th century, it was also observed that the declination (D) and inclination (I) which are respectively the angle between the horizontal component of the geomagnetic field and the geographic north and the angle that the geomagnetic field makes with the horizontal plane, measured at a place change on a time scale of decades. Around 1722, George Graham, a well known clockmaker in London, discovered that D measured at one location also undergoes a regular daily variation, while in 1741, in collaboration with Graham, Celcius observed an unusual deviation from this regular variation, which occurred at the same time in London and Uppsala. These events were christened as 'magnetic storms' by Alexander von Humboldt in 1808. In India, the first hourly eye observations of the geomagnetic field were started at the Madras astronomical observatory in 1822 and these continued till 1861. In 1836, Alexander Von Humboldt took the first step towards organization of regular measurements of the geomagnetic field at different locations around the globe. Towards this end, he was joined by Carl Friedrich Gauss and Wilhelm Weber in forming the Göttingen Magnetic Union, which consisted of 50 locations around the world, where regular hourly observations of magnetic declinations were to be made. Madras, Simla (1841-1845), and Trivandrum (1841-1871) were three of these locations.

Colaba observatory was established in 1823 for astronomical observations to support navigation. The magnetic observatory at Colaba (Bombay) came into existence in 1841, and regular observations commenced in 1846. With the decision of Bombay city fathers to electrify the fleet of trams in the city in the year 1900, re-location of the magnetic observatory away from Bombay became inevitable, and the Alibag observatory was set up, where the characteristics of the geomagnetic field were similar to those observed at Bombay. The Colaba-Alibag geomagnetic records together are an extremely important set of uninterrupted data: Colaba data for the period 1841 – 1904 and Alibag data from 1906 onwards, being only one of four such data sets to study both the temporal

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changes in the main magnetic field and also major magnetic storms due to solar events in the 19th century. The International Geophysical Year (IGY) (1957-1958) marked the beginning of the era of major international cooperation in probing the near earth space environment through rocket and satellite measurements. During the period of IGY, two magnetic observatories were established at Trivandrum and Annamalainagar respectively, the former located close to the dip equator. Magnetic measurements from this equatorial observatory have made immense contribution towards the rocket launching programme in the country. Later, four more observatories were established by the Indian Institute of Geomagnetism (IIG) at locations in central India (Ujjain and Jaipur), North-east (Shillong) and at Gulmarg, under the International 145° E meridian project. At present there are 14 magnetic observatories in India, of which 11 are operated by IIG, and the remaining three by other national Institutes (Figure 1).

The first model of the geomagnetic field was put forth in 1839 by Gauss who represented the geomagnetic field by the gradient of a potential function, expanded in a series of spherical harmonic functions. Analysing data obtained from measurements of the three components of the geomagnetic field at different locations, Gauss concluded that the contribution to the observed geomagnetic field from external sources was much smaller than that from sources within the Earth. Today satellite measurements of the geomagnetic field provide an accurate picture of the spatial variations of the main geomagnetic field down to scale sizes of about 1000 km. Role of the Sun in causing day-to-day variations in the geomagnetic field has also been studied extensively using ground and satellite data. In addition to electromagnetic radiation of various wavelengths, a stream of charged particles, mostly protons and electrons, is also continuously emanated from the Sun in the form of the solar wind. Changing configuration of solar magnetic field allows the build-up of magnetic energy in some regions of the solar atmosphere. The sudden release of this energy leads to solar flares and coronal mass ejections (CMEs). Solar activity follows an approximately 11-year cycle. EUV and X-rays radiated from the sun are responsible for ionization of neutral particles in Earth's upper atmosphere in the low and mid-latitudes, while particle precipitation also causes ionization at high latitudes. The plasma ejected from the sun carries with it a part of the solar magnetic field referred to as the interplanetary magnetic field (IMF), and the orientation of the IMF is often found to be an important factor in causing magnetic storms. The CMEs have often been identified as drivers of major magnetic storms.

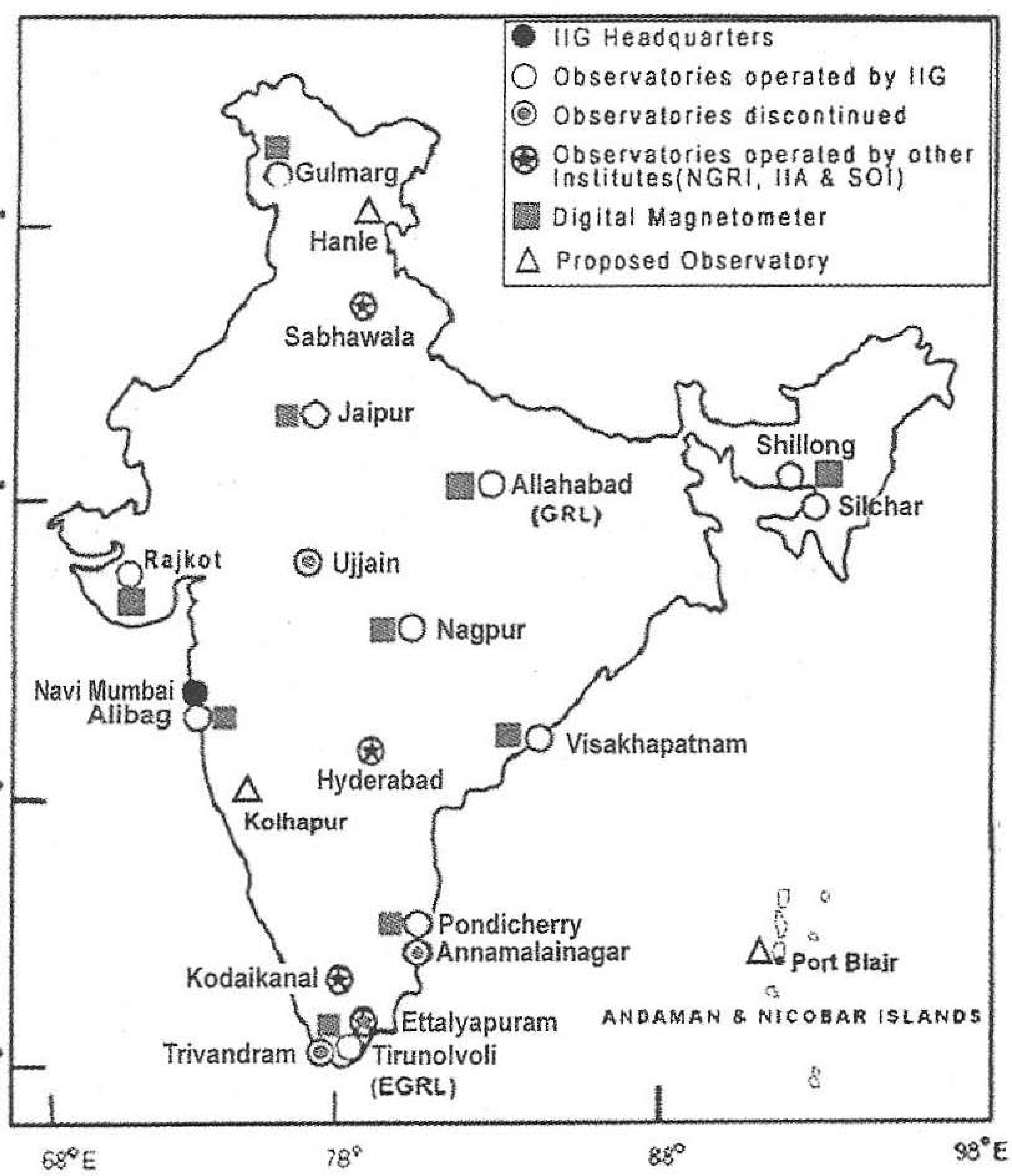

Fig. 1. Network of magnetic observatories operated in India.

The geomagnetic field measured at any point has contributions from various sources: (a) the main field produced by a self-sustaining dynamo mechanism in the electrically conducting fluid outer core of the earth extending in depth from 2900 km to 5160 km below the surface of earth; (b) magnetic field arising from magnetized material in earth's crust, referred to as magnetic anomalies because of their localization; (c) magnetic field produced by currents flowing in earth's ionosphere and magnetosphere; and (d) the field due to currents induced within the conducting earth by temporally varying external magnetic fields. In this article, some aspects of the spatial and temporal variations of the main field and the field produced by currents flowing in the ionosphere and magnetosphere shall be discussed. Variations of the latter are controlled by electromagnetic UV radiation and charged particles emitted from the sun, and form an important component of the solar-terrestrial relationship.

Earth's Main Magnetic Field

To a first approximation, the observable present day main field is dipolar in nature, with the dipole axis being tilted at an angle of about 11.3° from the axis of earth's rotation. The largest magnitude of the surface field ~ 60000 nT is to be found near the geomagnetic poles and lowest at the dip equator, where it is ~ 30000 nT. However, a more accurate representation of the main field is given by the eccentric dipole whose centre is displaced from the centre of the Earth. The non-dipolar components of the main geomagnetic field are significant and give the field a more complex spatial structure. On the basis of studies of magnetized rocks of different geological ages, scientists concluded that earth has had a magnetic field for nearly 3 billion years[1], which has been approximately dipolar as it is today, except during periods when the poles underwent a reversal, which has happened at irregular intervals. The last reversal took place about 780,000 years ago.

As seismic observations coupled with laboratory experiments increased our knowledge of Earth's structure and composition, the possibility of a self-sustaining geodynamo operating in the fluid outer core, where molten iron flows at the speeds of 10-30 km/year, emerged as a plausible candidate for generating the main geomagnetic field[2,3]. Thermal convection driven by radioactive heating and buoyancy forces arising due to density gradients produced by slow cooling of the whole Earth, are possible causes of flow of the molten iron in the outer core. In addition to this there is compositional convection when the inner core solidifies from centre outwards, the lighter elements mixed with liquid iron separate and rise up stirring the liquid[4]. This process would have caused the solid iron inner core to gradually grow to its present size with a radius of about 1215 km over a time period of the order of a billion years. Coriolis force due to Earth's rotation also influences the nature of the flow, but this rotation does not drive the flow. As the electrically conducting fluid in the outer core moves across an ambient magnetic field, an electromotive force is generated, which drives a current that sustains the original magnetic field against decay by diffusion. In 1934, Cowling had provided a theoretical proof that axisymmetric magnetic fields cannot be maintained by a self-sustaining dynamo process. Thus the geodynamo involves complex fluid motions that produce a non-axisymmetric magnetic field. Only the poloidal part of the main field is observed as this is the part that emerges from the core. Within the core, in addition to the poloidal magnetic field, there is a toroidal magnetic field with field lines that remain within the core, and hence is not observable. It is only in recent years that computer simulations based on highly simplified assumptions have shown that fluid motions in Earth's outer core sustain a nearly dipolar magnetic field which shows some features of the non-dipole field and reversals which are not realistic[5].

The fluid motion in the outer core also contributes to the variation in the main field over time scales of tens to thousands of years, referred to as the secular variation of the geomagnetic field (Figure 2). With the assumption that the molten iron in the outer core is a perfect

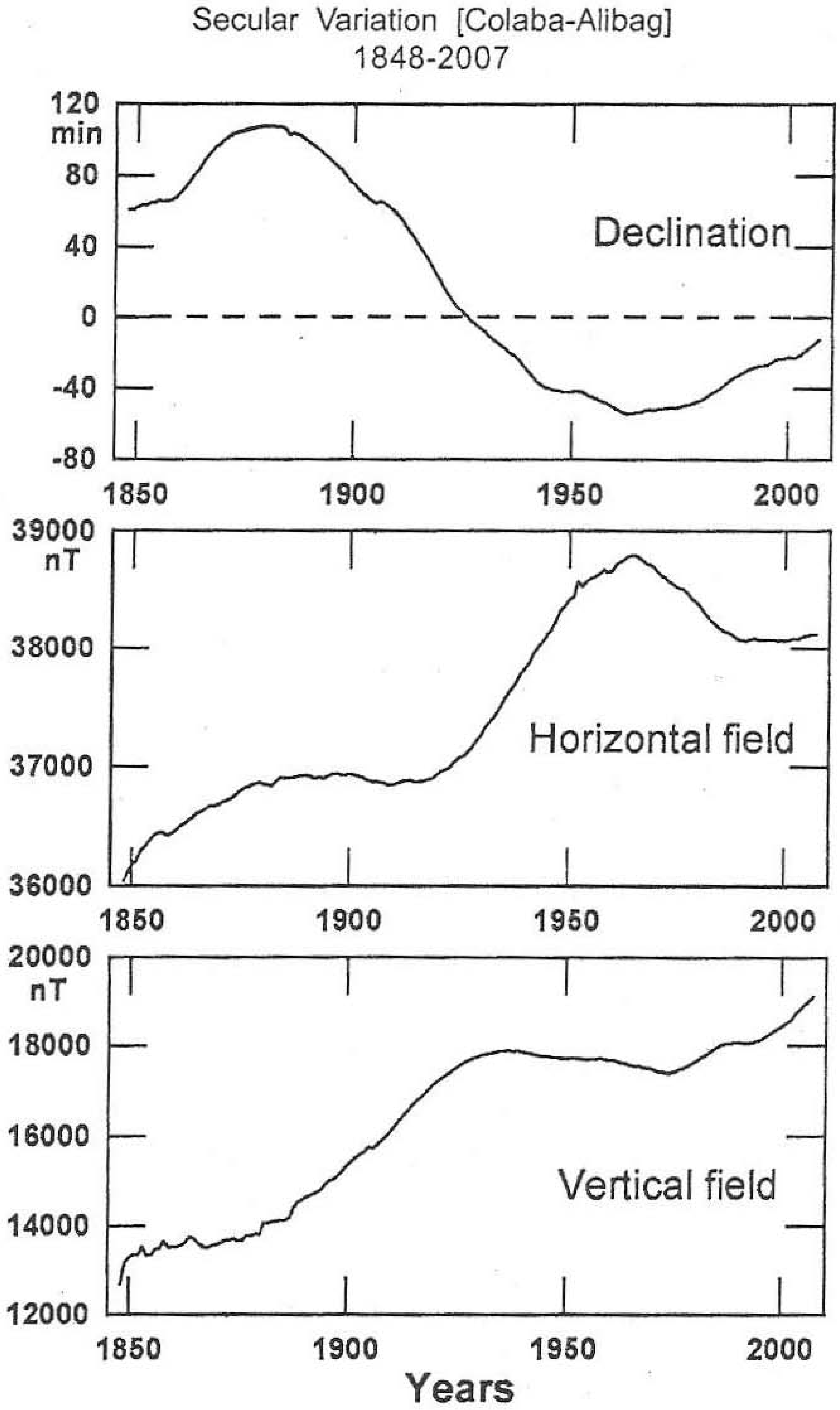

Fig. 2. Secular variation of the three components of the earth's magnetic field from the Colaba-Alibag combined observations for 160 years.

conductor, the magnetic field lines may be considered to move with the fluid, and the secular variation of the observable poloidal part of the main geomagnetic field is then due to re-arrangement of the magnetic field lines by the movement of the fluid at the top of the core. This idea has been used to estimate the horizontal fluid flow at the top of the core from time-dependent maps of the magnetic field at the core-mantle boundary (CMB) obtained by downward continuation of the observed poloidal magnetic field to the CMB assuming earth's mantle to be an insulator[6] . One of the forces acting on the fluid in the outer core is the Lorentz force, which is the force experienced by the current flowing in the fluid due to the prevalent magnetic field. A major question regarding the geodynamo is how strong is the unobservable toroidal field in the core? The radial gradient of the toroidal field could be large enough to make the Lorentz force comparable in strength with the Coriolis force, and hence temporal variation of fluid flow at the top of the core could contain some information about the radial gradient of the toroidal field. Temporal variation of fluid flow in turn would be related to the changes in secular variation, or secular acceleration of the observed poloidal magnetic field. This idea has been used to obtain an estimate of the rate of increase of the strength of the toroidal magnetic field with depth just below the CMB using available secular acceleration models for the poloidal field[7]. From Figure 3, it is seen that below the geographic South Pole the toroidal magnetic field is zero even within the outer core just below the CMB. This has been found to be true of the vertical (poloidal field) as well continued down to the CMB, and is attributed to the effect on the fluid flow of the presence of the solid inner core[5, 8]. This is the reason for the observed tilt in the dipole axis with respect to the rotation axis.

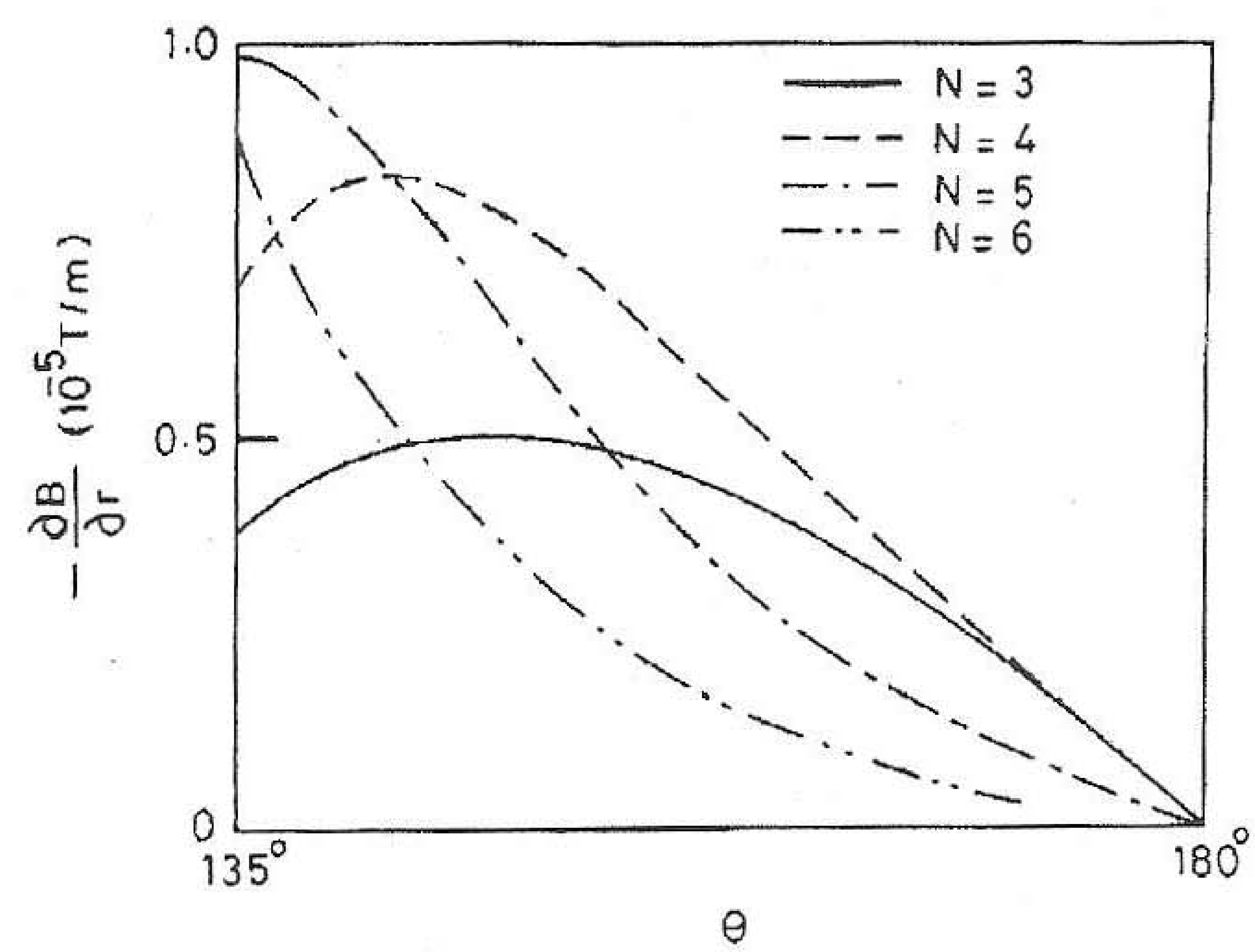

Fig. 3. Radial gradient of a steady, axisymmetric, toroidal field B at the core-mantle boundary in the co-latitude (θ) range of 135° to 180° , estimated using geomagnetic secular variation and secular acceleration models of different complexities represented by N (after Bhattacharyya[7]).

There are other unresolved issues as well concerning our inferences about the geodynamo drawn from the observed main field. One of these is the effect of a finite electrical conductivity of the mantle on the estimation of the poloidal field at the CMB. For instance, a uniform region of enhanced electrical conductivity at the base of the mantle, could introduce a change of 40% in the secular variation of the horizontal components of the poloidal magnetic field at the top of the core compared to the insulating mantle case[9].

In recent years, there have been attempts to find a link between Earth's magnetic field and climate. A mechanism that has been proposed is the enhanced cosmic-ray induced nucleation of clouds due to recent changes in the main geomagnetic field[10]. In fact an exact calculation of the changes in cosmic ray cut-off rigidities due to secular variation of the geomagnetic field approximated by that of an eccentric dipole, during a 150 year period from 1835 to 1985, shows that the largest decrease in the cut-off rigidities are to be found in tropical regions, because at high latitudes, where the geomagnetic field is nearly vertical, charged particles coming down to the atmosphere from above move nearly parallel to the magnetic field and hence are not deflected by it[11].

Equatorial and Low-latitude Ionospheric Current Systems

The densities of various neutral molecules and atoms present in the atmosphere above 100 km is basically governed by hydrostatic equilibrium of the individual species, with the density decreasing exponentially with height at a rate determined by a scale height that depends on the mass of the neutral particle and the temperature. Below about 100 km, the different components are mixed together by atmospheric turbulence to yield relatively uniform composition, so the mean molecular mass determines the scale height. Due to the variation in composition of the neutrals with altitude in the middle and upper atmosphere, UV radiation and X-rays of different wavelengths emitted from the solar atmosphere are responsible for producing ionization at different altitudes in earth's atmosphere. Recombination of the various ions produced, with the electrons also occurs at different rates. Hence the ionosphere is organized into different layers. With the density of the neutrals decreasing exponentially with increasing altitude, in the F layer of the ionosphere above 150 km collision frequencies of electrons and ions with neutrals become much smaller than the respective frequencies with which electrons and ions gyrate around the ambient geomagnetic field. But at altitudes of about 100 km, the movement of ions is dominated by collisions with neutrals, while that of electrons is controlled by the geomagnetic field. Electrical conductivity of different regions of the ionosphere depends on the mobilities of electrons and ions, which are influenced by the rate at which these particles collide with the neutral particles and their gyro-frequencies. Thus the height variation of electrical conductivity of the ionosphere at any time depends not only on the altitude dependence of electron density but also on the ratio of the collision frequency and gyro-frequency for each species. The presence of the geomagnetic field also gives rise to an anisotropic ionospheric conductivity. The electrical conductivity tensor is expressed in terms of the specific (parallel to the geomagnetic field), Hall, and Pedersen conductivities, the parallel conductivity being much larger than either the Hall or Pedersen conductivities, which are largest in the daytime E region extending from about 95 to 130 km. Hence this is the region where ionospheric currents flow in the equatorial, low-, and mid-latitudes, to cause the quiet time daily variation in the geomagnetic field.

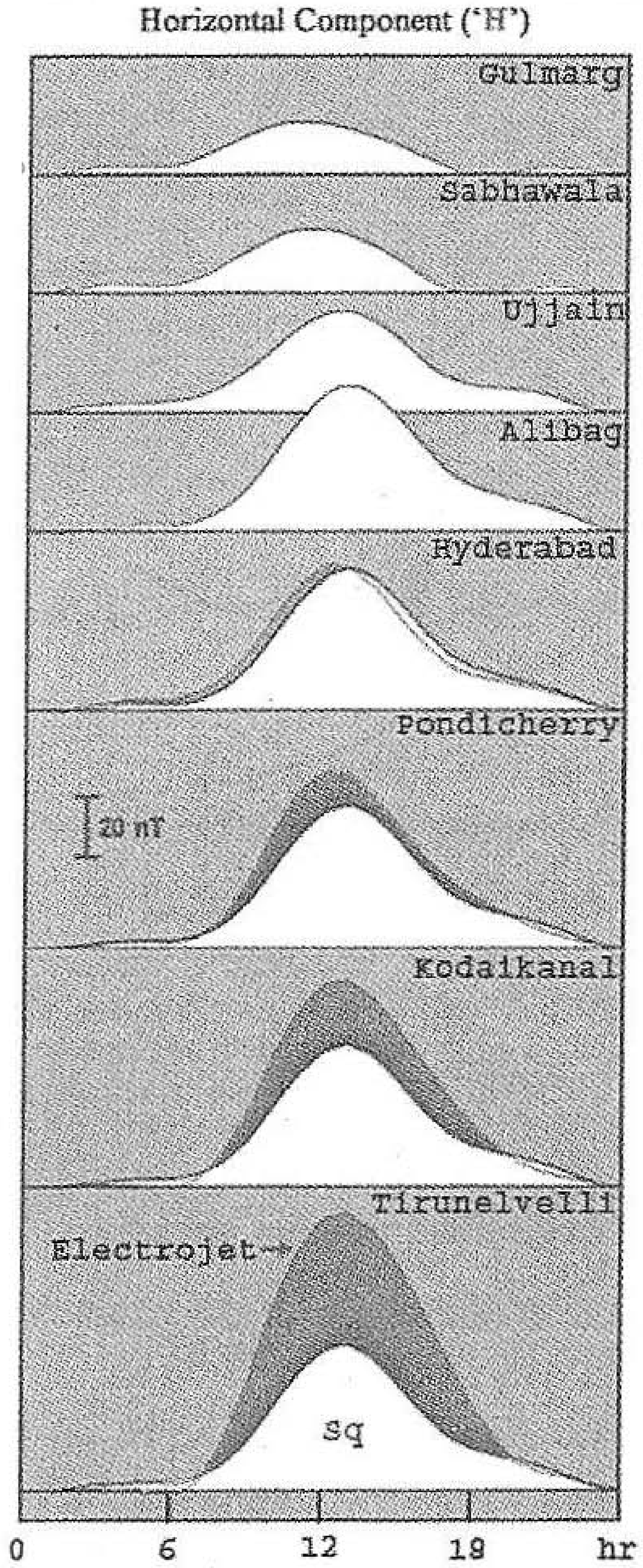

Fig. 4. Pattern of average quiet day variation of the horizontal component of the geomagnetic field at a chain of magnetic observatories extending from the dip equator (Tirunelveli) to the latitude of Sq focus (Gulmarg). Enhanced magnitude shown by the shaded portion depicts the effect of eastward electrojet current over the dip equator.

Electric fields are required to drive the currents and these arise due primarily to winds in the E region. Solar heating and to a lesser extent moon's gravitational pull give rise to tides in the atmosphere. In the E region collisions with neutrals influence ion motion whereas electron motion is influenced by the geomagnetic field. Hence the tides drive a global current system and set up a large scale electric field such that the resultant dayside ionospheric currents are divergence free. The resultant currents constitute the solar quiet (Sq) current system[12]. The limited vertical extent of the E region and the horizontal geomagnetic field at the dip equator, give rise to an enhanced electrical conductivity in the E region over the dip equator and hence to the phenomenon of the equatorial electrojet (EEJ), which is a narrow band of intense eastward current that flows in the E region centred on the dip equator[13]. The geographical location of India with its latitude coverage extending from the dip equator, which passes through the southern tip of India, to the focus of the ionospheric Sq current system at ~30° N, provides an ideal setting for investigation of the temporal and spatial characteristics of the EEJ and Sq current systems, as well the effects of magnetic activity at equatorial and low latitudes. Latitudinal dependence of average quiet day variations of the horizontal component of the geomagnetic field recorded at a chain of magnetic observatories in India is displayed in Figure 4, which shows the systematic decrease in the diurnal variation with increasing latitude. The enhanced magnitude of the horizontal component seen in the dip equatorial region is caused by the EEJ. Both the EEJ and Sq current systems show day-to-day variability superimposed on changes with respect to season and solar activity.

On occasion the equatorial electrojet has been found to display anomalous behaviour when there is a reversal of the horizontal field (H) variations during certain hours of a day. This phenomenon was named as counter electrojet (CEJ) and attributed to the reversal of the electric field resulting in a westward current. Rastogi *et al.*[14] established this from observation of sudden disappearance of the daytime equatorial E region type II irregularities, which implied a reversal of the electric field during the period of reduction in the 'H' field at the equatorial station. The cause of this reversal of the electric field is yet to be established, although the role of local winds in producing CEJ has been investigated extensively[15, 16]. A case study to show the limited longitudinal extent of the noon time counter electrojet effect[17] is shown in Figure 5.

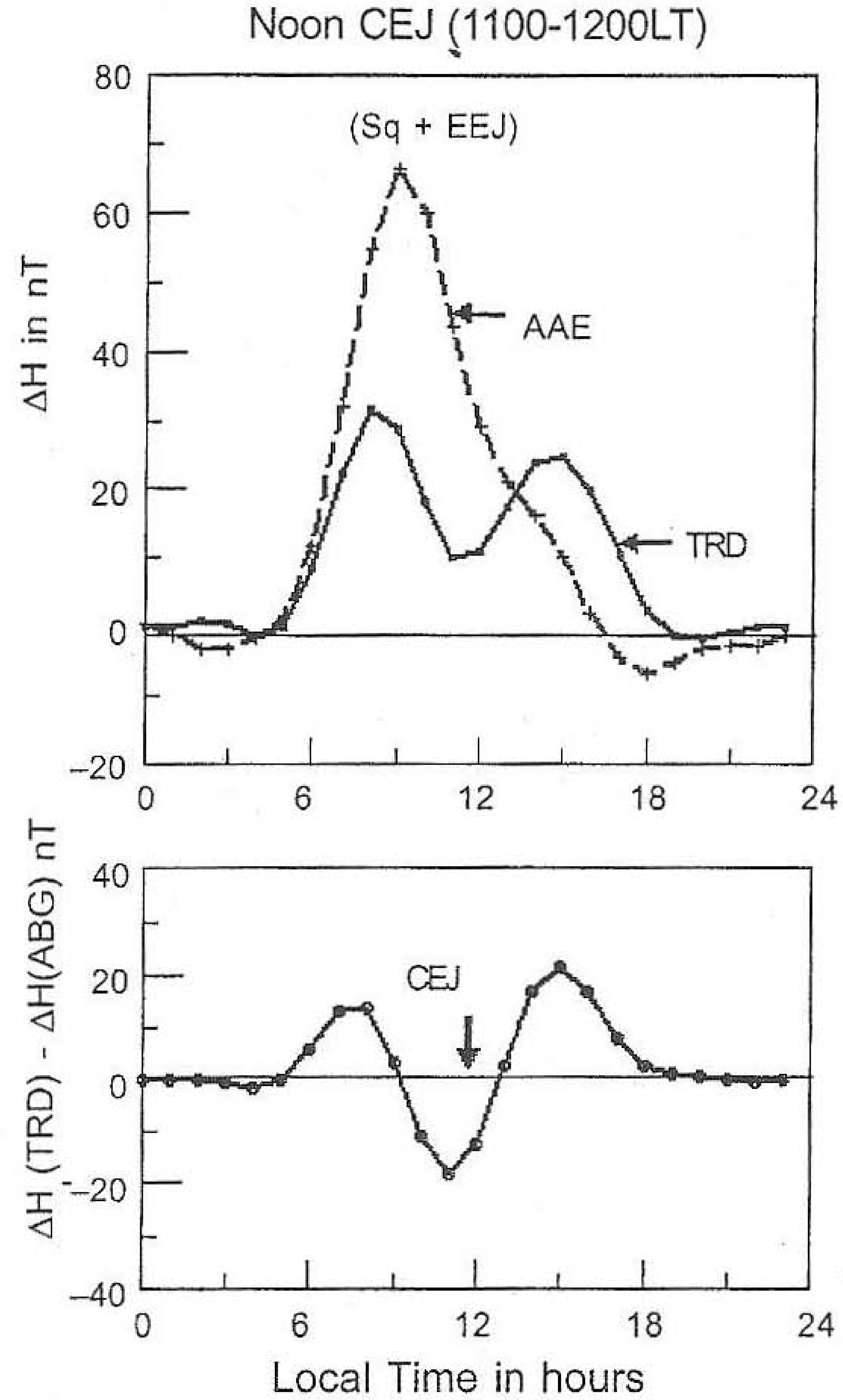

Fig. 5. The occurrence of noon Counter Electrojet (CEJ) event at Trivandrum (TRD) averaged for 6 cases is shown in bottom panel. Top panel depicts the difference in the average diurnal variation patterns at the equatorial stations Addis Ababa (AAE) and TRD, separated in longitude by 40° (after Alex and Mukherjee[17]).

Magnetic Storms

The near earth space is also influenced by sporadic outbursts of solar energy in the form of solar flares and coronal mass ejections (CMEs). While the enhanced levels of short wavelength electromagnetic radiation from the sun during solar flares may cause large changes in the electron densities in Earth's ionosphere within a few minutes, CMEs spew out billions of tons of charged particles, which plough through the solar wind at several times the speed of the normal solar wind, which is basically the sun's continuously expanding outer atmosphere, moving with a typical speed of 400 km/s. Magnetic field of the sun is embedded in the fully ionized solar wind plasma as it moves through interplanetary space. The main magnetic field of the earth creates a cavity in interplanetary space called the magnetosphere, where earth's magnetic field dominates over the magnetic field carried by the solar wind. The magnetosphere is shaped like a comet in response to the dynamic pressure of the supersonic flow of the solar wind. Earth's magnetosphere is compressed on the sunward-side to about 10 Earth radii (R_E) (1 $R_E \sim 6371$ km) and is extended tail-like on the side away from the sun to more than 100 Earth radii[18] (Figure 6). The size and shape of the magnetospheric boundary depends on the balance between the kinetic plasma pressure of the solar wind and the magnetic pressure inside the magnetosphere. The boundary where the two energy densities (or pressures) balance each other is called 'magnetopause'. The magnetosphere deflects the flow of most solar wind particles around the Earth, while the geomagnetic field lines guide charged particle motion within the magnetosphere. The magnetosphere consists of several plasma domains

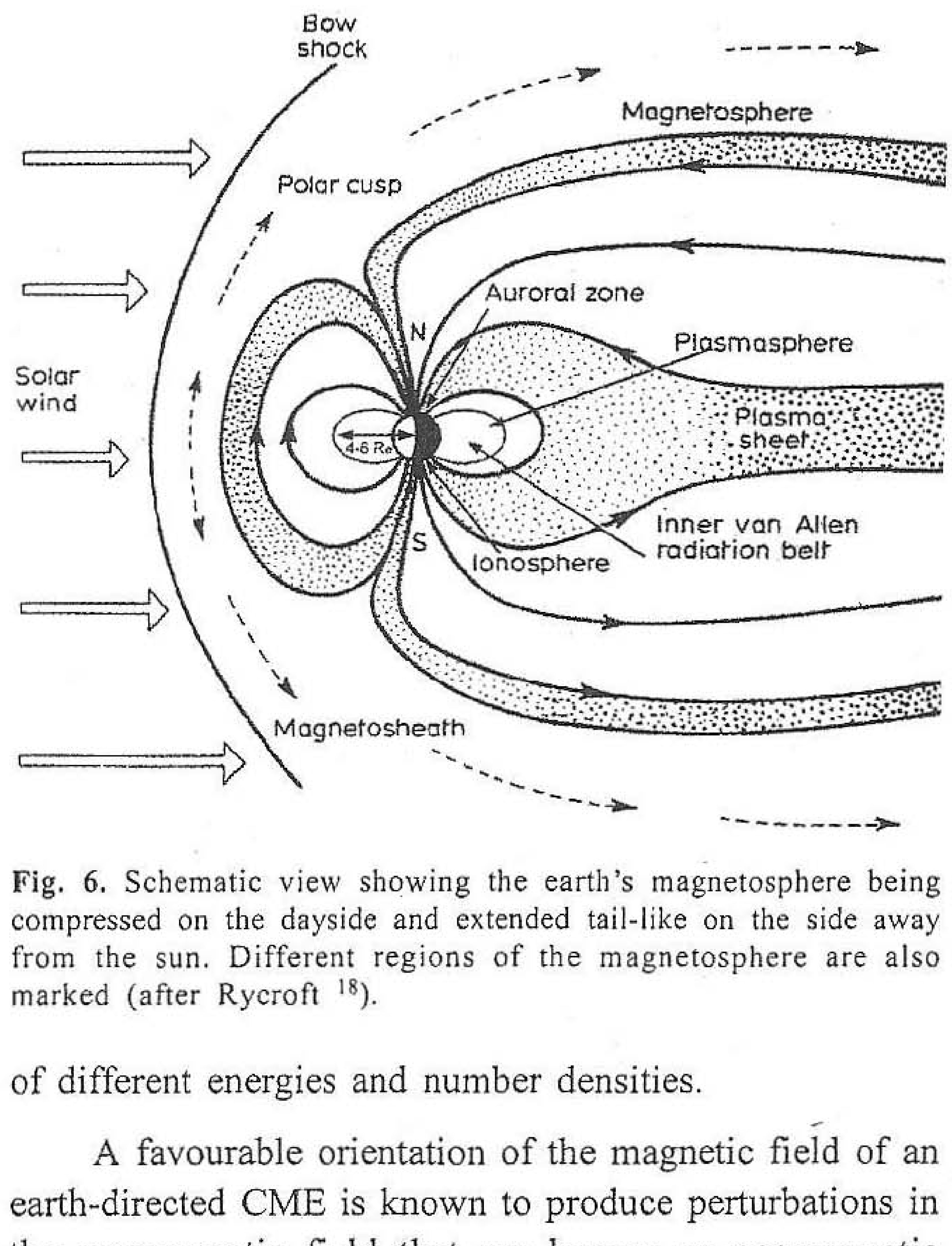

Fig. 6. Schematic view showing the earth's magnetosphere being compressed on the dayside and extended tail-like on the side away from the sun. Different regions of the magnetosphere are also marked (after Rycroft [18]).

of different energies and number densities.

A favourable orientation of the magnetic field of an earth-directed CME is known to produce perturbations in the geomagnetic field that are known as geomagnetic storms. Perturbations of varying magnitude observed in the ground magnetic records in response to solar activity are signatures of physical processes occurring on the Sun, in interplanetary space, and in earth's magnetosphere and ionosphere. Solar energy and plasma are transferred to earth's magnetosphere via the solar wind-magnetosphere coupling process of magnetic reconnection between a southward directed Interplanetary Magnetic Field (IMF) and the northward magnetopause fields[19]. Most of the energetic particles get deflected around the earth by the magnetosphere, whereas some get trapped in earth's magnetic field. The trapped electrons are accelerated along the magnetic field lines towards the polar regions and strike the neutrals in the upper atmosphere there to form the aurora. Visible auroras occur within the auroral zones, i.e. at geomagnetic latitude locations in the 65° to 75° range and at altitudes between 100 and 200 km. Geomagnetic storms recorded at magnetic observatories are also manifestations of the transfer of solar wind energy into the earth's magnetosphere, which leads to the generation of several current systems. The initial impact of the solar wind –magnetosphere interaction is seen as a sudden enhancement in the horizontal (H) component of the magnetic field in the equatorial and low latitudes, following the compression of the geomagnetic field at the magnetopause boundary. After that the main phase of the storm sets in as a depression of the horizontal component of the geomagnetic field at equatorial and low latitudes on Earth's surface, lasting a few hours to even days. This decrease in the geomagnetic field is due to the intensification of the 'ring current', consisting of protons, oxygen ions and electrons in the 10-300 keV energy range, located usually between 2 to 7 R_E. A southward IMF sets up a dawn-to-dusk convection electric field over the magnetospheric tail. As a result, the plasma drifts Earthwards and it is accelerated to higher energies. The curvature and gradient of the geomagnetic field cause the plasma to drift in more circular orbits around the Earth, with positive ions drifting westward and electrons drifting eastward around the Earth resulting in enhancement of the ring current in the equatorial plane. This is considered to define a magnetic storm[20]. A necessary and sufficient condition for the occurrence of major storms put forward by Tsurutani et al.[21] is the maintenance of southward direction of the IMF for 3 hours or more and with a southward component magnitude of 5 nT above the normal field.

Influence of Varying Solar Conditions on Ground Magnetic Records

Intense UV radiation and X-rays from a solar flare travel to the earth in eight minutes and their effects are visible in the daytime geomagnetic field records from ground observations. Often, but not always, a solar flare is followed by a CME. Figure 7 highlights the day to day variability in the ground magnetic records for three consecutive days of April 2001, showing the effects of a

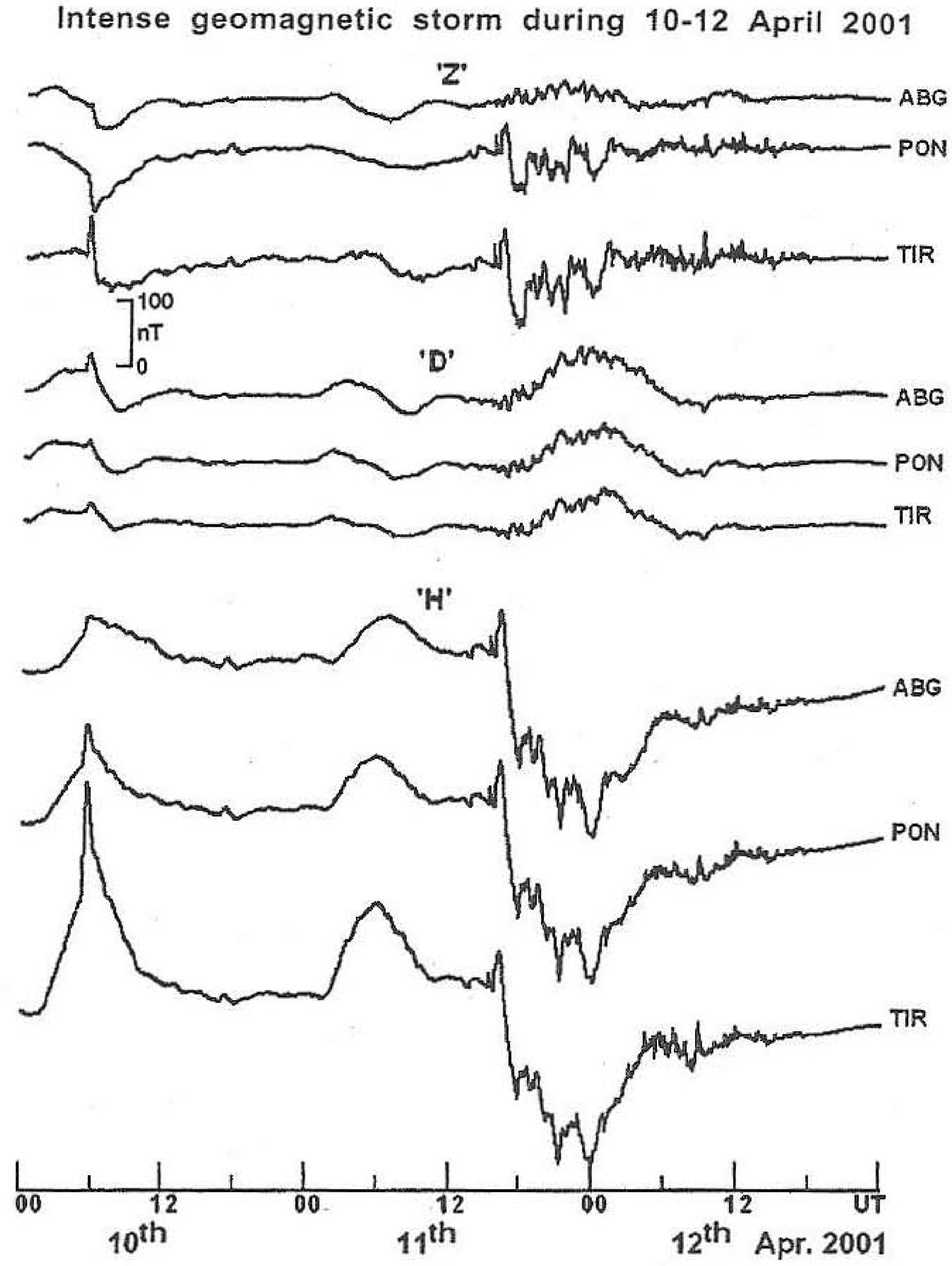

Fig. 7. Three consecutive days of different solar activity conditions during April 2001 showing the solar flare effect followed by the magnetic storm effects seen in the geomagnetic field components at three magnetic observatories.

solar flare followed by a CME. The three components of the magnetic field are shown for the equatorial station, Tirunelveli (TIR), for the station Pondicherry (PON) at the fringe of EEJ and a low latitude station, Alibag (ABG), from 10 to12 April 2001. A major (X2.3) solar flare that occurred at 05:25 UT (IST = UT + 5.5 hrs) on 10 April, as recorded by GOES satellite instrument to measure X-ray flux, gave rise to an abrupt increase in the near noon time ionization and hence electrical conductivity within a few minutes, and the H components increased significantly . The following day, April 11, showed the expected daytime variation of the 'H' field on a quiet day at all the locations since the Halo CME that occurred shortly after the solar flare, travelled with a speed of ~2400km/s, which though supersonic was much slower than the speed of the electromagnetic radiation. The supersonic CME produced an intense shock on 11 April, which was observed by the ACE satellite located at the L1 Lagrangian point (~ 240 R_E) where the combined gravitational forces of the Sun and Earth keep the satellite in an orbit locked to the Earth-Sun line. The shock front finally impacted the earth's magnetosphere resulting in a geomagnetic storm sudden commencement on 11 April at 1545 UT, nearly 34 hours after the solar flare occurrence. Subsequently the development of an intense main phase associated with the westward ring current was observed.

Super Intense Storm of September 1-2, 1859 and other Intense Storms

The unique storm data decoded from the meticulously recorded observations of Colaba magnetic observatory during September 1-2, 1859 has become one of the most well- documented records of a super intense storm[22, 23], probably because they were taken by eye observations (Figure 8). At other observatories using photographic records, the deflection went out of range due to the severity of the disturbance. Carrington an English astronomer, who was taking systematic solar observations by observing projected images of the sun, spotted the brightest solar flare event of September 1, 1859 [24, 25]. The super storm of September 1-2, 1859 was associated with this famous Carrington flare and was caused by a combination of several events that occurred on the Sun at the same time. Kimbal[26] in his indexing of auroral sightings described that within hours, telegraph wires in both the United States and Europe spontaneously shorted out, causing numerous fires. For this event, sighting of auroras were reported down to 23° geomagnetic latitude. The CME involved in the September 1859 event

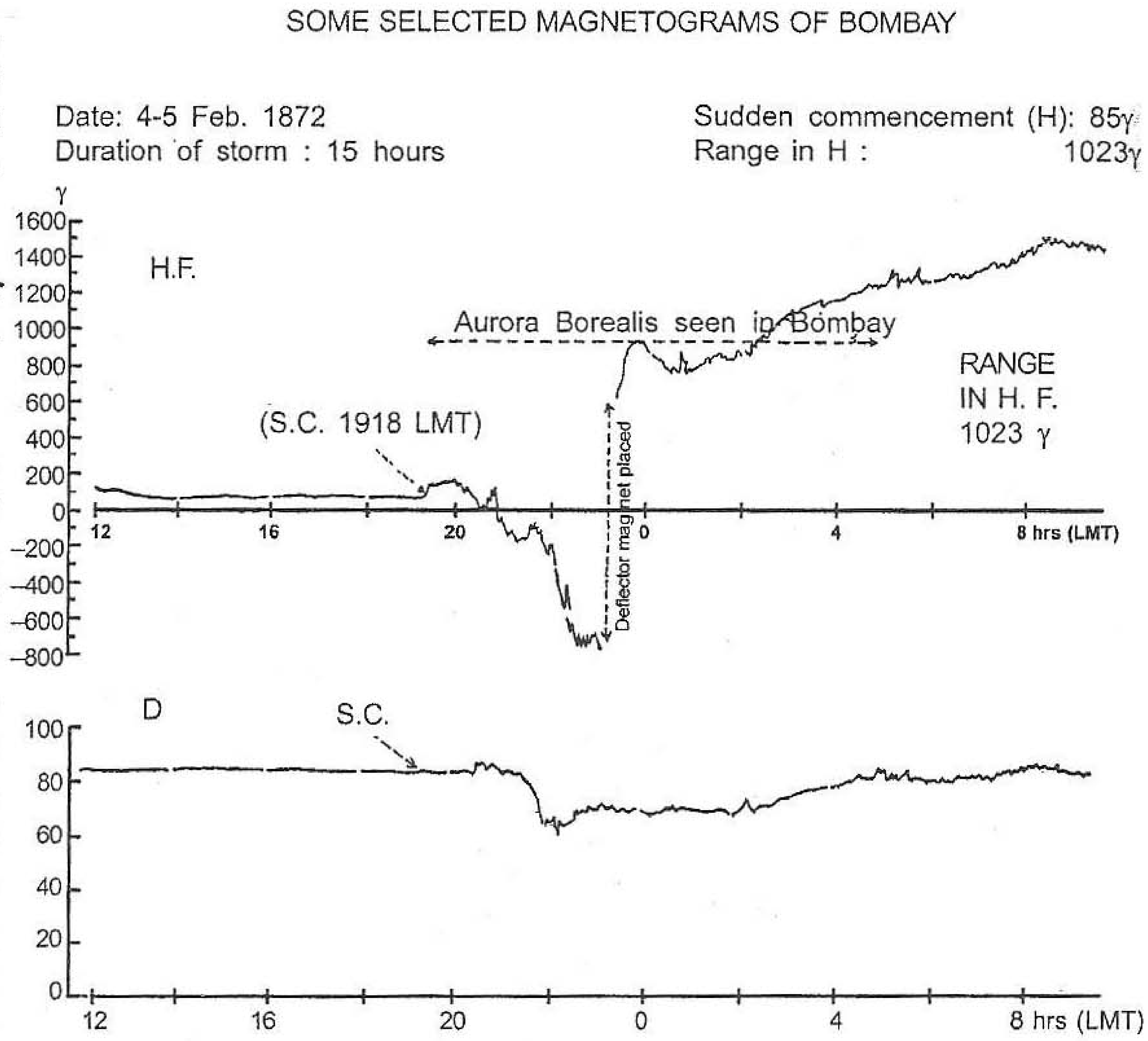

Fig. 9 : The Colaba (Bombay) magnetogram for the severe storm of February 4-5, 1872.

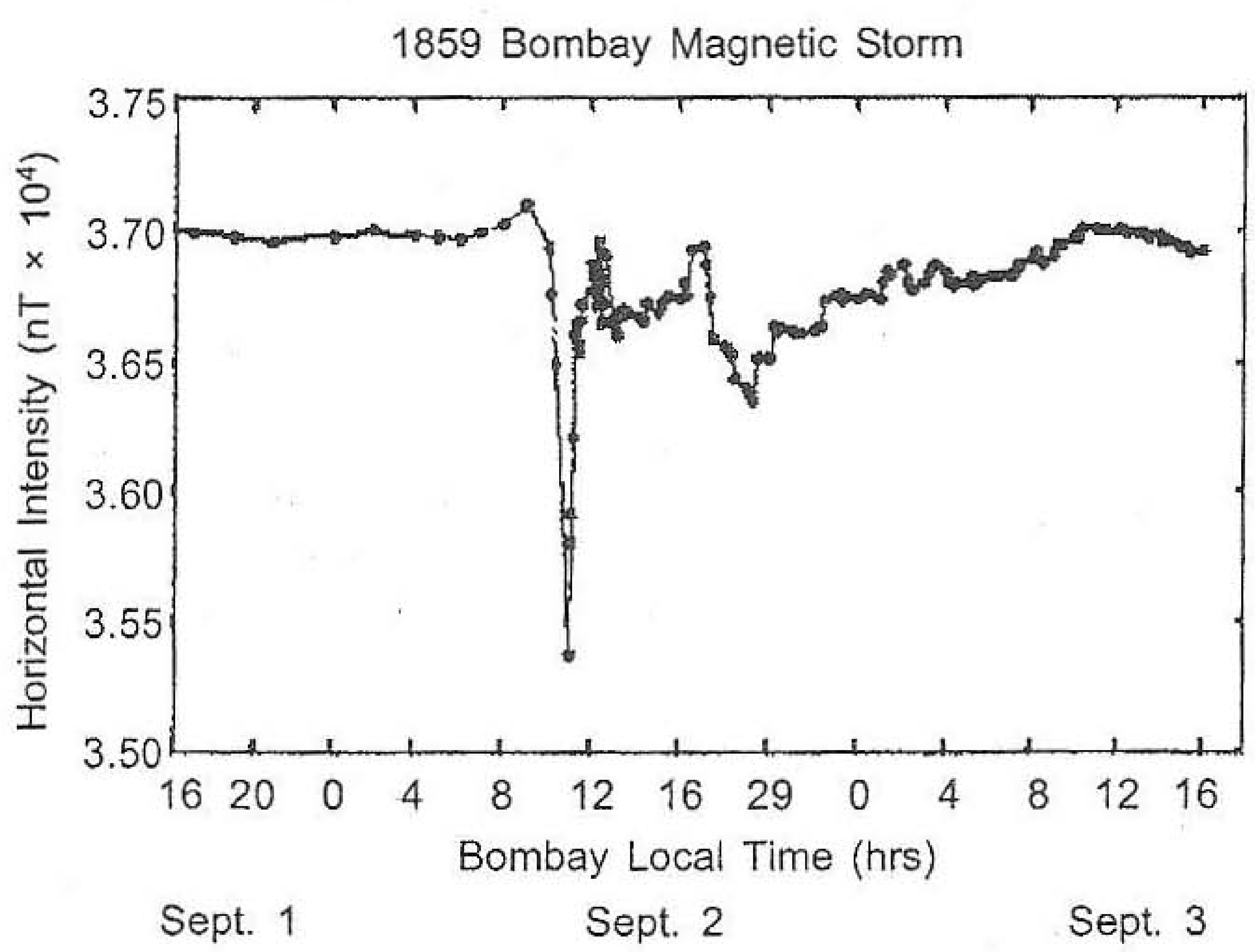

Fig. 8 : The unique super storm data decoded from the 'H' component of the magnetometer measurements made in the Colaba Observatory in Mumbai in September 1859 (after Tsurutani et al.[22]).

reached the Earth's magnetosphere in 17 hours and 40 minutes and produced the maximum storm magnitude in the H component at Colaba of ~ -1600 nT. There have been records of several intense and fast coronal ejecta arriving at the earth to produce magnetic storms, but none of them has produced a super storm of magnitude comparable to the one of September 1859.

For another severe storm that was recorded at Colaba magnetic observatory on February 4-5, 1872 (Figure 9), the aurora was even sighted in Bombay! An excerpt from the news item published in the Times of India on February 6, 1872, is given below:

"THE AURORA BOREALIS

Will it surprise our readers to learn that the Aurora Borealis was plainly visible in Bombay on Sunday last? Such was indeed the case and its effects were felt too. After sunset on Sunday, the Aurora was slightly visible, and constantly kept changing colour, becoming deep violet, when it was intense about 3'O clock on Monday morning. It was distinctly visible until sunrise on Monday. The influence of this atmospheric disturbance was unpleasant both for our person and our correspondence. The cold was unpleasantly keen, and all telegraphic communication was stopped for some hours.

Both before and after its height, the aurora affected the working of both sections of the British – Indian Submarine cable, section running east and west and the other North and South. At 8'O clock yesterday morning the magnetic disturbance in the telegraph offices was very strong. The extent of this disturbance may be gathered from the fact that all the lines to England in connection with the British – Indian Submarine cable were affected for hours and so were the Government lines. At Aden, Aurora was brilliant in the extreme."

Today information about solar wind features and interplanetary magnetic field configuration is continuously available from satellites such as ACE. Figure 10 illustrates the solar and ground magnetic variations for a recent storm that occurred near the maximum of solar cycle 23, during 28 to 31 October 2003, known as the Halloween storm. Major storm activity persisted following the eruption of a string of major flares and CMEs for an almost two week period from October 24 to November 4, 2003. Intense CMEs associated with the X17/4b flare on 28 October at 1110 UT, and the CME associated with the X10/2b flare produced an intense shock front at 0600 UT on 29 October as recorded at SOHO (also at L1) and ACE satellites. The impact of the shock wave was observed as a very strong sudden commencement within 12 minutes of its arrival at the satellites, as seen in the ground magnetic records at 0612 UT. The speed of the CME was reported as more than 2100 km/sec, so that the transit time of the CME was ~19 hours[27].

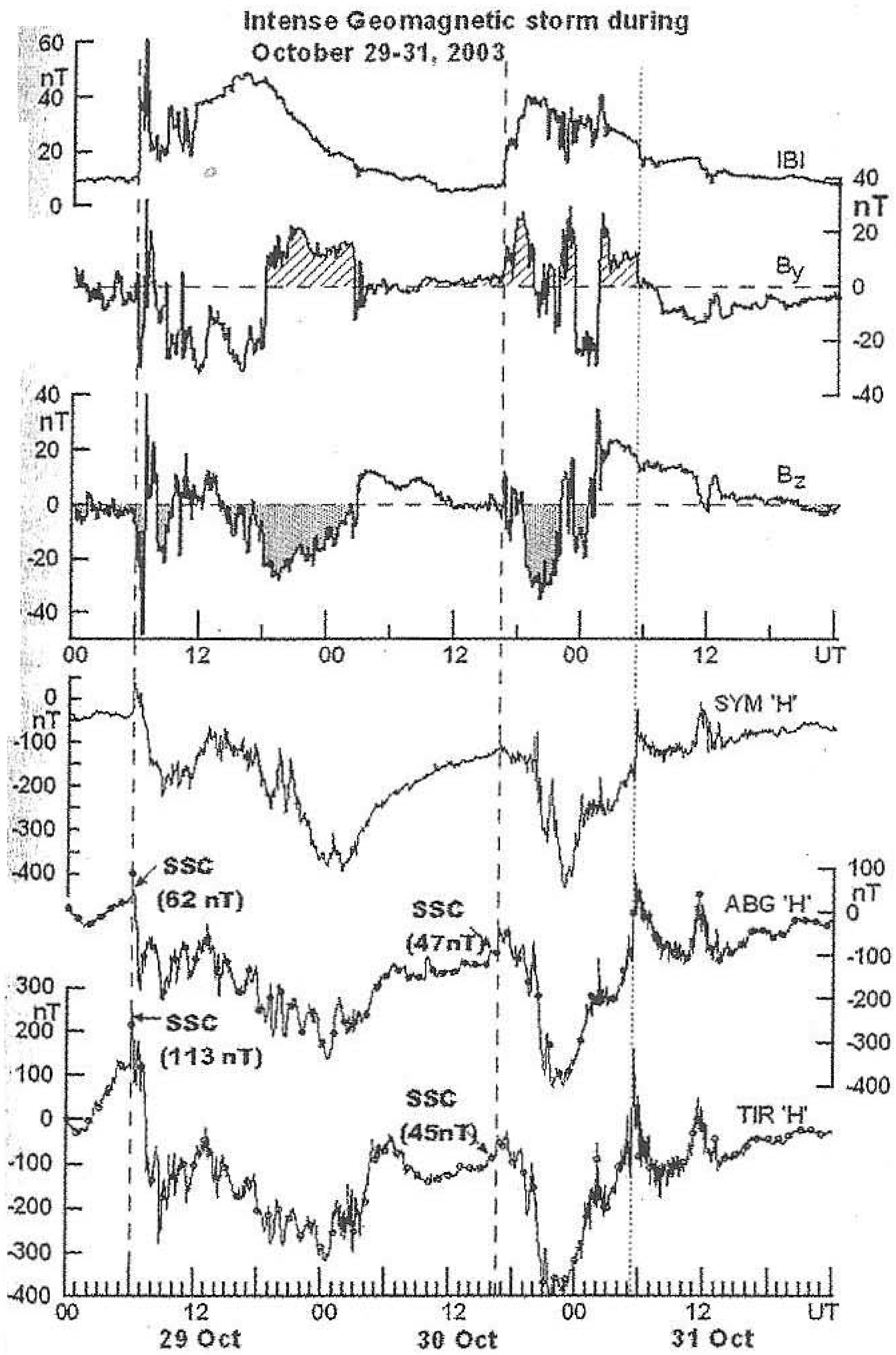

Fig. 10. One minute 'H' component data of ground magnetic field variations at Alibag (ABG) and Tirunelveli (TIR) and the Interplanetary magnetic field parameters |B|, By and Bz recorded by the ACE satellite for the magnetic storm events during October 29-31, 2003. The time of Storm Sudden Commencement (SSC) is marked (after Alex et al.[27]).

Concluding Comments

This article was written with the aim of giving a brief introduction to some of the physical phenomena that produce changes in the geomagnetic field on time scales ranging from over a hundred years down to a few minutes, and spatial scales extending from a few hundred Earth radii down to a few hundred km. As mentioned in the section on Earth's main magnetic field, the main field has been around for nearly 3 billion years, and has undergone many reversals at irregular intervals throughout its history. The field of palaeomagnetism, which has provided much information about the long term history of the geomagnetic field, and is a vast subject in itself has not been touched upon in this article. The other articles in this special issue would bridge some of the gaps that exist in this article such as the magnetic anomalies, effects of magnetic storms on Earth's ionosphere and thermosphere, and space weather effects on today's technological systems. ❐

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